35th PLEA Conference on Passive and Low Energy Architecture

Planning Post Carbon Cities

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Jorge Rodríguez Álvarez
&
Joana Carla Soares Gonçalves
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ABSTRACT: The paper presents and discusses new methods to identify, understand, develop and test novel timber composites for exergy-based adaptive behaviour. The aim of the paper is the development of new design integrated methods for the implementation of active responsive materials in architecture and construction, focused on application for intrinsic thermal responsive and adaptive architectural surfaces. Through material-driven and computational studies, the paper presents a material design survey across three groups of responsive timber composites – single-veneer elements, bi-layers and functionally graded materials (FGM) and a systematic comparative review of their dynamic thermal responsive and structural performance, in relation to operative temperature regulation. Based on the first studies, an oak responsive specimen is developed and further tested towards implementation, as part of an adaptive envelope demonstrator. The research findings suggest that the coordination between geometric arrangement, material layout, hierarchy and binding techniques between the different oak layers leads to the development of a wider range of behavioural system outputs and allow for high resolution steering of the exergy-based responsive timber composites performance in a architectural scale. Finally, the paper speculates on future fabrication strategies and architectural applications of multi-material composites that could introduce new hybrid properties in the responsive architectural system.

KEYWORDS: material studies, timber composites, thermal responsive, building envelopes

1. INTRODUCTION

Building culture is facing an increasing demand for new design and construction strategies that can improve a building’s energy efficiency during its erection and life cycle. The necessity for such change is affirmed by global events, such as ecological degradation, resource scarcity and other environmental-related issues [1]. Moreover, the built environment accounts up to 50% of the global CO₂ emission [2,3], when including the construction phase, just as it consumes vast amounts of energy in running mode, through HVAC systems. This challenge incites research into new material practices that allow for low embodied energy, and by focus on exergy-based responsive systems. Predominantly, responsive systems in architecture rely on digitally controlled mechanical systems with high building complexity, unsustainable material components, and high-energy consumption for their consistent operation and maintenance [4]. In contrast to this superimposition of technical equipment, the enquiry discusses new methods to identify, understand, develop and test novel timber composites for exergy [5] based adaptive behaviour, developable into adaptive building envelope. The aim of the paper is the development of new design integrated methods for the implementation of active and responsive materials in architecture and construction, focused on application for intrinsic thermal responsive and adaptive architectural surfaces. Current studies on the development of active-skin systems provide a wide variety of material systems and configurations, varying from hygroscopic performance of single and bi-layer veneer components [6,7] bi-materials combining wood with various isotropic metals and plastic [8] and multi-grain timber composites [9]. However, only few can predict the performance and efficiency of such skin systems [10]. Through material-driven and computational studies, the paper presents a material design survey across three groups of responsive timber composites, single veneer elements, bi-layers and functionally graded materials (FGM). The research employs a systematic comparative review of their dynamic thermal responsive and structural performance, in relation to operative temperature regulation. Equally concerned with design at the scale of material, element and system, an oak responsive specimen is developed and tested as part of an adaptive envelope demonstrator, focusing on the fabrication and assembly methods used for its development. The experimental case study provides a comprehensive overview of the parameters, variables and syntactic elements for the design, fabrication and steering of thermal adaptive exergy-based building composites. Moreover, it discusses their implementation into architectural design, allowing the potential to embed design into active, material-driven, building-scale construction. Finally, by utilizing the thermal responsive capacities of wood veneer as means of material thinking, the
paper discusses on future robotic fabrication strategies and advanced design methods for the development of multi-material composites. These could introduce new hybrid properties, allowing for local and global control within one thermally driven responsive architectural system.

2. METHODS

The research objective is pursued through a hybrid experimental method, integrating a set of prototypical and computational methods. Using oak veneer, the material studies are organized across three groups of material composites that are being activated, and tested, using a custom-made climate-controlled environmental chamber. The resulting bending behaviour of the responsive composites is being real-time tracked and implemented into a design-integrated high-resolution simulation framework. This, in return, allows for systematic comparative review of the composites’ dynamic thermal responsive environmental and structural performance, in relation to operative temperature regulation, as well as evaluation and cross-validation against the prototypical material studies.

2.1 Prototyping studies

Due to its high thermal expansion coefficient tangentially to growth rings, wood transfers thermally activated dimensional changes into responsive bending behaviour [11]. The direction and magnitude of this responsive capacity is ingrained in the material’s anisotropic characteristics, which are directly related to the anatomy of wood and specifically the fibre direction (fig.2). Employing a thermal environmental stimuli strategy, the selection of the right material is approached through research and understanding of the microstructural principles that facilitate the thermal actuation of wood. The enquiry employs a material survey across a large series of material layouts, configurations and compositions, where various wood types were tested in relation to their thermal responsive capacities. Quarter-cut oak veneer 0.6 mm was selected for its high thermal expansion coefficient [12] tangentially to growth rings (αT =11, 9%), its high material strength (E=343 Nmm²) and homogeneity of samples, presenting an almost linear grain topology. To maintain consistency among material experiments in relation to environmental stimulation, all material composites are being tested in a custom designed climate control environmental chamber. A thermal radiator of 1000 Watt, an ultrasonic humidifier, as well as relative and surface temperature and humidity control units provide a controlled climate conditioning. For the presented study, the conditions for activating the composites were programmed with the use of temperature and humidity sensors, as well as Arduino micro-controller. During all material experiments, a maximum of 38 °C Relative Temperature (RT) was reached, maintaining 30% Relative Humidity (RH). The climate-controlled setup allows the material composites to undergo several activation cycles under consistent conditions in relation to activation time, ensuring accuracy and high fidelity in the results.

2.1.1 Single-veneer elements

The experimental material studies use single veneer elements of 0.6 mm thickness and are based on variations in fibre directionality and material layout. In detail, the studies are organized across five fibre
direction angles, $0^\circ$, $30^\circ$, $45^\circ$, $60^\circ$ and $90^\circ$ and are combined with three material layouts, based on square, rectangular and triangular configurations. After being thermally stimulated, the material responds by dissipating the stress into an elastic deformation perpendicular to the fibre direction, expressed as bending (fig. 3). The synergy between fibre directionality and the element’s dimensional considerations provides us with a great variety of responsive behaviours in terms of bending direction and magnitude.

2.1.2 Bi-layer composites

Figure 4: Structure of bi-layer veneer composites based on differentiated thermal expansion coefficient.

Based on bilayer theory developed for thermally responsive bimetallic alloys, bi-layer composites describe the curvature resulting from combining multiple layers with different coefficients of expansion [13]. The bi-layer wood composite used for the research has been developed using two layers of oak veneer, one active and one restrictive, defined by their fibre direction (fig. 4). The research employs veneer elements of opposing fibre directions—tangential and radial to growth rings, with high and low thermal expansion coefficient respectively. The resulting bi-layer composites allows for higher rigidity in larger responsive surfaces and functional variation in responsive curvature. Moreover, there has been carried out extensive research [14] on different synthetic adhesives for thermal responsive composites, including acrylics, bonding materials and structural glues positioning the shear modulus as primary parameter for a suitable lamination. The material experiments show that alternative local binding methods such as sewing and snapping allow for fast assembly and disassembly, as well as eliminate the risk of delamination of the responsive composites after several activation cycles.

2.1.3 Functionally graded multi-grain composites

Figure 6: Composition of FGM through continuous (a) and stepwise gradation (b).

In a Functionally Graded Material (FGM) both the composition and the structure gradually change over the volume, resulting in corresponding changes in the properties of the material [15]. This is achieved when two different material ingredients change either gradually from one to the other (continuous gradation) or when this transition is performed in a discontinuous way (stepwise gradation) (fig. 6). The research employs a stepwise gradation process to form high-resolution wood composites, using gradual material layering deposition of various grain directionality oak veneer. This material distribution allows for local control of bending stiffness and direction (fig. 7). In the presented prototypical method, binding of the oak layers occurs in the form of local customized PLA snap joints, allowing for control of moving freedom between the elements as well as reuse of the same elements in other geometrical configurations (fig. 4).

Figure 7: Various FGM configurations leading to monoclastic(a), synclastic(b) and anticlastic(c) curvatures.

2.2 Computational studies

Along with the material studies, the simulation, prediction and steering of the responsive behaviour and performance of exergy-based building composites incites research into the development of material-based computational methods and models. This give us a good insight into the possibility to reconceptualise the material use in architectural design, in order to fulful formalized design requirements. However, programming a system’s response in the material level requires an in-depth
understanding of the characteristics of wood as a natural material. Moreover, it requires the development of material-driven computation strategies that incorporate a range of design, fabrication and actuation parameters [16]. While single-directional responsive curvature can be estimated mathematically through Geometric Representation Models (GRM) [12], the interaction between multiple layers can be a computationally intensive and complex task. For that reason the form-finding and overall structural behaviour of the responsive composites, in terms of deformation and bending stresses, is simulated with spring-based physics engine, using K2 solver in Grasshopper, Rhinoceros. In order to compute the differentiated behavioural response of all three groups of material composites based on environmental conditions, the research employs custom-made modules. This allows for implementation of the dynamics and critical influencing parameters for each material configuration. The form finding of the reactive elements occurs by assigning the grain orientation of each fibre into weighted values for hinges, along the internal edges of a triangulated mesh, corresponding to the material layout. The resulted vertex map of graded weighted values is being informed by the thickness and elastic limitations of the material. Moreover, it is recalibrated based on measurements from the physical experiments, with the use of infrared camera (Kinect V2) for real-time object tracking and point cloud export. The accuracy of the simulation at this level can be up or down sampled by changing the resolution of the mesh topology, eliminating the deviation between physical and digital tests, at the cost of higher processing time.

The described digital experiment represents a bottom-up approach, where the designer provides material specification data affecting the responsive performance and utilizes computational tools for simulating the emerging behaviour. In order to create a design-integrated workflow relating informed design iteration with material-driven fabrication strategies, the computational model was further developed, adopting a top down approach. Starting from a target principal curvature as input, a triangulated mesh is re-constructed, carrying edges of the same spring strength. The target input curvature is then analysed and based on the resulting values coupled with the ratio between size and thickness of the desired material layout, the mesh edges are informed with differentiated strength values. After the geometry is simulated and unrolled using dynamic relaxation, the 2d pattern of the informed edges represent the grain topology. Thus, it can be used as fabrication file for the production of exergy-based wood composites with bespoke responsive capacities. This dual computational method allows for a synergy between design, performance and fabrication. Moreover, it proposes the emergence of a new design integrated workflow that not only entails high-resolution simulation of the system’s ingrained material capacities, but also form a predictive modelling framework for producing material specification data from formalized design criteria.

Figure 8: (a) Grain pattern bitmap, (b) Line detection, (c) Informed mesh topology, (d) Dynamic spring-based simulation displaying Gaussian curvature of activated FGM timber composite at 38 °C.

3. DESIGN EXPERIMENTATION

Through a series of design and material experimentation, this study attempts to analyse, manipulate and calibrate the hybrid bending behaviour of multi-directional oak veneer composites. Organized in a reciprocal open topology, the study discuss the development of a microclimate-sensitive responsive surface, which can be tuned to desired performance related to thermal sensation. Through a physical demonstrator of 2 x 3 m, the study explores the thermal responsive behaviour of functionally graded multi-grain oak composites in relation to differentiated geometry, as part of an adaptive envelope demonstrator. Moreover, the enquiry presents the fabrication and assembly methods used for its development. Computational methods and computer-controlled fabrication machines enabled the design and production of the uncoated veneer structure. The specimen consists of 50 reactive multi-layer oak veneer elements of various grain directionality, leading to single, double
and multi-directional bending. The system is developed around overlapping cells of 300 x 300 mm, using snap joints for binding the various oak veneer layers together, interlocked through CNC joints along their edges. The configuration ensures structural rigidity while minimizing weight. The dimensions of the elements used for the responsive composites were defined through an environmental benchmark model, created in Ladybug plugin for Grasshopper, Rhinoceros [17]. The model displays a parallel evaluation study of how the various bending states of the responsive membrane affect the amount of solar energy passing through the composite membrane, providing the designer with a direct relation between material behaviour and environmental performance. The experimental responsive specimen is being exposed and activated in 38°C RT, maintaining 30% RH. The responsive behaviour is expressed with variations in magnitude, ratio and bending direction and allows for local changes while addressing consistent global structural and environmental performance. Within these investigations, the hierarchy and the anisotropic characteristics of the composite is proved to be the driving force of the programmed deformation. With the use of infrared camera, the activated responsive material system is being real-time tracked and the resulted point cloud is used as validation method for the fidelity of the simulation. This allows for deviation analysis between the physical and digital studies. The system demonstrates the integration of a responsive material system into a functional, modular and highly adaptable system in an architectural scale.

Figure 9: Thermal responsive functionally graded surface, using three multi-directional layers of oak veneer. The benchmark model ensures that the design system is tuned to desired performance related to thermal sensation.

4. RESULTS

The enquiry presents an experimental hybrid prototypical method employing advanced material studies and high-resolution simulation tools for exergy-based building composites. The study focuses on the development of adaptive material systems, developable into adaptive building envelopes. Through a material design survey across three groups of responsive timber composites - single veneer elements, bi-layers and FGM- and a computational framework for systematic comparative review of their dynamic thermal responsive and structural performance, the enquiry explores the potentials of a design-integrated workflow that allows for bidirectional exchange of information, between design and fabrication. Within this process, the role of the designer lies on the interfacing of those parallel simulation and design models, as well as the coordination of qualitative and quantitative data processing between the various resolution design agencies. The case study proves that the integration of a hybrid material-driven adaptive workflow from design to production, can inform the design chain with a series of critical results, allowing for high precision performance steering of responsive systems:

1. The research findings suggest that fibre directionality constitute the main factor for steering the bending direction. The relation between size, shape and material thickness determines the bending magnitude as well as the reaction time needed for the responsive performance of the material composite. Thicker material samples require more time to address the temperature change into thermal material expansion and therefore will withstand the intrinsic deforming forces for a longer period. Moreover, in longer pieces that are cut across the grain direction, the resulting change in curvature is greater.
2. Homogeneity of samples. Even if oak is considered homogeneous wood type, it is still required a detection method of wood directionality for informing both the simulation and fabrication process and ensure consistent behaviour.
3. Single and bi-layer thermally activated veneer composites deliver single-directional curvature of various magnitude, while FGM multi-grain composites allow for multi-directional functional bending. These combine high resolution steering of performance with high material stiffness and thus, present an increased potential for implementation in building construction, as a responsive structural component. Moreover, the assembly strategy of tailoring responsive composites, combining multiple elements, overcomes the dimensional limitations of quarter-cut veneer (400-1200 mm in width) and allows for the production of increasingly larger systems.
4. Given the organic and extensive parameters of wood as a vascular tissue, the excessive or uneven distribution of heat due to UV radiation across the grain can cause uneven distribution of strain in the system. This may consequently result in...
microstructural damage (plastic deformation) and an overall reduction of responsiveness over time. This increases material fatigue [10] and can affect the operational life of the system. Thus, it is a performative aspect that we cannot exclude from the simulation methods, used in the design process.

5. Material calibration is directly related to the environmental conditions and therefore, the same control that is being carried out through activation must be also maintained through fabrication process. Thus, it is required diligent measuring of the ingrained Moisture Content of wood, as well as control over relative temperature and humidity levels during production.

5. DISCUSSION

The case study is a limited enquiry and further work is needed to evaluate the performance of the exergy based building composites for the development of adaptive material systems across multiple samples and scales with different strategies of differentiation. The development of a responsive architectural system based on anisotropic material properties of wood, presents methodological and technical challenges that need to be considered and further implemented, within the design chain. Thus, the emergence of new design integrated workflows that not only entail high-resolution simulation of the material behaviour and performance, but also form a predictive modelling framework of the system’s behavioural shifts and inconsistencies, after several operational cycles, becomes crucial. Further exploration needs to occur for the development of adopted and adapted design methods that can interface various resolution data between the prototypical material studies, the computational model and the fabrication process. This will allow for high-resolution steering of the system’s thermal responsive and environmental performance. This careful classification of data exchange will also allow for applying the presented methods in a bigger architectural scale, maintaining accuracy. Moreover, the possibility of employing robotic fabrication for the development of the responsive material composites could allow for high-resolution material specification that can address design and performance demands, with a build-per requirement approach. This in return could increase the product’s structural and environmental performance, enhance material efficiency, promote material economy and optimize material distribution, enabling the implementation of a bespoke material-driven fabrication into design, as an aspect of sustainability. Finally, along with the various grain material deposition that is being investigated in the presented study, the shift towards a multi-material layering could introduce new hybrid properties in the responsive architectural system.

REFERENCES

Validation of Metrics for Prediction of Daytime View-Out Quality and Privacy
Human Subjects in Virtual Reality

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ABSTRACT: Explicit models that rely on either measurements or calculations of physical quantities as input to express certain phenomena affecting the multi-sensory experience of ‘spatial quality’ are very useful in the early stages of building design. This paper proposes a modification of previously proposed metrics for expressing the phenomena ‘View-out quality’ and ‘Degree of privacy’ in living rooms during the daytime. The metrics were evaluated in a virtual reality experiment involving 90 subjects assessing two different window areas at three different urban locations. The results indicate that the proposed metrics to a wide extend are on par with the actual mean votes of room occupants and could, therefore, be useful to qualify the view-out quality and degree of privacy design proposals during the design process.

KEYWORDS: Spatial quality, View-out, Privacy, Window area, Urban environment, Virtual reality

1. INTRODUCTION

The spatial quality of indoor environments is a subjective human conviction based on a multi-sensory experience of a certain indoor space. Many architectural theoreticians have articulated various phenomena that seem to affect the ‘quality experience’ of indoor environments. Some describe phenomena using terms such as ‘bodily identification’, ‘spatial juxtaposition and interpenetration’, and ‘enclosure, demarcation, texture’ e.g. [1,2] but refrains from establishing any explicit rules or recommendations on how to obtain a perception of quality regarding these phenomena. Others describe desirable traits of indoor spaces and formulate descriptive guidelines for obtaining these traits [3,4]. Such explicit guidelines are interesting from a practical point of view where prediction and explicit articulation of spatial quality, e.g. in a design situation, often is desirable. Guidelines can also be used as inspiration for empirical investigations of relations between physical quantities (such as illuminance, temperature, decibel, etc.) and phenomena affecting spatial quality. This type of investigations is often employed by building researchers interested in making models of reality, e.g. Fanger [5] who studied the relation between indoor temperature (physical quantity) and thermal discomfort (phenomenon affecting spatial quality), or Wienold and Christoffersen [6] who studied the relation between light levels (physical quantity) and the notions of glare (phenomenon affecting spatial quality). As in the two examples above, this type of research often leads to the establishment of an explicit parametric model where a phenomenon affecting spatial quality is described by a model that relies on either measurement or calculation of physical quantities as input. Such models can be used e.g. for performance prediction in the early stages of building design; now the risk of thermal discomfort and/or glare in certain building design (set of design variables) can be derived from computer simulations of the indoor temperature and lux level (physical quantities), respectively. Figure 1 illustrates the overall principle of attempts to describe the perception of spatial quality by making models of a phenomenon relying on calculations of physical quantities (using models) – quantities that in the end is affected by the manipulation of design variables. Note that phenomena and design variables, respectively, might interact with or be a function of one another. For example, it is practically self-explanatory that design variables defining windows govern many phenomena that affect the perception of spatial quality. The phenomena ‘view-out quality’ and ‘privacy’ are completely governed by the number, size, placement, and transparency of windows. These design variables also have a significant influence on other important phenomena such as the perception of lighting, noise, thermal comfort, and air quality – phenomena that already have well-established models that relate them to a physical quantity (e.g. luminance, illuminance, temperature, and decibel).
which can be predicted during the design stage using simulation models.

![Figure 1: The principle of modelling phenomena affecting the spatial quality using measurement or model calculation of physical quantities as a function of design variables.]

However, the phenomena view-out and privacy does currently not have any well-established calculable physical quantity – a metric – which is why recent research has proposed calculable quantities that can be used to make explicit models of the phenomena view-out quality and/or privacy \[4, 7, 8\]. However, further research is needed to validate these proposals; in this paper, we present a validation study of a modification of a previously proposed metric for prediction of daytime view-out quality and privacy using virtual reality (VR).

2. METHOD

The study aims at validating a modified version of the metrics defined by Purup et al. \[8\] by exposing human subjects to various indoor environments in virtual reality and ask them a series of questions related to the perception of view-out quality and the notion of privacy. The following subsections briefly describe the proposed metrics and provide details about the VR experiment designed to validate the proposed metrics.

2.1 The metrics

The original proposal for a ‘view-out quality’ metric expresses the subjective desirability of the view when looking at the surroundings through a window from a certain point in the room. The scale is from 0 to 1, where 0 is ‘not desirable’ and 1 is ‘desirable’ \[8\]. This definition is maintained in this study, but whereas the original metric is based on a relation between the limited view-out area through the window and the area of the ‘view potential’ of the site (reference view), i.e. a view unobstructed by the room/window geometry, it is instead claimed that ‘view-out quality’ can be predicted as the area-weighed average of the desirability of view to different elements in the surroundings; we call this the ‘window view-out quality’. Figure 2 (left) shows an example of this where the desirability of view to a nearby group of trees has been rated 1 (covering \(1/2\) of the area in the view), to the sky 0.5 (covering \(1/4\) of the area in the view), and to a neighbouring building 0.0 (covering \(1/4\) of the area in the view) making the window view-out quality \(=0.63\). It is then the hypothesis that this average corresponds to the average subjective vote of a group of people assessing the overall window view-out quality from this specific point on a scale from 0-1. The ‘degree of privacy’ is a metric expressing whether privacy is being compromised due to unwanted exposure to the surroundings through the window. The scale is redefined so that the scale runs from 0 to 1, where 0 is ‘not private’ (yes, there is a privacy issue) and 1 is ‘private’ (no privacy issues). It is claimed to be calculable in the same way as the ‘view-out quality’ but the elements in the surroundings are rated binary, where 0 is ‘compromised’ or ‘I care’ and 1 is ‘not compromised’ or ‘I do not care’. Figure 2 (right) shows an example where privacy due to the exposure to an opposite building is rated 1, but privacy due to exposure to the sky and trees is rated 0. The area-weighted ‘degree of privacy’ is \(=0.75\).

![Figure 2: Example of how elements in the surroundings can be assigned factors. Left: The desirability to have the element in the view. Right: Risk of compromising privacy due to view-in from the element. Picture from ref. \[8\].]

2.2 Virtual reality experiment

Virtual reality (VR) refers to computer technologies that allow a user to interact with a computer-simulated environment. VR is intended to give users the feeling of being present in another visual environment than the one they are actually in. Using VR is thus a powerful and inexpensive way to expose people to many different visual environments in a short time. The VR technology available from VIVE and Unity was exploited for validation of the metrics proposed in this paper. The following sections explain the experimental setup.

Surroundings

Three locations in dense parts of the city of Aarhus, Denmark, were selected and used as surrounding in the experiment (Figure 3). Surrounding A was next to a green area and a local walking and biking route
between the city and a suburb area (figure 3A). Surrounding B was at a new residential area in the old industrial harbour (Figure 3B). Surrounding C was next to a railway (Figure 3C). A 5-10 minute long 360° video sequence was recorded at all three locations a height of 1.7 meters. The videos were recorded on a sunny day on the morning of 20 March 2018 (early spring, i.e. no leaves on the trees). These videos were imported to Unity, wrapped around the room geometries, and run in a loop during the experiment.

VR models of rooms
Two living rooms of 24 m² (4x6 m) with a room height of 2.5 m were modelled in SketchUp. The rooms were alike except for the window size in the façade, see Figure 4. The models were exported to Unity where they were inserted in the videos of the three surroundings; Figure 5 depicts the two rooms inserted in surrounding A. The rooms were situated on the ground floor throughout the whole experiment.

Questionnaires
Two questionnaires were developed. One for rating the desirability of view and privacy compromise of the eight different elements in the surroundings marked with yellow (?) in Figure 3, and one for rating window view-out quality and degree of privacy in each combination of room and surrounding (six scenarios in total) as described in section 2.1. The questionnaires were programmed on to an interactive ‘virtual tablet’ as shown in Figure 6.

Participants
A total of 90 participants were recruited for the experiment. Some descriptive statistics about the participants are shown in Table 1. The participants were recruited in different ways, 1) pitches in engineering classes with the possibility to sign up for the experiment, 2) Facebook bulletins in different groups, 3) physical posters in university buildings, and 4) private contacts. The prospect of a 25% chance to win a cinema ticket was used as an incitement for participation.

Experimental design
The experiment was a randomised crossover experiment. There are six possible combinations of the sequence of surrounding A, B, and C (Figure 3). The participants were exposed to one of these sequences starting with either the room with a moderate window area (R1) or the room with a large window area (R2),

Figure 3: The three locations used in the VR experiment. The yellow (?) mark the elements that the participants were asked to rate in terms of desirability in the window view-out and compromise of privacy. Elements in A: Building, creek, park, road, trees, B: Building, promenade, sea, gardens, C: Building, parking lot, railway, trees.

Figure 4: The living room used in the VR experiment. Left: Room with a moderate window area (3.6 m²). Right: Room with a large window area (9.4 m²).

Figure 5: Examples of VR environments where the subjects voted (sitting on a couch near the window). Top: large glazing area. Bottom: Moderate glazing area.
and then alternating between R1 and R2 throughout the sequence of surroundings. This led to six combinations of surroundings and rooms in 12 different sequences. The 12 sequences were copied eight times resulting in 96 lots; the first thing a participant did before entering VR was to draw a sequence no. from this pool of lots. The assessments inside VR was executed sedentary.

![Figure 6: Example of questionnaire questions on the interactive ‘virtual tablet’.](image)

**Table 1: Descriptive statistics of the participants.**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of participants</td>
<td>90</td>
</tr>
<tr>
<td>Sex</td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>44 %</td>
</tr>
<tr>
<td>Male</td>
<td>56 %</td>
</tr>
<tr>
<td>Age</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>25.7 years</td>
</tr>
<tr>
<td>Range</td>
<td>16.0 years</td>
</tr>
<tr>
<td>Nationality</td>
<td></td>
</tr>
<tr>
<td>Danish</td>
<td>86 %</td>
</tr>
<tr>
<td>Others</td>
<td>14 %</td>
</tr>
<tr>
<td>Vision aid</td>
<td></td>
</tr>
<tr>
<td>Glasses</td>
<td>3 %</td>
</tr>
<tr>
<td>Contact lenses</td>
<td>20 %</td>
</tr>
<tr>
<td>None</td>
<td>77 %</td>
</tr>
</tbody>
</table>

Once inside the VR, the participant starts by entering a ‘Start and exercise’ scene to practice how to use the controllers, how to answer the questionnaire on the virtual tablet (Figure 6), how to teleport (i.e. to move around in the model without the need of physical motion). The participant then entered personal information about age, sex, nationality, education, health, mood, fatigue, and visual aids before entering the surroundings (one at the time) to rate the elements marked with (?) as shown in Figure 3. The participant then rated the six combinations of surroundings and rooms in the drawn sequence. Inside each combination, the participant was first allowed to teleport around to explore the space to get a general impression of the space and its internal and external surroundings. The participant was then teleported to the couch in the room nearby the window; all participants were located in this position while they answered the questionnaire (see Figure 5). After rating all six combinations, the participant was teleported to the ‘Start and exercise’ scene where the lottery for a cinema ticket was executed before the participant left the VR environment. The above-described procedure took 25-30 minutes per participant.

### 2.3 Statistical analysis

The collected questionnaire data were first tested for bias between different subgroups generated based on the general personal questions (gender, education, health, mood, fatigue, visual aids, and time of day in VR) followed by a statistical analysis of the data as shown in Figure 7. All tests after the Shapiro-Wilk test applied a level of significance of p=0.05. The exception for the use of the flowchart in Figure 7 is for the binary questions about privacy; here a Chi-square test was used.

![Figure 7: Flowchart of the statistical analysis.](image)

### 3. RESULTS

The bias analysis showed that there was only a statistically significant difference (p<0.05) between subgroups for a very few numbers of questions. These statistically significant differences were spread quite randomly across the questions and were often only for very small differences in mean value; there were no reasons to divide the sample (90 participants) into subgroups before further statistical analysis of differences in the questionnaire data.

Table 2-7 shows the mean (µ) and standard deviation (σ) of the window view-out quality and degree of privacy votes for all elements in the three surroundings. Furthermore, the difference between the votes for each element is shown. For window view-out quality, the difference is always the mean of the element in the first column minus the mean of the element in column four and forward. For example, in Table 2, this means that the mean vote for the view to
the ‘Road’ is -.40 lower than for the ‘Creek’. For privacy votes, the difference is always yes-vote for the element in column four and forward minus the element in the first column. For example, in Table 3, 40 more votes ‘yes’ (i.e. a privacy issue) for the view to the ‘Road’ than for view to the ‘Creek’. The bold font indicates that the difference is statistically significant at p<0.05. This statistical analysis was made for dataset excluding outliers; there were only one or no outliers in each dataset.

For surrounding A (Table 2 and 3), the ‘Road’ was the least desirable element both in terms of window view-out and privacy followed by ‘Building’ but ‘Building’, and ‘Park’ had the same vote in terms of privacy issues. There were only minor non-statistical significant differences in window view-out mean vote between ‘Creek’, ‘Park’, and ‘Road’, and ‘Trees’ was the element with fewer privacy issues followed by ‘Creek’ which both were preferred over ‘Park’ and ‘Building’. Overall, it seems that view to nature elements are in general preferred over urban elements but that some mixed nature and urban elements (park) may lead to privacy issues.

Table 2: View-out quality votes of elements in Surrounding A. Significance test: Freidman’s test. Bold is p<0.05.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Creek</th>
<th>Road</th>
<th>Park</th>
<th>Trees</th>
<th>Building</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>.70</td>
<td>.30</td>
<td>.78</td>
<td>.80</td>
<td>.55</td>
</tr>
<tr>
<td>μ</td>
<td>.27</td>
<td>.23</td>
<td>.17</td>
<td>.17</td>
<td>.23</td>
</tr>
<tr>
<td>σ</td>
<td>-.40</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mean vote</td>
<td>.08</td>
<td>.10</td>
<td>.02</td>
<td>-</td>
<td>-.25</td>
</tr>
<tr>
<td>Positive vote</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Negative vote</td>
<td>-</td>
<td>-</td>
<td>.25</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3: Privacy votes of elements in Surrounding A. Difference yes-votes. Bold is p<0.05.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Yes</th>
<th>No</th>
<th>Creek</th>
<th>Road</th>
<th>Park</th>
<th>Trees</th>
<th>Building</th>
</tr>
</thead>
<tbody>
<tr>
<td>Promenade</td>
<td>18</td>
<td>71</td>
<td>40</td>
<td>19</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sea</td>
<td>58</td>
<td>31</td>
<td>-</td>
<td>-21</td>
<td>-48</td>
<td>-21</td>
<td>-</td>
</tr>
<tr>
<td>Gardens</td>
<td>37</td>
<td>52</td>
<td>-21</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Building</td>
<td>10</td>
<td>79</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>27</td>
</tr>
<tr>
<td>Parking lot</td>
<td>37</td>
<td>52</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

For surrounding B (Table 4 and 5), the ‘Sea’ and ‘Promenade’ was almost equally desirable in terms of window view-out quality elements compared to ‘Gardens’ and ‘Buildings’ which were approx. equally less desirable.

Table 4: View-out quality votes of elements in Surrounding B. Significance test: Freidman’s test. Bold is p<0.05.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Promenade</th>
<th>Sea</th>
<th>Gardens</th>
<th>Building</th>
</tr>
</thead>
<tbody>
<tr>
<td>μ</td>
<td>.88</td>
<td>.90</td>
<td>.62</td>
<td>.65</td>
</tr>
<tr>
<td>σ</td>
<td>.18</td>
<td>.14</td>
<td>.27</td>
<td>.25</td>
</tr>
<tr>
<td>Mean vote</td>
<td>-.26</td>
<td>-.28</td>
<td>-.26</td>
<td>-.25</td>
</tr>
<tr>
<td>Positive vote</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Negative vote</td>
<td>-.23</td>
<td>-.25</td>
<td>-.03</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5: Privacy votes of elements in Surrounding B. Difference yes-votes. Bold is p<0.05.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Yes</th>
<th>No</th>
<th>Sea</th>
<th>Gardens</th>
<th>Building</th>
</tr>
</thead>
<tbody>
<tr>
<td>Promenade</td>
<td>32</td>
<td>57</td>
<td>-15</td>
<td>5</td>
<td>-2</td>
</tr>
<tr>
<td>Sea</td>
<td>17</td>
<td>72</td>
<td>-</td>
<td>-20</td>
<td>-13</td>
</tr>
<tr>
<td>Gardens</td>
<td>37</td>
<td>52</td>
<td>-</td>
<td>-</td>
<td>-7</td>
</tr>
<tr>
<td>Building</td>
<td>30</td>
<td>59</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

It is noted that the element ‘Promenade’ had a high degree of ‘Sea’ view in it as well. There is a slight tendency for the ‘Sea’ to have fewer privacy issues over the remaining elements. Overall, ‘Sea’ seems to be very desirable in terms of window view-out quality as the promenade with only partial view to the sea (promenade) was voted almost just as high as ‘Sea’.

Table 6: View-out quality votes of elements in Surrounding C. Significance test: Freidman’s test. Bold is p<0.05.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Railway</th>
<th>Trees</th>
<th>Building</th>
<th>Parking</th>
</tr>
</thead>
<tbody>
<tr>
<td>μ</td>
<td>.33</td>
<td>.64</td>
<td>.47</td>
<td>.35</td>
</tr>
<tr>
<td>σ</td>
<td>.25</td>
<td>.22</td>
<td>.22</td>
<td>.24</td>
</tr>
<tr>
<td>Mean vote</td>
<td>.31</td>
<td>-.17</td>
<td>-.14</td>
<td>-.25</td>
</tr>
<tr>
<td>Positive vote</td>
<td>.14</td>
<td>-.29</td>
<td>-.02</td>
<td>-</td>
</tr>
<tr>
<td>Negative vote</td>
<td>.02</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 7: Privacy votes of elements in Surrounding C. Difference yes-votes. Bold is p<0.05.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Yes</th>
<th>No</th>
<th>Railway</th>
<th>Trees</th>
<th>Building</th>
<th>Parking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Promenade</td>
<td>20</td>
<td>70</td>
<td>-12</td>
<td>31</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>Sea</td>
<td>8</td>
<td>82</td>
<td>.43</td>
<td>.38</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Gardens</td>
<td>51</td>
<td>39</td>
<td>-.07</td>
<td>-</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>Building</td>
<td>46</td>
<td>44</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

For surrounding C (Table 6 and 7), the ‘Trees’ was preferred in terms of both window view-out quality and privacy compared to ‘Railway’, ‘Buildings’, and ‘Parking’. The ‘Railway’ was the least desirable element to have in the window view-out but in terms of privacy the less desirable was ‘Parking’ closely followed by ‘Building’. The mean votes (μ) and standard deviation (σ) for window view-out quality and degree of privacy in the rooms with different window areas in all three surroundings are shown in Table 8 and 9. Furthermore, the differences in mean votes between the different combinations are also shown. The differences are the mean for the combination in the first column minus the mean of the combination in columns two and three.

Table 8: View-out quality votes of elements in Surrounding C. Significance test: Freidman’s test. Bold is p<0.05.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Railway</th>
<th>Trees</th>
<th>Building</th>
<th>Parking</th>
</tr>
</thead>
<tbody>
<tr>
<td>μ</td>
<td>.33</td>
<td>.64</td>
<td>.47</td>
<td>.35</td>
</tr>
<tr>
<td>σ</td>
<td>.25</td>
<td>.22</td>
<td>.22</td>
<td>.24</td>
</tr>
<tr>
<td>Mean vote</td>
<td>.31</td>
<td>-.17</td>
<td>-.14</td>
<td>-.25</td>
</tr>
<tr>
<td>Positive vote</td>
<td>.14</td>
<td>-.29</td>
<td>-.02</td>
<td>-</td>
</tr>
<tr>
<td>Negative vote</td>
<td>.02</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

In terms of window view-out quality (Table 8), the large window area at surrounding B is preferred over all other variations. In general, a large window area is unequivocally preferred over a moderate window area in all surroundings but it is not statistically significant at locations A and C where the differences in the mean are also small compared to location B.
A moderate window area in surrounding B is preferred over a large window in surrounding A and C which suggests that surrounding B is a more desirable surrounding than A and C.

Table 8: Window view-out quality votes, moderate (mod.), and a large window at all surroundings (S). Bold is p<0.05.

<table>
<thead>
<tr>
<th>Window size</th>
<th>S</th>
<th>µ</th>
<th>σ</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mod.</td>
<td></td>
<td>0.40</td>
<td>0.23</td>
<td>-</td>
<td>0.36</td>
<td>0.10</td>
<td>-0.10</td>
<td>0.59</td>
<td>-0.18</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>0.76</td>
<td>0.21</td>
<td>-</td>
<td>-</td>
<td>-0.26</td>
<td>-2.26</td>
<td>0.23</td>
<td>-0.18</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>0.50</td>
<td>0.27</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.00</td>
<td>0.49</td>
<td>0.08</td>
</tr>
<tr>
<td>Large</td>
<td></td>
<td>0.50</td>
<td>0.22</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-0.49</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>0.89</td>
<td>0.13</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-0.41</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>0.58</td>
<td>0.27</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

In terms of the degree of privacy (Table 9), the large windows at all surroundings have a statistically significant higher privacy issue than moderate windows but the difference is small (.17, .09, and .11 respectively). A moderate window area is better in terms of privacy independently of surroundings except for surrounding C where a larger window area has fewer privacy issues than a moderate window area when compared to surrounding A and B; surrounding C has no element in the surroundings with a continuous flow of people passing.

The area-weighted window view-out quality and degree of privacy based on the votes in Table 2-7 are shown in Table 10. View to the sky was needed for this calculation; the participants when inside the rooms added votes regarding the sky in terms of window view-out and privacy. Furthermore, the mean votes from all combinations are shown for comparison.

Table 9: Privacy votes, moderate (mod.), and large window (win.) at all surroundings (S). Bold is p<0.05.

<table>
<thead>
<tr>
<th>Window size</th>
<th>S</th>
<th>µ</th>
<th>σ</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mod.</td>
<td></td>
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<td>0.27</td>
<td>-</td>
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<td>-0.15</td>
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<td>-</td>
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<td>-0.51</td>
<td>-0.11</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>0.02</td>
<td>0.08</td>
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</tr>
<tr>
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<td>0.26</td>
<td>-</td>
<td>-</td>
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<td>-</td>
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</tr>
<tr>
<td>C</td>
<td></td>
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<td>-</td>
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</tbody>
</table>

The calculated means for window view-out quality are rather close to the experiment means except for the moderate window in surrounding A. The calculated means for the degree of privacy are slightly off compared to the experiment means. A statistical analysis (paired t-test) of the data showed that it is not possible to reject that the difference between the means is zero, and therefore there is no statistical evidence of a difference between the calculated and the experimental window view-out quality and degree of privacy.

4. CONCLUSION

The results from the experiment indicate that the proposed metrics for predicting the room occupants’ mean votes of the spatial quality phenomena ‘window view-out quality’ and ‘degree of privacy’ to a wide extend is on par with the actual mean votes of room occupants; however, more detailed data analysis and more experiments are needed to tune the correlations and ensure validity. Furthermore, the results suggest that there is a certain trade-off between the daytime window view-out quality and privacy when it comes to the size of glazing areas. It is noted that there are some limitations to the study, e.g. that it only deals with daytime view-out and privacy, and that the investigated apartments are placed on the ground level.

REFERENCES

The influence of discomfort glare on shading devices and its implications for daylit offices in tropical regions

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Abstract: With the growing trend of using glazed facades on buildings to utilize daylight, the occupants usually install shading devices to prevent discomfort glare. It is necessary to determine the applicability of the criteria for the discomfort glare based on the perceptions of people in South-East Asia for applying a controlled-strategy for shading devices. Post-occupancy evaluations were performed in office spaces. The optical properties of glazed façades were investigated with the monitoring of the occlusion level of shading devices to determine their performance based on the opening-glass area and the shading area. High dynamic range (HDR) images were collected to obtain daylight glare probability (DGP). Meanwhile, questionnaires were given to survey the occupant’s responses. The results revealed a preference for lower DGP than that current recommendations. Statistical approaches were applied to determine the level of actual glare perception. To achieve visual comfort, glazed façades are required to use shading devices. Important features of the building’s façades system are highlighted, and its implications for shading devices usage are discussed. The finding from this study can be considered as an initial step for improving comfort evaluation and buildings’ façades guideline for tropical regions, which are currently being encouraged to utilize daylight without discomfort glare control strategies.

1. INTRODUCTION

The strategies to enhance human health and well-being have advanced the occupants of the buildings to the forefront of building practices to make them environment and inhabited people friendly [1]. Office buildings have been gaining popularity worldwide, particularly in Southeast Asia, and new office space is predicted to increase owing to regional economic growth [2]. As the trend toward highly glazed facades continues to increase [3], the transmitted solar effect has become crucial to avoid excessive brightness that can cause visual discomfort.

Visual comfort in these interior spaces is commonly indicated by discomfort glare [4]. For indoor daylit spaces specifically developed for large area sources or daylight, the well-known glare index is Daylight Glare Probability or DGP. It considers luminance contrast as well as vertical illuminance on the observer’s eye. The concept has been tested with human subjects, resulting in statistically high correlations [5]. It is marked as DGP below 0.35 is perceived as imperceptible, between 0.35 and 0.40 is perceptible, between 0.40 and 0.45 is disturbing, while above 0.45 is intolerable [6]. However, the study has been conducted on western subjects. The visual perception in South-East Asians is different from that in the west, owing to a difference in climate, demography, and cultural aspects [7]. In tropical regions, the field studies to determine DGP were carried out by Mangkuto et al. [7] in Indonesia and by Hirning et al. [8] in Malaysia. These studies demonstrated a lower threshold values of glare sensation with a preference of DGP below 0.35, which is perceived as imperceptible glare. Both considered solar glare control strategies. The glare sensation of the occupants was expressed in the questionnaire survey. Mangkuto suggested that imperceptible glare was at the rankings of DGP below 0.21. Meanwhile, Hirning recommended a DGP below 0.22, and both suggested the threshold of intolerable glare as DGP above 0.26. The agreement in the tropical study illustrated that South-East Asians prefer low amounts of DGP. Thus, the post-occupancy evaluation method is a required process for obtaining occupants feedback thoroughly.

The main function of glazed windows is stated to be daylight utilization. The geometry and its specifications becomes more important, since it has a great impact on the interior lighting with consideration on discomfort glare. The glazing area known as the window-to-wall ratio or WWR is the percentage area determined by dividing the building’s glazed area by its total exterior wall area. On the contrary, the optical properties of glazed facades are another key referring to the amount of visible light that is allowed to pass through a glazing system. It can be described as visible light transmission or VLT. However, the occupants usually install internal blinds to allow themselves to maintain their comfort [9]. Thus, it is important to study discomfort glare and the occupants’ behaviour with the shading devices usage taking into account their influence on interior spaces,
which can satisfy the occupants by providing comfortable conditions to them.

2. RESEARCH METHODS

2.1 Case study office spaces

Eight high-rise office spaces located in Thailand, and the other three in Singapore were selected, and all reflect the generic physical environment of an open-plan daylit spaces, which was commonly found in the urban context of tropical regions. The field-study was performed for 3-5 days during working hours from 8.00 – 17.00 h local time. All the sample data were homogeneous in terms of the number of buildings, and individual in terms of the subjective responses on their corresponding DGP. The results were presented based on the countries with considerations on their mean values.

The target occupants were a seated-persons with the direction of facing-to-window, since the glare sensation from this direction has a higher potential of causing visual discomfort to the eyes [10]. The seats facing 45° diagonal to the building’s facades or less were considered as the ones in the facing-to-window direction [10]. Furthermore, the occupants in the perimeter and interior zones had a different perceptions of lighting environments because they experienced different transmitted solar effects [11]. Thus, the occupants’ survey in this study were only the ones who seated in a facing-to-window direction inside a perimeter zone, which is within 15 feet from the building’s edge. This post-occupancy survey involved HDR images collection along with a questionnaire survey. The specified time of 11.00 am and 3.00 pm were applied with both data collections.

2.2 Discomfort glare index

In this study, the DGP index used for discomfort glare evaluation could be generated from HDR images processing. A series of low dynamic range images (LDR) were captured using a Panasonic DMC-G1K digital single-lens reflex (DSLR) camera with a Lumix G F3.5 fisheye lens. The camera was placed at the seated-occupants’ eye level, approximately 1.20 m from the floor. It was installed with an adjustable tripod in the same location in the same direction, at the area near the occupants’ chair to maintain their normal working conditions. For the camera setting, fixed values of ISO at 100 and the camera aperture at 4.0 were applied with 15 shutter speed by increasing or decreasing the exposure value. The LDR images were stored in a RAW file format, and were then post-processed using the Aftab Alpha software to create HDR images and to evaluate DGP index with the detection of glare sources by the Evalglare interface [12]. Meanwhile, the vertical illuminance measurements were used to calibrate the software-generated values using image-calculated vertical illuminance from the software process. It was measured using a LX-200SD light meter at each position same as the camera placement. Fig. 1 illustrates the strong correlation between the image-calculated vertical illuminance and the measured vertical illuminance. Therefore, the accuracy of the data generated from HDR images is reliable for further analysis.

![Figure 1. Comparison on the vertical illuminance from image-calculated in software process and measurement.](image)

2.3 Buildings’ façades performance

The specifications of the building-facades were studied by using their specification-sheet or from documents with the building stakeholder. The occupants’ interactions with shading devices was evaluated in terms of the occlusion level by visual inspection at 11:00 a.m. and 3:00 p.m. The occlusion level could be segmented into 1 different rate starting from 0 (fully opened) to 1 (fully closed). These occlusion rates were then applied with WWR to determine the actual opening-glass area and the shading area separately. Thus, WWR in this study could be classify as the WWR of the opening-glass area and the WWR of the shading area (or the occlusion level), which are denoted by WWRglass and WWRshading, respectively. The VLT of glazed facades was mentioned referring to the optical properties. The VLT measurement was held by vertical installation of illuminance sensors inside and outside the building to determine the difference of light-entering between the outdoors and the indoors. Two sets of the devices including were separately installed for both the opening-glass area and the shading area. Therefore, the VLT of the glazing area and the VLT of the shading area were then determined separately and could be denoted by VLTglass and VLTshading, respectively.

To describe the performance of buildings’ facades based on both the geometry and optical properties, daylight aperture (DA) was introduced in this study to
assess daylit spaces. DA is defined as the product of WWR multiplied by VLT. According to the occlusion of shading devices, the visual performance of both the opening-glass area and the shading area were determined based on DA. It was defined as DA glass (WWRglass multiplied by VLTglass) and DA shading (WWRshading multiplied by VLTshading).

2.4 Occupant comfort evaluation

The survey measured occupants’ responses in an anonymous paper-based questionnaire given to 1,806 samples. The questions could be divided into subjective and objective variables. The objective variables included time, date, identification number of the questionnaire, and personal data. Meanwhile, the subjective variable could be measured referring to comfort vote and glare sensation vote (GSV). It was assumed that the scale was roughly linear, and ordinal values were assigned to each point along the scale, from −2 (discomfort) to +2 (comfort), with 0 as the neutral midpoint. Initially, the occupants indicated their comfort. Then they took the sensation questions with the glare sensation about the source of comfort or discomfort by rating on a 4-point scale [39]. The predefined glare criteria were marked as 1 (imperceptible), 2 (perceptible), 3 (disturbing), and 4 (intolerable). Each data set of answering was then paired with its corresponding DGP and important features of the glazed facades as a single sample in the given seat position.

3. RESULTS AND DISCUSSIONS

3.1 Occupants’ comfort

From the field investigation, the mean DGP value ranged between 0.17 and 0.25, as Table 1 shown. It revealed a low rate compared to the current recommendations [6]. Furthermore, 89.63% of them were less than 0.35, which was perceived as glare-imperceptible. It is worthwhile to take a closer look into the subjective vote from the questionnaire. Each was paired with its corresponding DGP using linear regression. It showed a reasonable correlation, and led to be a selected metric to describe the local requirements. From the linear model, it indicates that the occupants’ responses started to shift inversely considering the DGP border as 0.26. The occupants were dissatisfied, even though they experienced DGP votes were assumed to be a binominal responses by simplifying to a binary form for statistical analysis. It was classified as the “discomfort” by the comfort vote below 0 with the presence of a glare sensation

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**Table 1: Basic information and surveyed data of office spaces in case study buildings.**

<table>
<thead>
<tr>
<th>Surveyed Items</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
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<tbody>
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<td>Thailand</td>
<td>Thailand</td>
<td>Thailand</td>
<td>Thailand</td>
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<tr>
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<td>18/09</td>
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<td>19/05</td>
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<tr>
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<td>88</td>
<td>170</td>
<td>152</td>
<td>23</td>
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<td>75</td>
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<tr>
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<td>25</td>
<td>22</td>
<td>48</td>
<td>25</td>
<td>7</td>
<td>3</td>
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<td>42,045</td>
<td>52,851</td>
<td>56,000</td>
<td>16,632</td>
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<td>11</td>
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<td>11</td>
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<tr>
<td>target floor area (m²)</td>
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<td>1,734</td>
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<td>floor to floor (m)</td>
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<tr>
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<td>0.88</td>
<td>0.72</td>
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<td>0.88</td>
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<td>0.18</td>
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<td>0.72</td>
<td>0.49</td>
<td>0.63</td>
<td>0.72</td>
<td>0.42</td>
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<td>0.48</td>
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<td>0.81</td>
<td>0.79</td>
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<td>0.81</td>
<td>0.77</td>
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<td>0.17</td>
<td>0.05</td>
<td>0.10</td>
<td>0.14</td>
<td>0.03</td>
<td>0.09</td>
</tr>
<tr>
<td>DAshading</td>
<td>0.01</td>
<td>0.11</td>
<td>0.12</td>
<td>0.01</td>
<td>0.11</td>
<td>0.08</td>
<td>0.06</td>
<td>0.13</td>
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<tr>
<td>DGP</td>
<td>0.17</td>
<td>0.25</td>
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</table>
vote above 2.5 [7, 13]. Cumulative histograms showing the cumulative percentage of the discomfort occupants under various DGP are presented in Fig. 3. The lower quartile, median, and upper quartile values can be determined by intercepting the percentage of 25%, 50%, and 75%, respectively. Meanwhile, in Fig. 4, the predicted percentage of discomfort (PPD) was simultaneously applied, and marked as 10%, 25%, and 50% [7]. Those values were summarized based on the quartile calculation and the PPD method, and suggested as thresholds values for imperceptible-perceptible: 0.16 – 0.20, perceptible-disturbing: 0.23 - 0.24 and disturbing-intolerable: 0.29 – 0.33. A consistency of both determination methods and countries indicate that the suggested threshold values are trustable for discomfort glare evaluation. In addition, the border between perceptible-disturbing can be recognized as the threshold of comfort-discomfort due to its comparable result to the prediction model with mid-subjective scale in Fig. 2. From the agreement in this study with other tropical studies [7, 8], it can be concluded that South-East Asian people prefer lower amount of DGP, giving possible explanation on why the several samples with lower DGP than 0.35 are considered discomfort.

3.2 Buildings’ façades with comfortable DGP

The monitoring of shading devices usage by visual inspection revealed that the occupants tended to close or lower the shading devices. The occlusion levels were mostly kept in down-position, as shown in table 1. It can be seen that WWRglass was decreased drastically, even though the buildings’ facades were designed with high glazing area. Moreover, the glazed facades that were continually obstructed resulted in a low rate of VLT. The partial shading area could greatly reduce daylight utilization. To describe glazed facades with shading devices usage based on discomfort glare, the glazing features, i.e. DA glass and DA shading, were paired with their corresponding DGP. Since the DGP threshold of comfort-discomfort was found as 0.23 – 0.24. The higher value of 0.24 was selected. Only the samples with DGP below 0.24 were highlighted to investigate its consequence from buildings’ facades characteristics referring to DA. In this part of the analysis, the data set from Singapore was excluded due to the limitations of building informations.

Only 1,263 samples were below DGP of 0.24. WWRglass and WWRshading were proportionally manipulated following WWR by the occlusion level of shading devices to apply to DA formula. The cumulative percentage of those comfortable DA was performed, as shown in Fig. 5. In the case that the visual comfort percentage of 75 is allowed according to the modified visual comfort probability (VCP) [14]. The histogram curve of DA can be read as 0.16 for opening-glass area or DA glass, and 0.12 for shading area or DASHADING.

As the DA result shown, all the comfortable samples were observed with the shading devices usage. Due to the large WWR, the controlled-pattern of shading devices can fulfill the preference of low DGP effectively. The result of the DA can retrace to the WWRglass with the WWRshading and VLTglass with VLTshading. According to the DA glass = 0.16 and DAshading = 0.12, as mentioned above, the contour curve in Fig. 6. illustrates the prediction model between glazed facades with the usage of shading devices in terms of the shading devices occlusion level (WWRglass, WWRshading) and the VLT (VLTglass, VLTshading) respect to their WWR. It is observed that the buildings’ facades with low WWR can apply the high rate of VLT for both the glazing area and shading area. Meanwhile, those with high WWR require the operation of shading.

![Figure 3: Cumulative histograms showing percentage of discomfort occupants under various values of DGP.](image)

![Figure 4: Predicted percentage of discomfort occupants (PPD) in relation to various values of DGP.](image)

![Figure 5: Cumulative histograms showing percentage of comfort occupants under various values of Daylight aperture (DA).](image)
devices with lower VLT for both the glazing area and shading area. 

Figure 6: Contour graph showing the correlation between VLT of glazing area and VLT of shading area with various value of shading devices occlusion level.

VLT for glazed facades is suggested to be 0.36 - 0.88 [15]. As the field-study revealed, the VLT ranged from 0.57 to 0.81 surpass those recommended values, with high WWR. The large amount of daylight can access interior spaces abundantly, which conforms to the promotion of daylight utilization as a strategy for electrical lighting saving [1, 15]. However, the finding from this study indicate that the occupants prefer low DGP level. The agreement with other tropical studies [7, 8] may suggest that people prefer low amount of daylight glare in interior spaces. Thus, the occupants usually control shading devices primarily to avoid discomfort glare.

The high occlusion level of shading devices leaves a low opening-glass area at 0.04 to 0.21, which are likely to the reference value of WWR for commercial buildings at 0.30 - 0.40 [16]. Based on the occupant’s behaviour, a smaller WWR can be possibly applied to South-East Asia. Conversely, as the shading devices are commonly used, it can be infer that the high WWR building following the current recommended value of VLT is inadequate to provide visual comfort. The application of shading devices is essentially required for discomfort glare control, and it may suggest as the WWR, occlusion level and VLT mentioned in Fig. 6.

The criteria of discomfort glare control in the well-being standards encourages the building designer or the occupants to install interior window shading, blinds, or external shading systems with a controllable strategy [1, 17]. It is found that the discomfort glare control behaviour in this study result in the high occlusion rate of shading devices. Thus, the installation of shading devices usage can be possibly incorporated into the buildings’ facades as a holistic system, based on the finding threshold of DGP with the discussion on DA. The discomfort glare evaluation must be updated and revised in accordance with the local requirements when decisions regarding the glazed façades are taken. Any improvement in the understanding of visual comfort allows researchers or designers to develop proper tools to provide design solutions, which can practically be expected to take a step towards reducing the buildings’ load and improving occupants’ comfort.

4. CONCLUSION

Visual comfort based on the discomfort glare index study has been revealed in a few studies in the context of South-East Asia. It is becoming more of a concern because the trend towards highly glazed façades continues to increase to optimize daylight utilization. The field investigations in office spaces were performed to clarify the correlation between the discomfort glare perception and the performance of glazed facades regarding to the shading devices usage by the occupants.

The post-occupancy evaluation was conducted using HDR images collection with the questionnaire survey. The results showed that the way users interact with shading devices greatly influenced the performance of the glazed facades and interior environments. Daylight was rarely utilized because of the high rate of shading devices occlusion. It was found that glazed facades with partially shading area resulted in a low rate of visible light transmittance (VLT) and low opening-glass area. However, the high occlusion level positively affected the occupant’s responses on discomfort glare, since they preferred lower level of discomfort glare than that current recommendations.

The Daylight Glare Probability (DGP) index measurement which was obtained and measured under the occupied spaces revealed a low rate, which was perceived as imperceptible glare based on the recommended DGP range. However, from the questionnaire survey, the occupants responded a preference for lower DGP level than that current recommendations due to their delicate perception. Statistical approaches were applied to the group of discomfort occupants. These helped conclude that the following values are suggested as threshold between imperceptible and perceptible: DGP = 0.16 – 0.20, perceptible and disturbing: DGP = 0.23 - 0.24 and disturbing and intolerable: DGP = 0.29 – 0.33, with their agreement on lower DGP levels to other tropical studies.

To describe the impact of glazed facades on discomfort glare perception, the data set of comfort samples were selected as DGP of 0.24 or less to pair
with corresponding Daylight aperture (DA). The suggestions of important features, i.e. WWR, occlusion level, and VLT, were discussed using the prediction model from statistical analysis. Due to the preference of low discomfort glare, it was found that the shading devices were operated for achieving visual comfort. To apply the high visual-performance facades with high WWR or high VLT, the shading devices are essentially required.

To this end, since the use of the shading devices is commonly applied to the occupied spaces with the tendency of being encouraged to be installed from the green-building standards and the well-being standard, it can be incorporated as an effective layer into the buildings’ façades system based on the finding threshold of DGP with consideration on buildings’ façades features in this study. With the integration of glazed facades and shading devices, the performance of buildings’ facades can be developed to provide comfortable indoor conditions to interior spaces. The findings from this study can act as an initial step to improve the discomfort glare criteria and building-facades selection guidelines for South-East Asian countries, which are currently encouraged to access daylight without discomfort glare control strategies.

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Assessing the use of UTCI in semi-outdoor spaces
A case study in Hyderabad, India

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ABSTRACT: The Universal Thermal Comfort Index (UTCI) has been used to evaluate thermal comfort in semi-exterior spaces using a case study in Hyderabad (India). The study shows that for this climate, solar shading combined with enhanced air movement via ceiling fans and adiabatic cooling via water misters, can substantially improve thermal comfort. UTCI is a very useful tool to communicate the effectiveness and validate the suitability of specific environmental design strategies at a qualitative level. However, the use of UTCI as a methodology to accurately quantify thermal comfort is limited by the use of a fixed walking activity, its inability to capture time as a factor for thermal adaptation and the difficulty to reflect re-radiation effect of surfaces and the effect of wind in lightwell spaces. KEYWORDS: Comfort, UTCI, Solar radiation, adiabatic cooling.

1. INTRODUCTION

Extreme temperatures and humidity levels in hot semi-arid and tropical climates can create high thermal stress to building occupants during the transition from the outdoor environment to full conditioned indoor buildings. In such climates, the use of transitional semi-outdoor spaces can provide some relief and improve the thermal experience of building users.

Whilst the benefit of introducing this type of spaces is known, calculating thermal comfort for semi-outdoor conditions remains a challenge due to the absence of a suitable metric. [2 Zarea S. 2018], SET, PET, PMV, PPD and WBG and UTCI are commonly used metrics for indoor spaces. However, thermal comfort metrics for outdoor environments, such as the Universal Thermal Comfort Index (UTCI) are still experimental and not widely used across the industry.

This paper is focused on the use of UTCI to evaluate thermal comfort in semi-exterior spaces. A case study of a building in Hyderabad (India) was used to understand the possibilities and limitations of this metric.

2. THE CASE STUDY

Hyderabad’s climate is split in a mild season (from October to March) a hot and dry period (from March to June) and a tropical wet monsoon period (from June to October), characterised by heavy and intensive rainfall, high humidity combined with warm temperatures.

Hyderabad is located near the Tropic of Cancer, which means there is very high and steady level of solar radiation all year round, with the sun located overhead for a large part of the year. Radiation is dominated by the direct component except during monsoon season when cloud cover is high and diffused radiation component is equal to direct.

2.1 The building

The case study is a 20-storey office building located in Hyderabad, India. The building will feature a ten-storey semi-outdoor lightwell, with circulation galleries in each floor. These galleries will also be used as amenity spaces and provide a physical and psychological connection with the outdoor environment.

Figure 1: Hyderabad temperatures
The circulation route from the outdoors into the building requires occupants to follow a series of transitional spaces from an open-air lobby (1), into an atrium (2), a lightwell with circulation galleries (3-4) and finally into a fully conditioned office space (5).

In response to the client’s aspirations the lightwell, which is open to the outdoor environment, was designed to achieve reasonable thermal comfort levels for the occupants during extreme conditions.

2.2 Environmental strategy

The human body requires a few minutes in order to adapt to large temperature differences. The sudden transition between the lift lobby, the gallery and the office, each at varying temperature, can cause thermal discomfort. In order to mitigate thermal discomfort, the design team recommended a combination of three strategies:

- Baseline: fully exposed to solar radiation and outdoor wind conditions.
- Option 1: Solar shading to protect from direct solar radiation during the whole year.
- Option 2: Solar shading with enhanced air movement via ceiling fans. This strategy is expected to help comfort during the monsoon.
- Option 3: Solar shading, enhanced air movement via ceiling fans and adiabatic cooling via water misters. Adiabatic cooling is expected to help thermal comfort during the hot dry season.

2.3 Calculation methodology

There are a number of different standards and methods of measuring thermal comfort. For the study of the project in Hyderabad, the Universal Thermal Comfort Index (UTCI) methodology was selected.

UTCI is a methodology tailored to outdoor environments which has been developed scientifically by COST Action 730 (Cooperation in Science and Technical Development) but it has not been incorporated into international thermal comfort standards yet.

UTCI captures the following environmental factors: air temperature, solar radiation, relative humidity and air movement (wind). It also understands that occupants can alter their clothing levels based on outdoor level comfort expectations – from 0.5 Clo to 1.5 Clo and assumes a fixed walking activity at speed of 1.1m/s (2.3 Met).

UTCI assumes that occupants are in outdoor conditions and have higher tolerance levels and lower comfort expectations that in an indoor space.

The results of an UTCI calculation are expressed as 10 different bands or thermal stress ranges, as shown in Figure 4, that can be translated into perceived operative temperatures for each specific environmental condition.
UTCI is a very useful tool to communicate the effectiveness of these strategies to validate the suitability of specific environmental design strategies at a qualitative level. However, the use of UTCI as a methodology to accurately measure thermal comfort shows a number of limitations:

- UTCI assumes a fixed walking activity at speed of 1.1 m/s (2.3 met). This means the space can only be analysed as a circulation area (in movement). It does not allow the possibility of analysing the space as a seating or resting area.
- It does not capture time as a factor for thermal comfort adaptation. If the transition occurs in a short period of time (i.e. as circulation), the body will suffer a higher thermal stress than if the space is used as a resting area where the body has time to adapt to the new conditions.
- It is difficult to incorporate the effect the re-radiation effect of surfaces which have been temporarily exposed to the sun.
- In order to adequately factor in the impact of the air speed in complex semi-indoor spaces such as a lightwell, a computer fluid dynamic CFD simulation may be required.

It is understood that UTCI can be used to assess the adequacy of environmental strategies but does not provide a measurable, unbiased and absolute result.

2.4 Targets and modelling

The aim is to achieve reasonable thermal comfort levels for the occupants during extreme conditions. For the solar shading analysis, in agreement with the client, a maximum of 1 hour of direct sunlight averaged over the warm period was set.

2.5 Assumptions

A 3D Rhino model has been used to model the building geometry. UTCI simulations have been carried out using a bespoke ladybug/honeybee script. Calculations have been carried out using the Nagpur IWEC weather data, as a similar IWEC weather file for Hyderabad was not available.

The analysis is focused on the summer period, from March to the end of October.

3. MODELLING RESULTS

3.1 Baseline: Fully exposed location

The baseline scenario represents building users walking fully exposed to sun. In these conditions, solar radiation has by far the highest weighting on the thermal experience of occupants.

Results of the UTCI calculations (Figure 5) show that the occupants will frequently experience thermal discomfort. The hot dry season is the most challenging period of the year due to the extremely high temperatures combined with intense solar radiation and clear skies.

During the hot dry season, extreme heat stress will be expected to occur for at least 19% of the time and during the warm humid season, extreme heat stress will occur for at least 3% of the time.

The lightwell galleries will be designed to reduce the frequency of heat stress. A series of measures are explained and tested in the next sub-sections.

3.2 Option 1: Solar shading

Effective shading can eliminate exposure to solar radiation and substantially improve thermal comfort of occupants of the galleries during the summer period.

Results of the UTCI calculations (Figure 6) show that the provision of solar shading can substantially reduce the frequency of heat stress. Solar shading completely eliminates extreme heat stress during the hot dry and warm humid season. During the hot dry season, the occupant is expected to experience very

![Figure 5: UTCI – Fully exposed to solar radiation and outdoor wind conditions](image-url)
strong heat stress for 24% of the time, and during warm humid season very strong heat stress is expected to occur for at least 6% of the time.

Whilst the occupant will still experience very strong and strong heat stress, solar shading shows a substantial improvement in thermal comfort conditions and it is recommended as the first design strategy to improve the conditions in the lightwell gallery. Solar shading has been refined based on the analysis of the average sunlight hours per day in the gallery areas. This is shown in more detail in Section 3.5.

Although solar shading proves to be an efficient strategy, further measures to achieve reasonable thermal comfort conditions within the galleries were proposed.

3.3 Option 2: Shading + ceiling fans

The introduction of air movement via ceiling fans, in addition to solar shading, has the potential to improve thermal comfort, particularly during warm humid conditions. Air movement, creates a cooling effect due to moisture quickly evaporating from the skin, absorbing heat from the body. Ceiling fans are a low-tech and low-maintenance strategy that can easily be implemented in the lightwell gallery.

Results of the UTCI calculations show a minor impact during the hot dry season. However, during the warm-humid season heat stress levels are substantially reduced. Strong heat stress will still be experienced by occupants.

3.4 Option 3: Shading + ceiling fans + water misters

Direct evaporative cooling via water misters has the potential to significantly lower air temperature, particularly during the dry season.

Results of the UTCI calculations show that a combination of shading, fans and water misters can substantially improve thermal comfort. Heat stress periods are reduced to almost zero and only during a few hours, the occupant will experience strong stress.

Whilst this is a very effective strategy, following a detailed review with the client, water misters were rejected due to potential health risks with aerosol-borne bacteria if high quality water cannot be guaranteed and stagnant water if the mister operation is stopped overnight, which could potentially cause legionella.

Although the degree of discomfort and the frequency have both been improved by introducing shading and ceiling fans, the results of the UTCI calculations show that with the provision of shading and air movement
via ceiling fans, occupants will still experience thermal discomfort in the lightwell gallery during the best part of the hot dry season. An alternative semi-conditioned access route was recommended to the client for periods of extreme heat.

3.5 Sunlight hours analysis

Since solar protection was agreed to be the most efficient step to provide comfort, shading was analysed in more detail in three steps:

- **Step 1:** Average sunlight hours analysis on the floorplate of the gallery with no shading.
- **Step 2:** Average sunlight hours analysis on the gallery facade with no shading.
- **Step 3:** Average sunlight hours analysis on the floorplate of the gallery with shading.

**Step 1:** Average sunlight hours analysis on the floorplate of the gallery with no shading (Figure 9).

This first simulation was carried out during the summer period (March to October). This analysis has been used to identify the areas which are more frequently exposed to direct sunlight.

The aim is that galleries are not exposed to more than one hour of direct sunlight per day on average. The results of the average direct sunlight hours calculation show that the three more exposed floors are levels 21, 20 and 19. Level 22 is partially shaded by the oculus overhang and levels below 19 are less exposed to direct sunlight. In the east and west areas of floors 21 to 19, the average direct sunlight is higher than 2 hours with some areas in level 21 reaching 3 hours. This indicates a requirement for solar shading in these areas.

**Step 2:** Average sunlight hours analysis on the gallery facade with no shading.

The results of the calculation confirm that the more exposed floors are levels 21 and 20. Figure 10 shows that in the east and west façades of levels 21 to 20, the daily average direct sunlight is higher than 2 hours with some areas in level 21 achieving 3 hours. The red and yellow areas require solar shading and the blue areas require little or no solar shading.

The architect developed the shading strategy shown in Figure 11, which consists of vertical fins alternated with circular and triangular-shaped openings to allow views into the courtyard.
In response to the sunlight analysis, the density of vertical fins was been fine-tuned for each orientation and floor level (Figure 12). Vertical fins density is higher in the top band than in the middle and bottom bands and higher in the East and West orientations, where sunlight incidence is more frequent. The triangular-shaped openings in the upper levels were eliminated.

**Step 3:** Average sunlight hours analysis on the floorplate of the gallery with shading.

A final simulation analyses the performance of the refined shading strategy (Figure 13), in floors 21 and 20. The results show that shading provides good solar protection with most floor area receiving almost zero hours of direct sunlight on average.

**4. CONCLUSION**

This paper showed via a case study in Hyderabad that UTCI can be used to assess the adequacy of environmental strategies but does not provide a measurable, unbiased and absolute result. The case study shows that for the climate in Hyderabad solar shading combined with enhanced air movement via ceiling fans and adiabatic cooling via water misters can substantially improve thermal comfort. However due to health and maintenance risks of water misters, adiabatic cooling was finally abandoned. The case study shows the effectiveness of localised vertical shading in within the lightwell.

**ACKNOWLEDGEMENTS**

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Analysis of thermal bridging in Arabian houses:
Investigation of residential buildings in the Riyadh area

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The electrical energy demand in Saudi Arabia has been increasing over the last decade. The building sector (residential, governmental and commercial) consumes about 80% of the total electricity produced. Residential buildings consume about 50% of the total electricity consumption in Saudi Arabia. Up to 70% of the electric energy consumed in buildings is for air conditioning of internal space. This study investigates the relative impact of thermal bridging through the building envelope as a cause of this scenario. The analysis focuses on typical detached villa housing, which represent 29% of all residential accommodation. The results of this paper show that insulated clay blocks by themselves do not ensure compliance with the minimum requirements of the Saudi Code. Bridging caused by mortar joints and structural elements can increase the U-value of the building envelope by 141% above the hypothetical unbridged base case. Through simulation study the impact of thermal bridging on the building is calculated at 68% increase of the total energy consumption. A 55 mm additional external insulation layers can improve the performance considerably and achieve compliance with new building codes.

KEYWORDS: Thermal bridging, Thermal performance, Finite element analysis, Whole building energy modelling, Thermal simulation

1. INTRODUCTION

Saudi Arabia has experienced a rapid population and economic growth over the last decades. This growth led to marked increase in the demand for electricity at an annual rate of 6% [1] and it is expected to increase by 50% by 2020 [2]. The increase in electrical energy demand in Saudi Arabia in the period 2005 to 2018 is shown in Figure 1. Moreover, according to the International Energy Agency (IEA) Saudi Arabia ranked 15th worldwide in energy consumption per capita in 2017 [3]. Also, the electrical energy consumption per capita in Saudi Arabia increased from 6.11 MWh in 2004 to 9.60 MWh in 2017 [3]. The Saudi Arabian Monetary Authority annual statistics [4] documented that residential buildings consume about 50% of the total electricity consumption in Saudi Arabia as presented in Figure 2. Also, several studies have indicated that, the building sector (residential, governmental and commercial) consumes about 80% of the total electricity produced [5],[6]. Moreover, the electricity demand will increase even more to cover the Saudi plan to build 2.32 million new homes by 2020 to service the ongoing rapid population growth of 2.5% per year [1].

According to Felimban et al. [5] up until January 2019, the old building codes (from 2007) were still being used for about 33% of the new homes. Moreover, the Saudi Energy Efficiency Center (SEEC) documented that more than 70% of the existing residential buildings are energy inefficient and lack thermal insulation [7]. Also, there is a massive national cooling demand caused by the 5.47 million existing residential building [5]. As presented in several studies, up to 70% of the electrical energy used in building in Riyadh is consumed for air conditioning as presented in Figure 3 [8], [9].

Figure 1: Electricity consumption in Saudi Arabia from 2005 to 2018 (Data abstracted from [4])

Figure 2: Average energy consumption per sector in Saudi Arabia from 2005 to 2018. (Data abstracted from [4])
Saudi Arabia experiences extreme weather conditions, with a maximum summer temperature of 46°C and an annual average temperature of 27°C [10]. It is clear from these high temperatures that the building envelope in Saudi Arabia is hence facing extreme conditions and extreme heat stress. As a result, transfer heat is highly expected.

A primary and essential function of the building envelope is to enable thermal comfort for the building's inhabitants and protect the building's interior from the outdoor climatic conditions. A well-designed envelope should enable a reduction of energy consumption from air-conditioning and heating. A weakness of a poorly designed building envelope is thermal bridging, which is caused by materials of high thermal conductivity creating a bridge between the tempered indoor environment and the varying, and often extreme conditions, on the building exterior. Thermal bridges can result in high energy consumption, when heat is conducted across the envelope. The present study focuses research attention on this matter and investigates ways to improve building energy conservation by improving the design of the building's envelope. It aims to investigate compliance with the requirements of the Saudi Code 2018 (SC2018).

Firstly, the study identifies thermal bridges in common residential Arabian building typologies. Subsequently it quantifies the energy impact of these thermal bridges; this is achieved using Finite Element Models. The study investigates bridging due to cast concrete structural elements in external walls but also due to small-scale bridging in insulated clay blocks used to infill between the concrete frame elements. Finally, we present the effect of the thermal bridge on building energy consumption using building simulation modelling software. Proportions and quantifications of thermal bridges are incorporated into simulation models of examples of a typical villa design. The villa in Saudi Arabia is a detached residential building surrounding ground with various sizes. 29% of the total housing units in Saudi Arabia are recognized as villa. In Riyadh the capital city of Saudi Arabia, villa is the most commonly built housing by about 45% of the housing units [11] as presented in Figure 4.

Thermal bridging due to the cast concrete frame structure is clearly shown by thermal image presented in Figure 5. The image shows the surface temperature of the structural concrete to be 42.6°C on the interior 36.7°C higher than the surface temperature of the adjacent in-fill block wall.

This paper presents experimental and simulation analysis of thermal bridging through the building envelope, and quantifies the energy impact of this. This is part of an ongoing study to evaluate reasons for inefficiency in Saudi Arabian dwellings and propose means by which their performance can be enhanced.

2. METHODOLOGY

This paper analyses thermal bridging endemic in Saudi Arabian building designs. Particularly it looks at bridging in the main wall fabric, which encompasses insulated clay blocks. Subsequently it investigates the heat flow through the mortar joints and cast concrete structural elements. Finally, evaluate the energy performance of the whole building and the impact of thermal bridging in the building envelope.

The results outlined in this paper will be compared to results presented in a journal paper submitted and due shortly for publication [12]. To study the effects of mortar joints on thermal bridging two methods are used in this larger analysis using simplified calculation methods including; parallel path, zone and combined methods, outlined by organisations CIBSE and ASHRAE [13], [14] or by using
Finite Element Method (FEM). For brevity, in this short paper the FEM is used.

2.1. Block types analysis

Investigating the energy performance of the clay block types used in Saudi Arabia shown in Figure 6, is an essential step to determine the thermal bridging impact on buildings. Eight blocks are analysed – the first four blocks (C1(ins), C2(ins), C3(ins) and C4(ins)) are insulated and the other four (C5, C6, C7 and C8) are not insulated. These blocks are commonly used in Saudi Arabian residential construction to provide for insulation and/or trapped air insulation. Alternative concrete typologies are also used, and these have separately been analysed [12]. Here, the best performing clay block is evaluated and that is utilized for further investigation in this study.

Figure 6: Clay block types used in Saudi Arabia

2.2. Thermal bridging due to mortar joints and structural elements

As well as the localised thermal bridging in the insulated clay blocks models, a major thermal bridging is specified in Saudi Arabian residential construction via bridging due to mortar joints between blocks and an uninsulated structural element.

Figure 7: Detailed wall section of common building style used in Saudi Arabia A) elevation, B) horizontal section, C) detailed column and D) 20 cm insulated concrete block (B2(ins)) or 20 cm insulated Clay block (C1(ins)) infill.

Figure 7 shows a section of wall used in Saudi Arabian residential building (typical villa), the construcational style including the reinforced concrete structural frame, and concrete or clay blocks infill. Structural elements such as columns and beams cover about 35% of the façade area and usually are not insulated in Saudi Arabian dwellings (Figure 8). Therefore, their effects of transferring heat from outside to inside the building is greater than for the mortar joints. To determine the thermal impact of this a Finite Element (FEM) analysis is undertaken using ANSYS 19.2.

Figure 8: Residential construction method in Saudi Arabia

2.3. Boundary conditions and material properties

The weather of Riyadh King Salman AB (WMO: 404380) station (latitude 24.710 N, longitude 46.725 E, Elev. 635) is applied in this paper. The FEM boundary conditions set to 47.3 °C for hot side and 25 °C for the cold side. The simulation weather data was imported from ASHRAE handbook- fundamentals (SI) 2017 and Onebuilding.org data [15][16] for a 15 years period (from 2003 to 2017).

All the material properties used are presented in Table 1. Those materials properties chosen in Table 1 were from some reliable resources such as ASHRAE [13], ISO 10456 [17]and CIBSE [14] or the most used in research papers done for Saudi Arabia.

Table 1: Material Properties used

<table>
<thead>
<tr>
<th>Common Materials</th>
<th>Density $\rho$ kg/m$^3$</th>
<th>Design thermal conductivity $k$ W/ (m.K)</th>
<th>Specific Heat Capacity $c$ J/ (kg. K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay Blocks 200 mm</td>
<td>800</td>
<td>0.65</td>
<td>840</td>
</tr>
<tr>
<td>Cement mortar</td>
<td>1800</td>
<td>0.72</td>
<td>1000</td>
</tr>
<tr>
<td>Cement plaster</td>
<td>1800</td>
<td>0.72</td>
<td>1000</td>
</tr>
<tr>
<td>Reinforced concrete (2 %</td>
<td>2400</td>
<td>2.5</td>
<td>1000</td>
</tr>
<tr>
<td>steel)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extruded polystyrene</td>
<td>40</td>
<td>0.035</td>
<td>1450</td>
</tr>
<tr>
<td>Air Space (15mm)</td>
<td>1.1</td>
<td>0.16 ($k_{air}$)</td>
<td>1007</td>
</tr>
<tr>
<td>Air Space (20mm)</td>
<td>1.1</td>
<td>0.17 ($k_{air}$)</td>
<td>1007</td>
</tr>
<tr>
<td>Air Space (25mm-300mm)</td>
<td>1.1</td>
<td>0.18($k_{air}$)</td>
<td>1007</td>
</tr>
</tbody>
</table>

A FEM mesh independent study is undertaken for both 2D and 3D meshes before starting the analysis in
2.4. Whole building energy analysis

2.4.1. Case study building

Figure 8 shows an image of a residential construction method in Saudi Arabia, which include of concrete frame construction with blocks infill. The frame structure is reinforced concrete structural frame and the blocks used are typically either an insulated or cavity and concrete or clay blocks. An example of these villa style residential buildings used in Saudi Arabia are shown in Figure 9 along with a perspective view of the model that used for whole building energy analysis.

![Figure 9: The floor plans and perspective of an example studied villa](image)

DesignBuilder v6.1.2.009 is used to investigate the effects of thermal bridging on the energy consumption of the whole building. Two case studies are simulated, one with standard and identified levels of thermal bridging and the other hypothetical case without thermal bridging. Details of the villa construction are presented in Table 2.

<table>
<thead>
<tr>
<th>Table 2: The villa construction properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude position</td>
</tr>
<tr>
<td>Face direction</td>
</tr>
<tr>
<td>No. of floors</td>
</tr>
<tr>
<td>height of floors</td>
</tr>
<tr>
<td>Total floors area</td>
</tr>
<tr>
<td>Total walls area</td>
</tr>
<tr>
<td>Windows to wall ratio</td>
</tr>
<tr>
<td>Window type</td>
</tr>
<tr>
<td>Air conditioning system</td>
</tr>
<tr>
<td>Heating system</td>
</tr>
<tr>
<td>Thermostat setpoint</td>
</tr>
</tbody>
</table>

External walls
- Model-1 bridged walls U-value = 1.57 W/(m²·K)
- Model-2 un-bridged walls U-value = 0.65 W/(m²·K)

Roof construction
- 20 mm cement plaster, 200 mm reinforced concrete slab, 50 mm EPS extended polystyrene, 4 mm waterproof membrane, 50 mm lightweight cast concrete and 20mm Terrazzo tiles

3. RESULTS

3.1. Investigation of insulated clay block types

The results of the thermal analysis of the clay blocks shown in Figure 6 are presented in Figure 10. As expected, the blocks with insulation show better thermal performance, quantified by its U-value (W/m²·K), than the uninsulated blocks. Also, the more the amount of insulation as in C1(ins), the greater the thermal performance. The solid block C8 shows the worst performance. Using block type C1(ins) could reduce the heat flux gained by up to 80%, 62% and 66% when compared with the uninsulated solid block C8, and cavity blocks C6 and C7 respectively. Furthermore, the insulation when included as one piece (as in C1(ins)) makes for better performance than in the case of C2(ins), C3(ins) and C4(ins) where the insulation is included in multiple pieces.

In general, the result of clay blocks show better thermal performance than the result of concrete blocks [12]. In instance, the solid clay block (C8) shows better thermal performance than the solid concrete block (B8). However, as a consequence of continuous insulation in the concrete blocks B1(ins) and B2(ins), they perform better than insulated clay blocks.

![Figure 10: Thermal transmittance of clay block types shown in Figure 6](image)

FEM heat profiles are shown in Figure 11, for the boundary conditions outlined in Section 2.3. Although, the insulation (as in C1(ins), C2(ins), C3(ins) and C4(ins)) reduced the heat movement compared to uninsulated blocks. However, discontinuity of insulation by the clay joints, creates a bridge that allows for transfer of heat to the other side. In C6, the alignment of clay joints between air gaps increases the heat transfers compared to non-alignment alternatives (as in C7) as shown in Figure 11.
Figure 11: Heat transfer through different clay block types, total heat flux transfer [W/m²]

3.2. Investigation of mortar joints and structural elements

The effective evaluation of the villa building envelope’s thermal performance that investigate all the thermal bridging impacts, not only the ones occurs in the insulation clay clock but also due to mortar joints and structural elements.

The effects of mortar joints and structural elements on the building’s performance are presented in Figure 12 and Table 3. Figure 12 presents the total heat flux calculated using the FE method for bridged elements in a wall section with insulated clay block (C1(ins)), mortar joints and structural elements. The heat flux distribution Figure 12 shows that, the majority of the heat flow moves across the structural elements which has the highest thermal conductivity of the wall section. Also, it presents the impact of mortar joints between the clay blocks. It is evident from the heat transfer image shown that heat flow through the structure (~160W/m²) is between 2 and 3 times as high as through the mortar joints (~60W/m²). This is due to the difference in density between the structural (2400kg/m³) and mortar (1800kg/m³) concretes respectively, that results in a thermal conductivity difference, as outlined in Table 1.

When comparing the insulated clay block with and without the mortar joint, it is observed that the mortar joint can cause up to 50% increase in U-value of the wall. Furthermore, when the structural elements are also included this increases the U-value by 141% above the hypothetical base case wall built purely with insulated clay block. The cast concrete structural elements are responsible for 61% increase in the wall U-value compared to the block wall with mortar joints.

Table 3: The impact of the different bridging sources on the U-value of the building

<table>
<thead>
<tr>
<th>U-value (W/m²K)</th>
<th>Difference between unbridged and bridged case (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulated block wall section</td>
<td>0.65</td>
</tr>
<tr>
<td>Insulated block wall section with 10mm mortar Joints</td>
<td>0.98</td>
</tr>
<tr>
<td>Insulated block wall section with structural elements &amp; mortar Joints</td>
<td>1.57</td>
</tr>
</tbody>
</table>

3.3. Evaluation of whole building performance

The impact of thermal bridging on the building is calculated as responsible for a 68% increase in the total energy consumption as presented in Figure 13. That is reflected in the summer energy load which shows a difference of 64% due to the air-conditioning load, when compared to the base case house with an insulation layer and no bridging (built solely of insulated clay blocks (C1(ins))). Moreover, the impact of thermal bridging increased the yearly energy consumed per floor area from 92.90 to 136.60 kWh/m²/year, for the unbridged building and bridged building, respectively.

Figure 13: Energy consumption comparison of buildings with bridged and hypothetical unbridged envelopes (simulated for a year for clay blocks building)

4. DISCUSSION AND SOLUTION

It should first be noted that all the clay block types by themselves do not comply with the minimum requirements of the Saudi Code 2018 (SC2018) [18]. Results show that the best performance insulated clay block exceeds the Saudi Code 2018 and 2007 by 60% and 3%, respectively [18], [19].

As a solution, several studies indicated that, the external wall insulation systems (EWIS) could eliminate the effect of thermal bridging by up to 50% and that will lead to a reduction by about 16% of the total annual energy load [20],[21],[22]. In this study, through simulation it has been identified that adding 20 mm external extruded polystyrene reduced the U-
value by 57% and the reduction increased by increasing the insulation thickness as shown in Table 4. Moreover, to reach the Saudi code 2018 climatic zones regulation requirements for Riyadh city, we need to add 55 mm external insulation to reduce the U-value by 79% compared to bridged walls.

<table>
<thead>
<tr>
<th>External insulation thickness (mm)</th>
<th>0</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>55</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-Value W/(m²·K)</td>
<td>1.57</td>
<td>0.68</td>
<td>0.49</td>
<td>0.41</td>
<td>0.35</td>
<td>0.33</td>
</tr>
<tr>
<td>% reduction</td>
<td>0%</td>
<td>57%</td>
<td>67%</td>
<td>72%</td>
<td>78%</td>
<td>79%</td>
</tr>
</tbody>
</table>

5. CONCLUSION

This paper concludes that insulated clay block designs used in Saudi Arabian houses by themselves do not ensure compliance with the minimum requirements of Saudi Code. Moreover, in general, the clay blocks show better thermal performance; however, as a consequence of continuous insulation in the concrete blocks B1(ins) and B2(ins), they perform better than insulated clay blocks.

Thermal bridging caused by the mortar joints between blocks, and the cast concrete structural elements can increase the heat gain by about 141%. The cast concrete structural elements are responsible for the majority of thermal bridging by about 61% increase in the wall U-value compared to the block wall with mortar joints.

Finally, applying 55 mm external insulation will reduce the U-value by 79% to comply with the Saudi code 2018 regulation requirements for Riyadh city, whereas the concrete blocks building needs 60 mm.

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Adopting Conflict Zones Perception in Strategic Environmental Planning: Case Study Egypt

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ABSTRACT: The strategic environmental assessment (SEA) is a logical support method for decision makers. It aims at maintaining the consideration of sustainability aspects in policy, plan and program making. Some current planning notion conflicts raised recently to discuss both the development and protection of Sensitive Ecological Areas. The research discusses the term “Conflict zone” with regard to the sensitive ecological areas with high potential for urban development. This requires engaging new methods and techniques as the Geographic Information System (GIS) to support urban planners. The research uses the GIS overlaying and querying tools to deduct two maps, the first one categories the area of interest (AOI) into high, moderate and low sensitive areas, while, the second map classes the AOI according to its potential to urban development (high, moderate and low). Afterwards, the weighted sum GIS technique applied on the two maps to determine the conflict zones locations. This is considered as a pilot method that can be applied anywhere. The results sets mitigation measures for biodiversity loss, risks to natural habitat, and marine life disturbance hydrogeological environmental impacts to support the strategic planning objectives.

KEYWORDS: Conflict Zone, GIS, Mitigation Measures, Strategic Environmental Assessment.

1. INTRODUCTION

The last decade has perceived a core change in the planning process for urban development[1], in which the environmental protection is noticed as of vital importance for sustainable urban development[2]. The rapid pace of urbanization, especially in developing countries, continues to encourage the urban communities' construction without endorsing sustainability aspects [1]. Therefore, they are facing various challenges to apply long-term plan sustainable development.

The sensitive ecological areas’ development is the most remarkable amongst the practices of planning evolving in Egypt in the recent years. This is because of the cost benefit for developing in ecological vulnerable lands [3]. This shows a weak implementation for environmental laws in Egypt as well as a negative implications to the environment [4]. While, urban Development proposals that establish good environmental stewardship for the protection of sensitive ecological areas build [5] distinctive developments especially in developing countries[2].

The strategic planning level needs to consider the environmental aspect especially to what regards sensitive areas with high potential for urban development; termed ‘Conflict zones’[5]. Furthermore, the SEA is an organized support process, which ensures implementing both the environmental and sustainable aspects among policy, plan and program making. This paper aims to present a pilot method to pinpoint the location of conflict zones in both Sinai and the Egyptian western desert using the geographic information system (GIS).

The research determines the current vacant lands in the Area of interest (AOI) for both zones and prioritises their urban development initiatives according to the national development plan 2030. Following that, number of mitigation measures have been proposed to support the objectives of strategic planning for urban development projects therein.

1.1. Site description

Sinai considered the heart of the world due to its central location (between Asia, Africa, and Europe with almost 60,000 Km$^2$) which covers 6 % of Egypt's land area[6]. Due to the international political constraints, one sector of Sinai is only applicable for urban development, this is called sector “A” in reference to Camp David international agreement and this will be the first AOI to apply the research methodology on. Sector “A” covers 17,732 Km$^2$ and is rich in natural resources, which considered as a great potential for urban development as shown in Fig. (1). In addition to its location on Mediterranean Sea, Red sea and Suez Canal that reasoned as the shortest link between the west and the east. Sector “A” also has great potential of conservation areas, archaeological sites and coral reefs as well as vulnerable lands.

The Egyptian western desert is almost 680,000 Km$^2$, which covers 67 % of Egypt's land area. The second AOI will be the northern part of the western desert that covers 235,339 Km$^2$. To the north, it overlooks the Mediterranean Sea; to the
south, it overlooks the Wadi Elgheed governorate as shown in Fig. (1). This AOI has been chosen for many reasons starting by urban development that originates within different activities (Industry, Agriculture, Trade, Residential, and Tourism) without the presence of planned policy and strategy for this area to organize this growth. Followed by the presence of Cairo- El-Almen desert road, which is considered the important among the other linear development spines coming out of the Greater Cairo region. Finally, the presence of conservation areas and floras that have a great environmental potential.

![Figure 1: The area of interest location](image)

### 2. The Status of Applying the SEA in Egypt

The SEA process promotes positive planning actions and minimizes adverse effects for the strategic environmental urban development process. It is considered a flexible process in dealing with uncertainties and reacting to diverse data inputs[7]. This ensures transparency and stakeholders’ participation in the planning process. Furthermore, it enriches the decision-makers’ view towards sustainable development, accordingly it should be early involved in the strategic planning development process to be able to adopt new proposed sustainable actions [8].

The SEA method works on the bigger scale of policies, plans and programs [9], adding to this it is linked with the process of determining planning means and objectives through a sequence of actions to attain the supposed sustainable goals. Hence, it is used as a participatory and protective tool for managing the environment[10][11].

This SEA is also concerned with the strategic environmental risk appraisal for the sensitive ecological areas that have high potential for urban development [12]. In high-income countries, the implementation of SEA becomes obligatory to policy, plans and programs [13] while, it considered challenging in middle and low-income [14][15]. Fischer et al. (2006) argued that the SEA process may develop well in informal planning practices where policies and strategies are developed but not considered [16]. McGimpsey et al. (2013) stated that SEA needs engage decisions as well as incentives like mandatory strategic alternatives linked to the environmental assessment [17]. This shows why implementing the SEA in determining and applying the mitigation measures for conflict zones is sponsored by the World Bank as an international funding agency [18][19].

The SEA process is much like the EIA process encompassing; screening, scoping, impact assessment, mitigation, public participation, report preparation, and may include feedback and monitoring mechanism [20]. De Montis et al. (2016) discussed the deficit for outlining the aim of the screening and scoping processes besides their related concepts and criteria [14]. Moreover, Salheen et al. (2010) pointed that there is a lack of practical management for choosing the suitable SEA methods and frameworks in relation to diverse contexts especially sensitive ecological areas with high potential for urban development [21].

More studies discussed the SEA report in reference to its lack of data, quality of assessment, and managing uncertainties[22]. These problems are associated to the presences of a weak environmental assessment database in Egypt. Other researches identified the role played by the public participation and institutional organizations [23][11], which is regarded as a missing practice in the Egyptian context [24].

Hence, De Montis et al. (2016) presented a qualitative comparative approach and established proposed criteria for the SEA implementation, counted on three assemblies of macro-themes; (1) specifics macro-themes, (2) process macro-themes and (3) general macro-themes. However, it is well-known that there is a current knowledge gap still exists in dealing with sensitive ecological areas with high potential for development [14].

### 3. Development of Sensitive Ecological Area

Peng Zhenwei et al. (2013) argued that the sensitive ecological areas extend beyond their close spatial limits to nearby rural and urban settlements[25]. You Jia. (2007) added that this requires conscious actions towards the consequences of any urban development project, accordingly proper mitigation measures should be proposed [26][27]. Also, Wang et al. (2019) stated that sensitive ecological areas are the assembly of both vulnerable ecological lands and the areas surrounding them [28].

This shows that there are conflicts about the development and protection of sensitive ecological areas. A communal perception is noted that the conservative preservation through unchangeable control for the space and non-development is considered as preservation for the sensitive ecological area [27]. These conflicts come from the perplexity of the two notions "Sensitive Ecological Area" and "Sensitive Ecological District". Peng Zhenwei et al. (2013) claimed that likewise the protection of sensitive ecological district, firm
implementation for planning rules on the development control of the rural and urban settlement [25] is required. Liquan et al. (2016) stated that the development of sensitive ecological area includes the dual implications for both urban development and environmental protection [27].

Hoffmann-Kroll et al. (2003) stated that both protection and development for the sensitive ecological areas will bring varieties of problems. Referring to the Chinese experience of urban-rural twin structure, the implementation of the controller standards for the cities is difficult in these areas, and the implementation of the controller method for the rural area is also difficult to adapt [29].

In Egypt the preservation of sensitive ecological area is receding all along. The rural and urban construction is growing fast due to the absence of urban environmental policies and plans [21]. Elsayed et al. (2019) added to the previous fact that users get continuously whatsoever offered from the nature to maintain the demand for their life [22]. Mahmoud et al. (2011) argued that users violate the nature for the development sake, in order to gain short-term benefits [30]. They discount the future needs; as construction and development held on with discarding the natural resource [31]. The urban development speed excels the environmental self-recovery capacity, and endanger the ecological balance of that area. Wang et al. (2019) claimed that nowadays the environmental complications are not only due to the misuse of natural resources, but also due to the absorption and violation of natural laws[31].

4. Research Method

This paper adopts a meta-analysis investigative two-step method primarily, using the GIS to determine the location of conflict zones and secondly applying the SEA method to propose the proper mitigation measures for adverse impacts expected from the urban development process. The method applied in two steps, the first step follow three stages; in the second stage, two phases are applied. The second step executed in one stage to propose the suitable mitigation measures with reference to the SEA and proposed land use in the conflict zones.

The research accommodates both qualitative and quantitative set of data. Sinai and the Egyptian western desert are chosen for case study application due to their vulnerable ecosystems and strategic locations, which makes them prone for major urban development projects.

Step (1) is carried through the following three stages:

a) Stage 1; Data gathering stage: where a set of qualitative and quantitative data gathered from different sources (maps, statistics, charts, reports ... etc.).

b) Stage 2; Data combination stage: where all the maps and data are populated to the GIS database, then they are combined in one joint overlaid feature class as shown in Fig. (2). Then, two maps developed to express the sensitivity of the AOI and the expected land use, respectively.
Tourism places. Land plots hang on the presence of touristic places.

Ecological sensitive areas. Protected areas with reference to the Egyptian law.

**Phase 2**: A second query is applied for the alternatives defined in step (1). This query reflects the national strategy for Egypt 2030, which helped defining potentials of urban development. This is categorized into the following; areas with high potentials, areas with moderate potentials, and areas with low potentials.

c) **Stage 3; Data interrogation stage** includes an overlaying of the two aforementioned maps to pinpoint the conflict zones, which have high ecological sensitivity and high potential for urban development. The GIS "Weighted Sum" tool is used to develop the conflict zone map. Then, the output raster image determines the "Conflict Zones" location map as shown in Fig (3) and Fig (4).

**Step (2)**: The mitigation measures are identified for conflict zones in both case studies which aims to improve the environmental performance strategy. The SEA actions could have positive or negative environmental impacts; these impacts are reduced through applying the mitigation measures. Accordingly, the researcher proposes mitigation measures for the conflict zones in order to enrich the environmental performance actions.

The areas selected by the GIS as conflict zones in Sinai are suitable for the touristic development accordingly, the biodiversity loss, risks to natural habitat, and marine life disturbance impacts are expected. On the other hand, the areas selected in the Egyptian western desert as conflict zones are suitable for agriculture development; therefore, the hydrogeological environmental impacts are expected.

**5. Discussion and Results**

The result presents a geo-referenced map that defines the location of conflict zones in Sinai and the Egyptian western desert as shown in Fig. (3) and Fig. (4). This supports adopting the Conflict Zones perception in Strategic Environmental planning and would definitely reflect back on investors' decisions for the proper mitigation measures to take as shown in table (2).

<table>
<thead>
<tr>
<th>Estimated impacts</th>
<th>Suggested Mitigation measures</th>
</tr>
</thead>
</table>
| Protected areas, endangered species & migratory birds disturbances | Applying the environmental management procedures and control on site during the construction activities.
| Decline in number of biological communities. | Activating laws to control activities held during the migration periods of birds.
| Breakdown in the functioning of the ecosystem. | Selecting materials that adopt the environmental design and planning.
| Water turbidity and quality of marine life. The growth of microorganisms in the Sea. | Enforcing regulations and laws to monitor the sensitive locations chosen for touristic activities.

*Figure 3: Conflict zone for Sinai map*

*Figure 4: Conflict zone for the Egyptian Western Desert*
Overfishing, oil spills and destruction of marine habitats

- Appropriate environmental management for construction, fishing, as well as snorkelling and diving activities.
- Further restrictions and researches on fishing and marine activities etc.

Possible infrastructural pipeline leakage, which shall lead to the contamination of the underground aquifers and groundwater.

- Appropriate site investigation to verify urban construction process
- Calculations of water usage quantity to monitor water storage capacity.
- Implementing the environmental management standard and control measures during the urban construction phases.
- Conducting hydrogeological studies to identify the locations of existing aquifers and choose the proper drilling scenarios.
- Applying Managed Aquifer Recharge method
- Proper study to decide priority for crops cultivation.

Impacts on the water quality and drainage conditions.

Pollution due to discarding of wastewater or groundwater lowering table.

Over use for the aquifers lead to salination of groundwater.

Cultivating Crops that adds stress to the soil.

Several drawbacks to the SEA implementation method are discussed in previous studies. Li et al. (2016) showed the absence of cooperation between different parties and the absence of sufficient data [7]. Bidstrup et al. (2014) discussed the conflict of implementing the SEA practice and process [32]. This linked with the insufficiency of mitigation measures and assessment indicators for the sustainability principles [33]. Also, some researchers offered recommendations to the SEA method; this comprises the systemic and early combination of the SEA method with other environmental assessment schemes.

The contribution of this study coins the relationship of applying environmental assessment for the strategic and building scale through the SEA and the Environmental Impact Assessment methods, respectively, as suggested by Ismaeel (2018) [34]. The result conforms to a relevant study by Shalaby et al. (2018) for the urban development of Sinai that has accounted for all possible environmental impacts of the current and the proposed urban land uses[5]. This also compliments previous studies for determining the land suitability analysis for renewable energy sources in Sinai [6] and the mitigation measures in the western desert [22].

6. CONCLUSION

The process of defining the location of conflict zones is a vital necessity in the urban planning process to be able to integrate the environmental perspective into consideration and balance sustainable targets. Accordingly, the required mitigation measures should be defined in advance and declared for planners, policy makers and investors.

Both area of interests (Siani and Egyptian Western Desert) carry many potentials and threats. Previous studies have recommended various kinds of urban development without keeping an eye on Conflict zones. The GIS system used as an innovative tool to explore the conflict zones in the AOI. Four main impacts have been discussed; biodiversity loss, risks to natural habitat, marine life disturbance and hydrogeological environmental impacts. Accordingly, the researcher has proposed their mitigation environmental measures. Hence, this study presents a pilot method to determine the location of conflict zones using the GIS, and then propose mitigation measures that support the SEA implementation and consider the ongoing studies while setting development scenarios for both areas.

Some researchers argue that it would certainly benefit to pinpoint the conflict zone location with regard to the AOI potentials and constrains as many environmental concerns may be raised due to the expected long term and short-term effect on the environment. This calls for foresting environmental mitigation measures for the expected urban development impacts, which is considered as a challenging progression due to the various environmental impacts and the ecological sensitivity of the site.

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REFERENCES


A Tool for Assessing Visual Comfort Through an Immersive Environment

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ABSTRACT: This paper describes the working principles, methodology and preliminary results from the development and testing of an immersive tool to assess the visual comfort of indoor spaces. The novelty of this open-source tool lies in its ability to synergize the advance features of a gaming Application Programming Interface (API) with the physically-based rendering capabilities of a validated raytracer. The functionality incorporated through the physics engine of the gaming API allows the users to experience an architectural space with realistic movements and collisions. The raytracer is used to leverage physically validated concepts such as High Dynamic Range (HDR) Imaging, backward raytracing and weather-based sky models to generate panoramic 360° images. These images are visualized through a custom functionality in the tool that allows users to teleport from the game interface to spherical 360° HDR view. The users can evaluate a variety of lighting conditions and corresponding shading configurations in real-time as the tool allows pre-simulated results to be loaded into the mapping environment. The tool is compatible with virtual reality headsets and standard desktop displays.

KEYWORDS: Virtual Reality, Daylighting, Simulation, Raytracing, Building Simulation

1. INTRODUCTION
Ensuring the availability of appropriate daylighting conditions for occupants has been an enduring challenge in the design of buildings for centuries. The two principal goals of daylighting design relate to ensuring adequate quantity of light and minimizing the potential for visual discomfort, i.e. glare [1].

1.1 Daylighting simulations
In contemporary architectural design practice, computer simulations are extensively used to predict daylight availability and potential for glare in indoor spaces. Surveys have indicated that daylighting simulation software are used in different stages of building design to inform the selection of site orientation, building form and construction material [2-5]. Conventional daylighting simulations are used to estimate illuminance as shown in Figure 1. Such simulations typically generate a large quantum of numerical data. This data is then summarized into single-number metrics like Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI). Illuminance-based metrics, while being credible indicators of daylight sufficiency, are not well suited for evaluating glare. This is primarily because the causal factors for glare are direct or indirect sources of glare that are within the entire visual field of the observer. As the focus of illuminance-based simulations is usually restricted to the horizontal workplace, they cannot be relied on to provide a direct estimation of glare [2]. Furthermore, illuminance, expressed in lumens/m² or lux, is a measure of light incident on a surface and cannot be employed to appropriately quantify light perceived by the eyes.

Figure 1. An illuminance-based analysis of a space. The values in the coloured grid on the right, correspond to the illuminance sensors indicated through red arrows on the left image.

In the last two decades, researchers as well as architectural designers have increasingly relied on luminance-based metrics to quantify glare. Luminance, expressed as lumens/steradian/m² is a more credible predictor of light perceived by the eyes as it quantifies the brightness and angular size of a light source in the visual field [2].

1.2 Image-based daylighting simulations with High Dynamic Range (HDR) imaging
The most common approach for luminance-based simulations is to generate physically-based High Dynamic Range (HDR) images, as shown in Figure 2, where the
Luminance values are mapped to the pixels of the image. HDR images can also be used to calculate several glare metrics like Daylight Glare Probability (DGP), Unified Glare Rating (UGR) and Visual Comfort Probability (VCP).

Figure 2. HDR images generated for a daylit space. The image on the right is a falsecolor image that maps luminance values on individual pixels.

As HDR imaging is primarily concerned with simulating the physical reality of a daylit space, the emphasis is on accurate generation and representation of luminance values on to an image. Such images are often unable to project the qualitative perception of a space to the observer as they are normally viewed on flat desktop displays. To address this issue, some recent studies have explored the possibility of incorporating HDR imaging with Virtual Reality (VR) interfaces.

1.3 Application of Virtual Reality in simulations and HDR

One of the primary advantages of using a VR interface is the ability to provide the user with a more immersive experience of the architectural space being evaluated. As shown in Figure 3, with such an interface, the field of view of the user is not restricted to a single direction. Special modelling considerations need to be applied to prepare HDR images for VR-based interfaces [6-8].

Figure 3. A schematic diagram of HDR image mapped for viewing in a VR environment. Credit: [8]

The applicability of VR in evaluation of architectural spaces has been addressed by past studies. These studies primarily focused on photo-realism to provide the users with an aesthetic perspective of an architectural space [9-15]. Recently conducted studies with VR-based tools, that rely on physically-based rendering and HDR imaging, have shown favourable responses from participants [7, 8]. The perceptions of daylit spaces evaluated through HDR images in VR tools were found to be comparable to that experienced in the physical space.

1.4 Limitations of current tools

Presently, the available tools for VR-based analysis of architectural spaces either focus on photo-realism or on physically-based renderings. Game-engine-based tools like Unity-3D or Unreal Engine that rely on photo-realism for visualization generally feature advanced controls and interfaces that allow better user interaction and immersive experience [16-18]. Tools that generate physically-based renderings, on the other hand, focus overwhelmingly on numerical accuracy of results. Beyond permitting movements in a space, such softwares have limited features for user interaction [19]. Additionally, physically-based raytracing of architectural models is a computationally demanding process even with the latest graphics hardware. Consequently, such softwares are capable of loading only a single lighting condition for analysis at a time. Considering that for a given building model, visual comfort analyses are needed for several lighting conditions a year, loading single daylighting scenarios for analysis each time is time-consuming and process-intensive.

2. DEVELOPMENT OF AN IMMERSIVE INTERFACE FOR VISUAL COMFORT ASSESSMENT: OVERVIEW

The prototypical tool developed by the authors, which is described in this paper, seeks to synergize the advantages offered by game-engine Application Programming Interfaces (API) and physically-based renderers. The following sub-sections discuss the development goals and methodology of this tool.

2.1 Development goals

As discussed in section 1.4, softwares that are currently available for VR-based analyses of architectural spaces either focus on photorealism or on physically-based accuracy. The authors sought to bridge the gap between these softwares by choosing to incorporate the following features and functionality into the new tool:

1. Realistic movements in architectural space by modelling collisions and textures through game engine API.
2. Analysis of multiple daylit scenarios through pre-simulation of HDR-based images for certain chosen locations, typically close to glazing. This contrasts with current physically-based VR renderers that generate HDRs in real-time.
3. Ability to toggle through multiple daylighting scenarios through user-controls.
4. Ability to teleport in and out of HDR viewer from the VR space.

The choice to pre-simulate HDR images was made to facilitate the deployment of the tool on desktop.
computers with inexpensive graphics cards or even laptop computers.

2.2 Methodology for development

Majority of the development workflow for the tool features the use of a pre-existing API and simulation engine. The HDR images were simulated through Radiance, a validated raytracer [20]. The VR space was created using the Unreal Engine gaming API [18]. The core software development work entailed creating a data-conversion pipeline for creating compatible models in Radiance and Unreal Engine. Figure 4 provides a schematic representation of the conversion from a CAD model to a VR-ready interface. Figure 5 shows the corresponding pictorial representation.

Based on the modelling tool used to created them, Architectural CAD models can be of different formats like DWG, 3DM or DXF. In contrast, the compatible input formats for creating models in Radiance and Unreal Engine are limited to RAD and FBX only. The conversion to RAD format can be done through commandline tools available within Radiance. Conversion to FBX can be done through the export functionality in modelling software.

While much of the conversion process is automated, manual intervention is required to define the material properties of the surfaces, assign view-points for generating HDR images and to pre-identify collision-enabled surfaces. Post the data-conversion process, HDR images are generated in Radiance through raytracing and then imported as spherical textures into the VR space for visualization. Details regarding HDR imaging are further elaborated in the following section.

3. HDR IMAGING

Visual comfort analysis of a space requires the assessment of that space under varying climatic conditions. For the HDR images generated for visual comfort analysis, the climatic conditions are incorporated into the simulation through sky representations based on the all Perez Sky Model[21]. Perez Sky Models for any location can be created through a Radiance program called gendaylight. Gendaylight requires geographical details such as longitude, latitude and standard meridian, and radiation data in the form of Direct-Normal and Diffuse-Horizontal radiation to generate a sky representation. This information is extracted from Typical Meteorological (TMY) weather datasets. The type of HDR images compatible for 360° viewing in VR environment can be angular sphere map, equirectangular panoramic or cube map [6].

Of these, equirectangular type was chosen in the workflow as it is possible to generate such images within a single simulation run in Radiance. Furthermore, the methodology for generating these images have already been developed in prior research [6]. Example of an equirectangular image generated for the tool is shown in Figure 6. It also illustrates the reason for the image appearing stretched out near its upper and lower periphery. To enable both perceptual and numerical evaluation of the daylit spaces, two versions of each HDR image, as shown in Figure 7, were created. The tone-mapped image incorporates exposure and gamma correction as per the human visual system while the falsecolor image indicates the luminance values for individual pixels.

The end user of the tool can pre-select multiple daylighting conditions and shade-setting configurations for analysis. Some examples of the HDR images generated for such scenarios are shown in Figure 8 and Figure 9 respectively. Once generated, the HDR images are imported into the game engine interface and mapped to spherical surface to enable 360° views in VR. This is accomplished through a custom algorithm implemented in C++ that relies on the Unreal Engine API to convert standard images to material textures. The details regarding the game engine interface and user interaction are discussed in the next section.
Figure 6. The top image shows the relative distortion associated with mapping a sphere (spherical image) onto a rectangle (equirectangular image). In the tool, as the images are mapped to a spherical surface, this issue is not detrimental to the user’s perception of the architectural space. The image on bottom shows an example within the context of an HDR image generated for the architectural model. Credit for top image: [6]

Figure 7. The image on top shows a tone-mapped HDR image and the next image shows a falsecolor representation of the HDR.

Figure 8. Images generated for different times and dates with the same setting for shading system.

Figure 9. Images generated for the same date and time with different shade (venetian blind) settings. The percentage values above the images refer to the extent to which the blinds have been lowered.

4. GAME ENGINE INTERFACE

As discussed in Section 2.2, the VR interface for the tool was created using the Unreal Engine API. This API, originally created for development of video games has been adapted to generate architectural visualizations for both commercial and research-oriented applications [18]. An exhaustive description of the intricacies of the Unreal Engine API and the scripting entailed in development of the tool is beyond the scope of this paper and unlikely to be of interest to the participants of the conference. Novel features in the development of the interface, that are meant to improve user interaction and immersive experience are discussed in the following subsections.

4.1 Texture mapping and collision modelling

The surfaces used to recreate the architectural model in the game engine interface feature the application of colour and image-based texture maps. The material properties can either be manually assigned or created by parsing through values chosen for the RAD model created for Radiance. The only aspect of the interface where surfaces cannot be customized are in the HDR 360° environment, where texturing is based on the image being viewed. Screen-captures of surfaces in the interface are shown in Figure 10.

To allow the users to experience the architectural space with physical boundaries and obstructions, just as one would in a reality, collision mapping was performed on certain meshes as shown in Figure 11.
The presence of collisions improves the immersive experience of the users as it prevents them from walking through walls and glazing. Furthermore, the presence of collision-mapped furniture objects provides a sense of real-world obstructions that one encounters in actual spaces. Collision-mapping can be automated by pre-identifying collision prone surfaces through separate layers in the CAD model.

4.2 Teleporting
One of the drawbacks of choosing between photorealism or physically-based rendering is that the benefits offered by one method is lost in the implementation of other. The authors attempted to address this issue by implementing the primary navigation of the architectural model in the photorealistic game-engine interface and permitting the user to visually evaluate certain pre-identified locations through HDR images. The transition between the game-engine interface and HDR 360° view was accomplished through a teleport option that allows the user to click on a spherical probe and view the HDR images. This functionality is illustrated in Figure 12. The HDR images are mapped inside a spherical mesh surface, so constructed to enable 360° views of equirectangular images.

4.3 Evaluation of multiple lighting scenarios
Within the HDR 360° viewing environment, the user can evaluate multiple daylit scenarios for a specific location by switching through different HDR images with a keyboard or joystick. Screen-captures highlighting this functionality are shown in Figure 13. The curvature of straight objects, such as pillars, visible in the screen captures is an inherent shortcoming of projecting a spherical scene onto a flat surface, i.e. taking a screen shot or displaying on a monitor. The curvature issue, however, is almost imperceivable in modern head mounted displays (HMD) such as the VR-headset used with the tool. This is due to the much smaller field of view (FoV) and the specially designed optical lens system of the HMDs. Assessment of different viewing angles is possible through either head-turns in a VR-headset or using mouse-movements in a desktop display.

5. DISCUSSION AND CONCLUSION
The preceding sections presented an overview of a new tool that attempts to provide architects and designers with a realistic perception and visual comfort assessment of an architectural space. By selectively utilizing the functionality of a gaming engine API and a validated physically-based renderer in the development of this tool, the authors have endeavoured to facilitate daylighting design-based decisions in real-time.
To the best of the authors’ knowledge, as of date, features relating to teleporting, realistic collisions, and evaluation of multiple daylit scenarios in a single runtime session have not been implemented in other VR-based daylighting simulation software. Limitations of the tool primarily relate to the emphasis on pre-simulation of HDR images for selective locations. It can be argued, however, that in standard architectural spaces, visual comfort related assessments are performed for locations close to the glazing. So, pre-identifying this detail should not represent a major hurdle in implementation and use.

Since the tool was developed as a prototype, exhaustive testing on a variety of hardware platforms has not been conducted at present. The functionality to instantaneously calculate glare metrics like DGP, VCP and UGR, is currently not incorporated in the tool. This feature, already implemented in software like Accelerad [19], requires hardware-intensive real-time physically-based rendering. Most desktop computers and mobile computing devices currently are unable to support real-time physically-based rendering. So, the authors chose not to include instantaneous glare calculation as one of the features in the tool.

Future development initiatives for this tool will focus on testing on additional platforms and the visualization of solar insolation through conventional glazing and complex fenestration systems. The value of solar insolation so visualized can be leveraged to provide the user with a sense of perceived surface temperatures in the space being viewed.

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ABSTRACT: This paper attempts to evaluate the accuracy of computer-simulated results of thermal comfort inside Hawa-Mahal, a traditional naturally ventilated building in the hot, dry region of India. The façade appears to be having a higher Wall-Window Ratio (WWR), which is contrary to the passive design strategies proposed for buildings in hot-dry climates. Thus, it was quite intriguing to experience comfort inside Hawa-Mahal. In the building-performance field, modelling is the most widely used tool. The comfort criteria have been studied using simulation software, DesignBuilder, which is based on EnergyPlus™ simulation engine. The simulated results obtained were validated against the real-time monitored thermal comfort data. This paper also presents the methodological procedure applied for validation of the model. Tropical summer index (TSI) has been used as a primary thermal comfort scale. The study was carried out for analysing the impact of passive design techniques (Courtyard size, thermal mass, Window Wall Ratio and Shading techniques) on thermal comfort inside Hawa-Mahal. This paper highlights the significance of infiltration input in terms of ‘Coefficient of Discharge’ (Cd).

KEYWORDS: Indoor Thermal Comfort, Whole Building Simulation, Passive Cooling Techniques, Vernacular

1. INTRODUCTION
In the field of thermal comfort, engineers, architects and other practitioners are focusing on the naturally ventilated buildings, as it is the best way to minimise the unconditioned buildings’ energy consumption (Walker, 2016). Researchers and scholars across the world are carrying out significant research analysing the passive design strategies applied in vernacular architectural systems (Supic, 1982). Following the principle of ‘Learning from the past’, researchers are turning to vernacular architecture to seek answers to contemporary problems as it serves as a base to develop new and better sustainable design strategies aiming at the minimisation of energy-intensive artificial means to provide thermal comfort (Supic, 1982).

Vernacular structures were built by local people, deploying climate-specific passive design technologies, which were evolved over centuries of trial and error, thereby making them responsive to the local climate. Hawa-Mahal is one such vernacular structure in Pink City of Jaipur (Rajasthan, India) known as Palace of Winds or Breeze. The cooler temperature inside Hawa-Mahal in summers captures the attention of every visitor; and drives one to contemplate about the traditional knowledge of the builders who were able to create such a comfortable building without any help of modern means (Gupta, 1984). The facade consists of 953 ‘Jharokhas’—a traditional fenestration element like small window. The façade, as shown in Figure 1, appears to be having a higher Wall-Window Ratio (WWR), which is contrary to the passive design strategies proposed for buildings in hot and dry climate (Koenigsberger, Ingersoll, Szokolay, & Mahwey, 2013). Thus, it is quite intriguing to experience thermal comfort inside Hawa-Mahal.

In the building-performance field, modelling is the most widely used tool (Maile, Fischer, & Bazjanac, 2007). Since computer simulation provides the most economical and fast method to evaluate any design including traditional passive design techniques, (Baharvand, Ahmad, Safikhani, & Majid, 2013) this strategy has been used to analyse the design of Hawa-Mahal.

2. DESCRIPTION OF HAWA-MAHAL

Hawa-Mahal, also known as the ‘Palace of Winds’, is situated in the heart of pink city Jaipur, Rajasthan (Figure 1). It was built in 1799 in the reign of ‘Maharaja Sawai Pratap Singh’ and designed by ‘Lal Chand ustad’ in the form of Lord Krishna’s Crown using red and pink sandstones. The 953 ‘Jharokhas’ (a traditional...
architectural element) in the front façade resembles the honeycomb structure when viewed from the outside. Each of the ‘Jharokhas’ consists of a small window along with the red sandstone ‘Jaalis’, and finials and domes above it (Figure 2). Amidst the hot and dry season of the city Jaipur, air flowing through the windows keeps the indoor temperature of the Hawa-Mahal cool and refreshing.

Figure 2: ‘Jaalis’ and ‘Jharokha’ in Hawa-Mahal

The intricate pattern of ‘Jaalis’ supplies the cool air caused by the venturi effect, thus air conditioning the whole area during the high-temperature season outside (Meena, Chaurasia, & Mathur, 2014). It is also accompanied by semi-octagonal bays, which provide the monument with its distinctive facade. The inside of the Hawa-Mahal is associated with coloured marbles and rich inlaid sections, whereas fountains embellish the actual centre of the King’s court (Figure 3).

Figure 3: Fountain in the king courtyard

The main façade consists of the stone wall, as well as brick wall plastered with ‘Surkhi’ (brick-dust) and lime. The thickness of wall is generally from 50 to 150 mm thick, whereas in some areas, it is 300 to 500mm. The width of ‘Jaalis’ is varying between 25-75 mm. Hawa-Mahal is minutely documented with construction details and drawings available from Archaeological Survey of India (ASI), which is the source for this information.

### 3. BASE CASE MODEL DEVELOPMENT

DesignBuilder is one of the most comprehensive user-interface for EnergyPlus™, a dynamic thermal simulation engine (Chowdhury, Rasul, & Khan, 2007). The next paragraph briefly describes the base model development of Hawa-Mahal.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness mm</th>
<th>Density kg/m³</th>
<th>Conductivity</th>
<th>Specific heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>External wall from outside to inside – U Value</td>
<td>1.269</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lime Plaster</td>
<td>25</td>
<td>2300</td>
<td>1.3</td>
<td>840</td>
</tr>
<tr>
<td>Brick</td>
<td>400</td>
<td>1500</td>
<td>.85</td>
<td>840</td>
</tr>
<tr>
<td>Lime Plaster</td>
<td>25</td>
<td>2300</td>
<td>1.3</td>
<td>840</td>
</tr>
<tr>
<td>Internal Partitions – 1</td>
<td>U Value</td>
<td>1.493</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lime Plaster</td>
<td>25</td>
<td>2300</td>
<td>1.3</td>
<td>840</td>
</tr>
<tr>
<td>Brick</td>
<td>230</td>
<td>1500</td>
<td>.85</td>
<td>840</td>
</tr>
<tr>
<td>Lime Plaster</td>
<td>25</td>
<td>2300</td>
<td>1.3</td>
<td>840</td>
</tr>
<tr>
<td>Internal Partitions – 2</td>
<td>U value</td>
<td>2.167</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lime Plaster</td>
<td>25</td>
<td>2300</td>
<td>1.3</td>
<td>840</td>
</tr>
<tr>
<td>Brick</td>
<td>100</td>
<td>1500</td>
<td>.85</td>
<td>840</td>
</tr>
<tr>
<td>Lime Plaster</td>
<td>25</td>
<td>2300</td>
<td>1.3</td>
<td>840</td>
</tr>
<tr>
<td>Intermediate Floors</td>
<td>U value</td>
<td>1.405</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stone Flooring</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lime Concrete</td>
<td>450</td>
<td>2300</td>
<td>1.9</td>
<td>840</td>
</tr>
<tr>
<td>Lime Plaster</td>
<td>25</td>
<td>2300</td>
<td>1.3</td>
<td>840</td>
</tr>
<tr>
<td>Top Floor</td>
<td>U value</td>
<td>1.405</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stone Flooring</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lime Concrete</td>
<td>450</td>
<td>2300</td>
<td>1.9</td>
<td>840</td>
</tr>
<tr>
<td>Lime Plaster</td>
<td>25</td>
<td>2300</td>
<td>1.3</td>
<td>840</td>
</tr>
</tbody>
</table>

The base model was prepared on DesignBuilder in the sequence of site, surroundings and the building. The building model was further developed into different blocks and zones which consists of walls, floor and roof represented by basic geometric shapes. This structure helps to add the physical and thermal characteristics of all the surfaces, individually. Internal partition walls help to create different thermal zones inside the block. The subsequent floors were modelled in a similar manner. Table 1 shows the material properties of these building elements as used in the base model, which is as per the details of constructions gathered from ASI. The construction details were provided as per Table 1. The walls are ranging from 150 mm to 450 mm in thickness with construction material of brick, stone and plastered with lime and ‘Surkhi’ (brick-dust). The intermediate floor thickness is around 450-500 with the plastered ceiling and ‘Kota stone’ Flooring.

The nearest available TMY2 Jaipur weather data file was used to carry out the whole building energy simulation, which is procured from the ASHRAE website. It is generally agreed that TMY2 weather file
gave the closest output match to measured consumption (Crawley, 1998). The data used from the weather file is depicted in Graph 1 for the duration of 15th-18th December 2015. Currently, as well as historically, no air conditioning and mechanical ventilation are being used in Hawa-Mahal. There is no light load as the building is intended to be used during daytime only. All the windows remain open during the day and remain open in the night as well. Traditionally in hot-dry climates, windows are closed during summer days and opened during summer nights and vice-versa in winters. However, due to lack of maintenance and operability, all windows remain open all day and night. The same schedule of all-time open windows has been used for the base case.

4. MEASUREMENT AND DATA RECORDING OF ENVIRONMENTAL VARIABLES.

In order to obtain the information and data related to thermal comfort characteristics inside Hawa-Mahal, each zone and floor of the building was investigated physically with the assistance of operations maintenance personnel. Due to the shortage of instruments and human resources, the location for measurement of real-time data was limited to the ground floor only with six distinctive locations as per Figure 4. These points are located in the vicinity of front façade.

Table 2: Description of Instruments used for Real-time monitoring.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Parameter</th>
<th>Instrument</th>
<th>Make</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Air Temperature</td>
<td>Digital Thermo-hygrometer</td>
<td>Sika MH-3350</td>
</tr>
<tr>
<td>2</td>
<td>Mean Radiant Temperature</td>
<td>Globe Thermometer (150 mm-Dia)</td>
<td>Scientific Equipment</td>
</tr>
<tr>
<td>3</td>
<td>Relative Humidity</td>
<td>Digital Thermo-hygrometer</td>
<td>Sika MH-3350</td>
</tr>
<tr>
<td>4</td>
<td>Air Velocity</td>
<td>Anemometer</td>
<td>Windtronic 2-Kändl</td>
</tr>
</tbody>
</table>

Experimental investigations of thermal comfort within Hawa-Mahal were conducted through real-time data monitoring using high accuracy instruments. Environmental Variables as per Table 2 were measured every 30 min at the height of 1.1m from floor level, following class II protocol (Feriadi & Wong, 2004). The recordings were carried out for four days (15th – 18th Dec 2015) between 9:00 AM to 4:00 PM. The Jaipur weather data was obtained from IMD (Indian meteorological department) for the period of monitoring.

The collected data for Indoor air temperature reveals that the indoor air temperature inside Hawa-Mahal at all recorded locations (point 1 to point 6, Figure 4) limits itself from 18°C to 23°C, whereas, the outdoor air temperature minima is 14.4°C. This is a clear indication of the effectiveness of building towards creating thermal comfort as the bandwidth of temperature inside the building is reduced.

The Relative humidity inside the Hawa-Mahal at monitored locations ranges itself between 28% to 36%, decreasing with the time. The trend followed by the RH is almost the same at all monitored locations. The following graphs 2-6 represent the Air Velocity at all monitored locations for the 4 days.

Graph 1: Air temperature for four days (15th – 18th December 2015) from Weather Data file (WDF) available on ASHRAE Website

Graph 2: Air velocity on Day 1

Figure 4: Hawa-Mahal Ground Floor Plan showing all six locations of real-time measurement.
alternative method was applied in the simulation process. The physics behind the ‘Jaalis’ lies in the ‘coefficient of discharge’ values which vary depending upon the ratio of open area to the closed area of the ‘Jaalis’. In DesignBuilder, however, for fenestration, only windows or ventilators could be modelled. A similar effect was obtained by varying Coefficient of Discharge (Cd) values. After that, Cd values need to be assigned to the windows of the same size to get the results, which are similar to the actual ‘Jaalis’. The Hawa-Mahal model is simulated with different coefficient discharge values ranging from 0.1 to 0.7 (i.e., 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, and 0.7). Simulated results—from all the models with different Cd values—are depicted in Graph 6. The process is repeated for all six points for the duration of four days, 15th-18th December 2015. Although as per ASHRAE guideline 14, it is necessary to monitor the building for 365 days to calibrate a model. Monitoring was done for only four days due to the constraint of resources and time.

The temperature obtained by varying ‘coefficient discharge value’ is compared with the monitored indoor temperature by using regression analysis. Table 4 shows the results of regression analysis. The most relevant results are obtained by using 0.4 as the ‘coefficient discharge value’ (Cd).

2. It is ascertained that the Cd value of 0.4 provided the results closest to the monitored indoor environment. A comparison was made, regression analysis was carried out, and the graph was plotted, and it was found that though the trend is similar, there is a gap (Graph 7). The reason for this gap could be the difference between outdoor weather data used for the monitoring period and the weather data file used for simulation (Graph 8).

3. To study the difference between outdoor versus indoor for both monitored and simulated results, another regression analysis was carried out (Table 3), and it was ascertained that the simulated results follow the same curve, and model is thus proved to be validated.
Graph 7: Difference in indoor recorded and outdoor recorded data as well as weather data file (WDF) and simulated data. For point 1, day 1.

Graph 8: Air Temperature from the weather data file and recorded data for all four days (between 15th Dec- 18th Dec)

Table 3: R value obtained from regression analysis of difference between outdoor data versus indoor data for monitored and simulated results (e.g., P1- Point 1)

<table>
<thead>
<tr>
<th>Location</th>
<th>Point 1</th>
<th>Point 2</th>
<th>Point 3</th>
<th>Point 4</th>
<th>Point 5</th>
<th>Point 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-value</td>
<td>0.91</td>
<td>0.92</td>
<td>0.835</td>
<td>0.85</td>
<td>0.87</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Although, ASHRAE recommends using hourly data for one year for the given data and simulation. The model is calibrated based on a four-day period of physical measurement.

Table 4: R value obtained from regression analysis of Simulated results and Real-time measured results. The Table depicts results for all 4 days (D1- Day1, D2-Day2, D3- Day3, D4 – Day4)

<table>
<thead>
<tr>
<th>Cd Value</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D1</td>
<td>D2</td>
<td>D3</td>
<td>D4</td>
<td>D1</td>
<td>D2</td>
<td>D3</td>
</tr>
<tr>
<td>Point 1</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
<td>0.97</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>0.82</td>
<td>0.81</td>
<td>0.82</td>
<td>0.82</td>
<td>0.83</td>
<td>0.82</td>
<td>0.83</td>
</tr>
<tr>
<td>Point 2</td>
<td>0.94</td>
<td>0.94</td>
<td>0.95</td>
<td>0.95</td>
<td>0.96</td>
<td>0.97</td>
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<tr>
<td></td>
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<td>0.98</td>
<td>0.96</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td>Point 3</td>
<td>0.89</td>
<td>0.89</td>
<td>0.90</td>
<td>0.90</td>
<td>0.91</td>
<td>0.91</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>0.89</td>
<td>0.88</td>
<td>0.90</td>
<td>0.90</td>
<td>0.91</td>
<td>0.91</td>
<td>0.91</td>
</tr>
<tr>
<td>Point 4</td>
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<td>0.87</td>
<td>0.87</td>
<td>0.87</td>
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</tr>
<tr>
<td></td>
<td>0.87</td>
<td>0.87</td>
<td>0.89</td>
<td>0.89</td>
<td>0.90</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>Point 5</td>
<td>0.93</td>
<td>0.93</td>
<td>0.93</td>
<td>0.93</td>
<td>0.94</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>0.87</td>
<td>0.77</td>
<td>0.77</td>
<td>0.77</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>Point 6</td>
<td>0.89</td>
<td>0.87</td>
<td>0.87</td>
<td>0.87</td>
<td>0.91</td>
<td>0.91</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>0.78</td>
<td>0.86</td>
<td>0.86</td>
<td>0.86</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
</tr>
</tbody>
</table>

One significant limitation for this study is the lack of measured data—over a longer period—to check the performance of the simulated model for a whole year. In order to accurately calibrate the data, yearly data should be measured, and calibration should be done.

6. DATA ANALYSIS AND COMFORT SCALE

Analysis of Jaipur climatic data reveals that November to February could be termed as winter season whereas April to September comes in the season of summer. Since the field measurement is conducted in the month of December, it is regarded as winter reading. The outdoor temperature during the study period ranges from 14.5 to 22 degree Celsius while the indoor temperature limits itself from 18 to 23 degree Celsius. The relative humidity inside the Hawa-Mahal limits itself between 30 to 40% during this period.

Tropical summer index has been used as a primary scale of thermal comfort measurement. It is based on the tropical characteristics of Indian climate (NBC, 2005). It is calculated using equation 1 provided in SP41 of Bureau of Indian Standards (BIS).

\[
\text{TSI} = \frac{1}{3} tw + \frac{3}{4} tg - 2\sqrt{v}
\]  

The coolness of the environment was found to be tolerable between 19 and 25°C (TSI). It was characterised as ‘too cold’ below 19°C (TSI) (SP 41, 1987). The TSI for all measured locations in Hawa-Mahal was above 19 and below 25 degrees Celsius considering the winter season. And for a free-running building, it is found to be thermally comfortable. The Graph 9-11 represents the TSI Measured, and TSI simulated at all points day wise. It was found that though there was a slight difference in values, the trend followed by the graph was the same, which is also the case with air temperature. This validates that:

1. The model is accurate for the period of physical measurement.
2. Hawa-Mahal was able to achieve thermal comfort for the monitored duration.
7. CONCLUSION

Although, the ‘whole-building simulation tool’ is one of the most popular tools to assess building performance. There lies a tremendous gap within simulation studies when it comes to actual performance, which is bridged by validation.

Validation of an existing traditional building is even more complicated for various reasons given below:

1. The limitations of the software in modelling complicated features such as ‘jaalis’.
2. The building under consideration may have undergone several renovations in the last two decades. It can change the physical property (U-value) of the building elements like walls and floors.
3. Schedules of window openings and other similar factors could be different from what has been recorded and used in modelling software. It could have a significant impact as far as uncertainty in results is concerned.

By varying $C_d$ in the case of Hawa-Mahal, it was possible to arrive at a model which provided a good approximation of the actual building.

REFERENCES

Clerestories for Daylighting Deep in Residential Apartments: A search for window to wall ratio for bedrooms for dining illumination

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2Department of Architecture, Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh

ABSTRACT: Majority of the residential apartments in Dhaka have windowless central dining spaces because of the spatial organization of surrounding rooms and functional spaces. Larger windows in external walls and clerestories in partition walls can provide more daylight in the dining; however, will create glare and heat gain in the peripheral rooms with external facades. This research aims to identify the effective placement of different sizes of clerestories in inner partition walls between the dining and surrounding bedrooms with optimum window to wall ratio (WWR) of the adjacent bedrooms to increase the amount of daylight in dining space under tropical sky conditions. Dynamic Daylight Simulation (DDS) technique with DAYSIM is used to evaluate the performances of different clerestories and WWR configurations using annual climate based performance metrics. The results show that insertion of clerestories between lintel and ceiling along the maximum possible length of the internal partition walls between dining space and bedrooms resulted increased DA and DAcon by 11.5% and 7.16% respectively. In addition to this, 40% WWR of full height corner windows on the bedroom facades increase the value of UDI100 to 60.8% to the core sensor points of the dining space without creating glare in the bedrooms. The distribution of daylight both in bedrooms and dining space is also improved.

KEYWORDS: Daylighting, Residential building, Simulation study, Clerestory, Window to wall ratio (WWR).

1. INTRODUCTION
Population growth and rapid urbanization create conflict between space-use efficiency and daylight penetration. To meet the demand of huge population, building codes and setback rules are compromised in majority of the existing residential buildings in Dhaka [1]. Due to lack of sensible daylight design inside the buildings, occupants rely on artificial lighting, results increased energy consumption. According to the Annual Report of Dhaka Electric Supply Company Limited (DESCO) 2017, 90% consumers of Dhaka are residential and they consume 49% of the total electricity used [2]. Among this residential use, 41% electricity is consumed for lighting purposes [3]. The size, shape and position of windows not only directly influence the availability of daylight but also indirectly influence the energy demand for cooling and lighting [4]. To increase the affordability of the inhabitants, it is necessary to reduce the energy consumption and dependency on artificial lighting by successful integration of daylighting.

Dining space, chronologically evolved from the rural concept of courtyard is the most visually integrated central space of a residential apartment which houses maximum of the daytime activities of the inhabitants [5]. Because of central location of the dining space in apartment layout and dense urbanization, majority of the residential apartment of Dhaka have central windowless dining space without any access to daylight (Fig. 1). Now-a-days, one of the most challenging issues in residential building design is to provide daylight in the deeper dining spaces through the peripheral windows, as large windows in external walls will create overheating and glare in peripheral rooms, i.e. bedrooms. An investigation on residential buildings of Hong Kong reported that about 90% of buildings had window to wall ratios (WWRs) between 25% and 35% in living and bedrooms [6]. Another study in the cities of Leeds and Florianopolis showed that ideal window area for energy efficient daylighting tends to be larger on the orientations whose energy consumption is lower due to small solar radiation and ideal window area is larger for larger rooms with narrow width [7]. On the other hand, multiple apertures- for example, windows on two sides of a space or clerestories can improve the distribution of daylight in a space [8]. At this point, optimization of WWR of the peripheral rooms along with insertion of clerestories on the peripheral walls of the dining space need to be investigated as it is rarely studied yet for the context of a tropical city, i.e. Dhaka.

This research aims to identify the possibility of placement of different sizes of clerestories in inner partition walls between dining and bedrooms, with appropriate WWR of the adjacent bedrooms to increase the amount of daylight in dining space under tropical sky conditions. Dynamic Daylight Simulation (DDS) technique using DAYSIM is used in this research to assess the performance of different configurations of clerestories and WWR.
2. METHODOLOGY

2.1 The Case Space

Almost 45% people of Dhaka fall on the category of middle and upper-middle income group, who prefer apartments comprising 85-111 m² in Mirpur, Uttara, Mohammadpur, Dhanmondi, Bashundhara, Banasri, Tejgaon among the planned residential areas of Dhaka [9, 10]. Three types of living-dining layouts are identified (considering the physical layout) in a previous research after surveying 50 randomly selected middle income group’s residential apartments from the target areas: attached, continuous and separate types of living-dining [5]. It is also found from the survey that the number of attached type living-dining layout (Fig. 1) is significant in number. Considering the above, following criteria are developed to select a case residential apartment to represent Dhaka’s buildings.

1. The area of the apartment should be within 85-111 m² as number of this type of apartment is significantly large and located on the preferred location of middle income group.
2. The apartment should have attached type living-dining layout as it comprises the major portion of the surveyed apartment.
3. Dining should be located at the center of the apartment surrounded by other functional spaces.
4. There should be no window in the dining space of the apartment that opens directly outside and serve as a direct aperture of daylighting.

Based on the above criteria, an apartment from 50 surveyed apartments [5] with attached living-dining layout, shown in Fig. 1 is selected as case apartment for simulation analysis.

The total area of the case apartment is 88 m² and it consists of two bedrooms, two toilets, a kitchen, an attached type living-dining space and one veranda. The area of the windowless dining space is 12.7 m². The average area and WWR of the bedrooms are 14.4 m² and 19% respectively. The floor to ceiling height is 3.0 m and width of the shading device is considered as 0.5 m, satisfying the regulation of the city authority, i.e. RAJUK [11]. The detailed material properties of the case apartment are presented in Table 1.

Table 1: Material properties of the case apartment for daylight simulation [13].

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Material Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall</td>
<td>Material: 110mm brick with 10mm plaster in both sides. Painted white on interior side. Reflectance: 0.7</td>
</tr>
<tr>
<td>Window</td>
<td>Material: Single pane of glass with aluminium frame (no thermal break). Reflectance: 0.92 Visual Transmittance: 72%</td>
</tr>
<tr>
<td>Ceiling</td>
<td>Material: Concrete Roof, painted white inside. Reflectance: 0.7</td>
</tr>
<tr>
<td>Floor</td>
<td>Material: 100mm thick concrete slab on ground. Reflectance: 0.6</td>
</tr>
<tr>
<td>Shading device</td>
<td>Material: Concrete with plaster. Reflectance: 0.6</td>
</tr>
</tbody>
</table>

In reality, the synchronous impact of numerous variables creates difficulties to isolate impact of one single variable from another. Daylight simulation allows to study the impact of one single variable by keeping others constant. To investigate the performance of clerestories and different WWRs on the daylighting of dining space, the interior of the case space and the surroundings are considered as vacant [13].

2.2 Computer Simulation Method

The initial 3D model of the case space is exported to a RADIANCE based simulation software DAYSIM 2.1P4 which is validated rigorously for daylight analysis [14]. DAYSIM can calculate illumination level on any point as a function of outside daylight availability and can provide more than 8760 (365 x 24) hours data for each sensor point considering the Perez All-weather sky illuminance models using an annual climate file [15, 16].

2.3 Simulation Parameters

For DDS, simulations are performed considering nine hours of daylight time from 8.00 to 17.00 for seven days a week without any lunch and
intermediate break [17,18]. The design illuminance is considered as 150 lux for dining space (on table top) and bedrooms (at bed head) on analysis grid, 0.75m from the finished floor level according to BNBC [19]. The dynamic daylight simulation parameters are presented in Table 2.

Table 2: Daylight Simulation Parameters.

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Parameters</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Location</td>
<td>Dhaka</td>
</tr>
<tr>
<td>2.</td>
<td>Longitude</td>
<td>90.40° N</td>
</tr>
<tr>
<td>3.</td>
<td>Latitude</td>
<td>23.80° E</td>
</tr>
<tr>
<td>4.</td>
<td>Local Terrain</td>
<td>Urban</td>
</tr>
<tr>
<td>5.</td>
<td>Precision</td>
<td>High</td>
</tr>
<tr>
<td>6.</td>
<td>Time Zone</td>
<td>+6 GMT</td>
</tr>
<tr>
<td>7.</td>
<td>Simulation Time</td>
<td>8.00 to 17.00</td>
</tr>
<tr>
<td>8.</td>
<td>Date</td>
<td>Whole Year</td>
</tr>
<tr>
<td>9.</td>
<td>Sky Illumination Model</td>
<td>Perez- All weather sky model round the year</td>
</tr>
<tr>
<td>10.</td>
<td>Unit of Dimension</td>
<td>SI metric (m, cm, mm and Lux, cd/m²)</td>
</tr>
<tr>
<td>11.</td>
<td>Daylight properties of glaze portion</td>
<td>Transmission: 90% Pollution factor: 0.70 Framing factor: 0.90 Maintenance factor: 0.85</td>
</tr>
</tbody>
</table>

The non-default RADIANCE parameters are: 5 ambient bounces; 1000 ambient divisions; 20 ambient sampling; an ambient resolution of 300; a specular threshold of 0.15 and a direct sampling of 0.0 values [14].

3. PERFORMANCE EVALUATION PROCESS

The entire floor of the dining space and adjacent bedrooms are divided into 0.5m x 0.5m grids with 66 and 130 intersecting sensor points respectively at work plane height [17-19]. Intersection points are coded according to letter and number system (Fig. 2). Six intersection points on top of the dining table are selected as the core sensor points (Fig. 2a). In adjacent two bedrooms, sixteen points that run through the bed heads of the two bedrooms are selected as core sensor points for bedrooms (Fig. 2b).

3.1 Performance evaluation of clerestories

To take the advantage of the internally reflected components of daylight, two types of clerestory window configurations (CS1 and CS2) are placed alternatively between lintel and ceiling of the partition walls between dining space and bedrooms (Fig. 3a), after placing full height corner windows on the north and south facades (Average WWR of 30%) of the bedrooms (Fig. 3b). Full height corner window is found as the most feasible window configuration for residential apartments to improve the daylighting condition of dining space in a previous study [17].

3.2 Performance evaluation of WWR

Bigger full height corner windows in bedrooms will result in higher illumination in dining space but will create overlight, glare and heat problems in bedrooms. Optimum window sizes in the bedrooms are necessary to balance the illumination condition both in dining and bedrooms. To investigate the effect of different window sizes for bedrooms, eight WWRs are simulated: 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90% (Fig. 3b) in two phases.

- First phase: Impact of the different WWRs of bedrooms on the dining space illumination are studied.
• Second phase: Impact of the different WWRs of bedrooms on the bedrooms illumination are investigated.

![Figure 3: (a) Two clerestory configurations for internal walls; and (b) Eight alternative WWRs of bedrooms for performance evaluation process.](image)

4. RESULTS AND RECOMMENDATIONS

5.1 Recommendation for clerestories for dining space

Table 3 presents the summary result of dynamic daylighting performance metrics for dining space of the case apartment with two alternative clerestory configurations. Simulations are performed to calculate the dynamic daylight performance metrics: Daylight Autonomy (DA), Continuous Daylight Autonomy (DAcon), Maximum Daylight Autonomy (DAmax) above 5%, and Useful Daylight Illumination (UDI).

<table>
<thead>
<tr>
<th>Code</th>
<th>DA [%]</th>
<th>DA con [%]</th>
<th>DA max [%]</th>
<th>UDI&lt;100 [%]</th>
<th>UDI 100-2000 [%]</th>
<th>UDI&gt; 2000 [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS1</td>
<td>29</td>
<td>67</td>
<td>0</td>
<td>53</td>
<td>35</td>
<td>0</td>
</tr>
<tr>
<td>CS2</td>
<td>41</td>
<td>74</td>
<td>0</td>
<td>65</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Values of the studied metrics indicate that the width of clerestory has a significant effect on the daylighting of the dining space. Clerestory with greater width (CS2) that is the maximum possible length of the peripheral walls of the dining space (Fig. 5) effectively produce a larger amount of daylight into the dining (DA and DAcon increased by 11.5% and 7.61% respectively) compared to clerestory only over the door (CS1).

5.2 Recommendation for WWRs of bedrooms

In comparative study, performance metrics can be utilized to guide building design or to benchmark a building element against a group of similar elements with different parameters. Rating between different configurations based on simulation analysis is easier to interpret using dynamic metrics. In case of rating system, it is more desirable to select a single metric or scheme for a space. Different rating systems are proposed in past for the dynamic performance metric i.e. DA, DAcon, DAmax and UDI [14]. In this section, the UDI scheme, proposed by Mardaljevic and Nabil in 2005 for residential spaces is used to compare the performance of the dynamic metrics [20]. Mardaljevic and Nabil consider daylight is “useful” if work plane sensors lie between 100 lux to 2000 lux range. Below 100 lux is not considered as working light and above 2000 lux daylight is not wanted due to potential glare or overheating. As the domestic tasks are less desk and screen-oriented comparing office settings, it is sensible to recommend a higher upper threshold for UDI achieved for residential spaces [20]. The DA scheme will not allow higher upper threshold level. Rating system is done considering the mean value of dynamic metrics of core sensor points for each configuration and rating points (R.P) are considered as 7 point to 0 point, to suggest the configurations from 1st to 8th place [14].

UDI analysis of eight WWRs for bedrooms are done to find out the most feasible WWR to incorporate daylight into the dining space through the adjacent bedroom windows without creating glare in the bedrooms. Performance of dining space and bedrooms of the case apartment based on UDI metrics, RP and ranks of eight WWRs of bedrooms (Fig. 3b) are presented in Table 4 and 5 respectively.

<table>
<thead>
<tr>
<th>Code</th>
<th>Value and Rating Points (RP)</th>
<th>UDI&lt;100 [%]</th>
<th>UDI 100-2000 [%]</th>
<th>UDI&gt; 2000 [%]</th>
<th>Total RPs</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>WWR1</td>
<td>Value 44</td>
<td>35</td>
<td>0</td>
<td>7</td>
<td>8th</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RP 0</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WWR2</td>
<td>Value 43</td>
<td>56</td>
<td>0</td>
<td>9</td>
<td>7th</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RP 1</td>
<td>1</td>
<td>1</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WWR3</td>
<td>Value 39</td>
<td>61</td>
<td>0</td>
<td>11</td>
<td>6th</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RP 2</td>
<td>2</td>
<td>2</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WWR4</td>
<td>Value 37</td>
<td>63</td>
<td>0</td>
<td>13</td>
<td>5th</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RP 3</td>
<td>3</td>
<td>3</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WWR5</td>
<td>Value 33</td>
<td>67</td>
<td>0</td>
<td>15</td>
<td>4th</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RP 4</td>
<td>4</td>
<td>4</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WWR6</td>
<td>Value 28</td>
<td>72</td>
<td>0</td>
<td>17</td>
<td>3rd</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RP 5</td>
<td>5</td>
<td>5</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WWR7</td>
<td>Value 27</td>
<td>73</td>
<td>0</td>
<td>19</td>
<td>2nd</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RP 6</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WWR8</td>
<td>Value 26</td>
<td>74</td>
<td>0</td>
<td>21</td>
<td>1st</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RP 7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 5: Performance of bedrooms of the case apartment based on UDI metrics, rating points (RPs) and ranks of eight WWRs of bedrooms.

<table>
<thead>
<tr>
<th>Code</th>
<th>Value</th>
<th>Rating Points (RP)</th>
<th>UDI &lt;100 (%)</th>
<th>UDI 100-2000 (%)</th>
<th>UDI &gt;2000 (%)</th>
<th>Total RPs</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>WWR1</td>
<td>Value 2.6</td>
<td>Rating Points 86</td>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>WWR2</td>
<td>Value 1.7</td>
<td>Rating Points 71</td>
<td>28</td>
<td></td>
<td></td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>WWR3</td>
<td>Value 1.4</td>
<td>Rating Points 55</td>
<td>44</td>
<td></td>
<td></td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>WWR4</td>
<td>Value 1.1</td>
<td>Rating Points 40</td>
<td>59</td>
<td></td>
<td></td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>WWR5</td>
<td>Value 1.0</td>
<td>Rating Points 26</td>
<td>73</td>
<td></td>
<td></td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>WWR6</td>
<td>Value 1.0</td>
<td>Rating Points 18</td>
<td>81</td>
<td></td>
<td></td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>WWR7</td>
<td>Value 1.0</td>
<td>Rating Points 13</td>
<td>86</td>
<td></td>
<td></td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>WWR8</td>
<td>Value 1.0</td>
<td>Rating Points 11</td>
<td>88</td>
<td></td>
<td></td>
<td></td>
<td>7</td>
</tr>
</tbody>
</table>

Fig. 4 presents the comparison of overall rating points for dining space and bedrooms with eight WWRs of bedrooms to determine the optimum WWR for bedrooms to improve the daylighting condition in dining spaces. In case of UDI of dining, RPs are increased with an increase in window sizes in bedrooms. On the contrary rating points do not increase gradually with the increase in window sizes in case of UDI of bedrooms because of over lighting and glare issues in the bedrooms. Considering the performance of eight different WWRs of bedrooms, 40% WWR is found to be the most balanced WWR to incorporate daylight in the dining space through the adjacent bedrooms with optimized glare and over light in the bedrooms (Fig. 5). Comparison of the UDI<sub>100-2000</sub> distribution in dining space and bedrooms with optimum WWR (40%) along with clerestories on the partition walls between bedrooms and dining space are shown in Fig. 6.

Figure 4: Comparison of overall rating points for dining and bedrooms with eight WWRs of bedrooms.

Figure 5: Optimum window configurations for external bedroom facades and internal partition walls between dining space and bedrooms.

Figure 6: Comparison of the UDI<sub>100-2000</sub> distribution in dining and bedrooms with optimum WWR (40%) along with clerestories on the partition walls between bedrooms and dining space.

6. CONCLUSION

This paper demonstrates that configuration of partition walls and window sizes of the adjacent bedrooms have important effect on the daylighting of the dining space of residential apartments in tropical
city i.e. Dhaka. Simulation with clerestory configurations indicates that the width of clerestory has a significant impact on daylighting of dining space. Clerestories with greater widths that is maximum possible lengths of the internal partition walls between dining space and bedrooms effectively produce large amount of daylight into the dining without glare compared to the clerestories only over doors. In addition to this, 40% WWRs of full height corner windows on the bedroom facades increase the value of UDI100-2000 to 60.8% to the core sensor points of the dining space without creating glare in the bedrooms. The distribution of daylight both in bedrooms and dining space is also improved. In the context of Dhaka, occupants spend more time in the dining space during daytime for various activities while the bedrooms are left unoccupied and could be used as a channel for daylighting deep in residential apartments. Operable internal blinds can be used for the windows of the bedrooms in case of over light and glare. Besides improving the luminous environment, daylight inclusion is also related to aesthetics, energy consumption (electrical lighting, mechanical heating and cooling), heat loss and gain, sound transmission, economics, glare control, ventilation, safety, security and subjective concerns of privacy and view. Considering time and resource constraints for the research, the consequence of those was beyond the scope of this paper. It is expected that the research can be used as a basis for further research to investigate other aspects as described above. This principle of developing internal wall configurations with clerestories and external windows of bedrooms considering the reflective components of daylight to improve the daylighting condition in dining space can help designers to create a sound indoor visual environment in tropical residential apartments.

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REFERENCES

New Platform to Quantify the Energy-Saving Potential in Existing Residential Buildings in a Northern Spanish Region

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Ciemat (Centro de Investigación Energética, Medioambientales y Tecnológicas, Madrid, Spain)

ABSTRACT: This article presents a new simulation platform to quantify the energy savings through the implementation of refurbishment strategies, solar thermal energy and geothermal technologies in existing residential buildings. With this aim, the energy performance of the representative building stock of the Principado de Asturias has been analyzed. This representativeness has been chosen through a parametric matrix that characterizes the residential building stock of the area. The energy improvements have been calculated through the coupling between TRNSYS and GenOpt. Output information obtained is annual thermal loads and monthly loads reductions.

KEYWORDS: Energy modelling, Refurbishment potential, Multivariable evaluation.

1. INTRODUCTION

The International Energy Agency (IEA) provides an overview of important current trends in two energy intensive sectors: buildings and buildings construction [1]. Both sectors combined consume around 36% of global final energy and are responsible of nearly 40% of CO2 emissions. Many factors have led to an increase of the global energy demand such as the continued growth in buildings floor area, a greater use of power-consuming devices and an enhanced energy access in developing countries. Also, residential building stock in developed countries such as in Europe, are characterized by its low energy efficiency, so the implementation of efficient measures has a great potential [2]. Consequently, many of the current buildings policies are focus on reducing the global building energy demand by promoting the refurbishment of existing buildings boosting their energy efficiency (net-zero energy buildings).

In this framework, this paper shows a new tool that calculates the energy-saving potential through the implementation of refurbishment strategies, solar thermal energy and geothermal technologies use in existing residential buildings. The use of this platform allows local government and end users to quantify the natural resources as well as the building stock available to minimize the energy consumption of residential building. This tool has been developed for a northern region of Spain characterized by temperate climate (Principado de Asturias).

2. PREPARING THE MANUSCRIPT

Examples of projects designed to help users and local governments to make decisions aimed at improving energy efficiency, reducing energy demand in the built environment, developing simulation environments to evaluate the energy performance of urban areas [3, 4] are widely available in the scientific literature.

The Spanish research project RehabilitaGeoSol [5] has developed a new platform to quantify the energy savings obtained through the implementation of retrofit measures, solar thermal panels and geothermal technologies in residential buildings. The studied area is the Principado de Asturias, located on the north coast of Spain. This platform gives as outputs the energy-saving potentials of different retrofit measures and the solar and geothermal fraction covered by these two renewable technologies. The final energy potentials calculated by this tool depends on the meteorological conditions, geomorphological characteristics, constructive requirements and normative restrictions. All these variables have been considered as input information into the platform, setting constrains and limitations of the final results. The use of this tool, only in Spanish at the moment, can be very useful to identify priority areas that maximize the reduction of the energy consumption and minimize the greenhouses emissions.

The study presented combines the need to analyse a great building patrimony whilst maintaining a high level of quality. The developed tool will assist the public administrators and end users dealing with the problem in making the most appropriate decisions.

This article shows the retrofitting potentials and the energy-savings achieved by the representative building stock of the Principado de Asturias, according to the Spanish Cadastre (Figure 1). The
energy potentials reached by these building models have been calculated through the use of dynamic simulation tools. Heating, cooling and total retrofitting potentials have been obtained for each building model, promoting the benefits of refurbishing existing buildings to improve the energy efficiency and reduce the energy demand.

3. KEY INPUT VARIABLES

The retrofitting potential of this new platform calculates the thermal loads obtained by each building model. The influence of the most relevant variables on the energy performance of residential buildings is assessed by means of dynamic simulation tools.

This study builds upon the dataset matrix composed of all the information related to the climatic, volumetric, constructive and operational characteristics of the representative building typologies in this region.

3.1 Local Climate conditions

The Köppen Geiger climate classification is one of the most used to identify different climate zones in the world. Based on it, the region of the Principado de Asturias is defined as a temperate climate, characterized with two zones: Cfb and Csb. In Spain, the regulation of energy savings in buildings [6] developed a specific climate classification based on seasonal severities [7], giving as result normalized climatic files for each Spanish region. This classification was done based on two indexes: winter climatic severity (identified by a letter) and summer climatic severity (identified by a number). Data of global solar radiation, heating degree-days and cooling degree-days were used to calculate these two indexes [8].

Based on the Spanish Technical Building Code for the Principado de Asturias, three climate zones have been used as input variables of this platform: C1, D1 and E1 [6]. The main differences between these three climatic zones are identified during the winter period.

The warmest values are reached in zones C1 while the coldest values are obtained in zones E1. In all these cases the summers are mild, registering average summer temperatures around 18ºC. The incidence of global solar radiation is higher in zones C1 and D1 (annual values of 2017 kWh/m² and 2007 kWh/m² respectively) and lower in zones E1 (annual value of 1413 kWh/m²). The average relative humidity is quite similar in the three zones (around 58-60%). Table 1 shows the monthly maximum, mean and minimum variables registered during the whole year for the three climatic zones studied. Air temperature (Tª), relative humidity (RH), global solar radiation (Ig) and wind speed (WS) are calculated.

<table>
<thead>
<tr>
<th>Climatic Zone</th>
<th>Monthly Values</th>
<th>Tª (ºC)</th>
<th>RH (%)</th>
<th>Ig (kWh/m²)</th>
<th>WS (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>8,2</td>
<td>40,2</td>
<td>35,5</td>
<td>2,4</td>
<td></td>
</tr>
<tr>
<td>C1 Mean</td>
<td>13,7</td>
<td>58,4</td>
<td>168,1</td>
<td>2,9</td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>19,3</td>
<td>74,8</td>
<td>270,8</td>
<td>3,6</td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>4,9</td>
<td>40,4</td>
<td>37,7</td>
<td>2,4</td>
<td></td>
</tr>
<tr>
<td>D1 Mean</td>
<td>12,0</td>
<td>58,3</td>
<td>167,3</td>
<td>2,8</td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>19,3</td>
<td>74,8</td>
<td>282,4</td>
<td>3,6</td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>2,9</td>
<td>42,6</td>
<td>46,1</td>
<td>2,4</td>
<td></td>
</tr>
<tr>
<td>E1 Mean</td>
<td>10,5</td>
<td>59,9</td>
<td>117,7</td>
<td>2,9</td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>19,3</td>
<td>74,8</td>
<td>194,4</td>
<td>3,6</td>
<td></td>
</tr>
</tbody>
</table>

3.2 Building characteristics and operational conditions

Building characteristics and operational conditions are needed to fill the inlet information of the simulation models. Four Spanish regulations have been used: before 1979, 1979-2005, 2006-2013 and after 2013. The most representative values defined by these regulations in Spanish certification tools are used [9]. These values meet the minimum construction and operational conditions required by the residential building stock selected for this study. Based on the cadastre statistics for the Principado de Asturias, four representative building typologies are identified: single-family detached, semi-detached house, residential isolated block and residential linear block of flats.

- Volumetry of the building
  Single-family and semi-detached: the dwelling house is a two-storey house with 100 m² of floor area.
  Blocks: consists of square-floor plan with three different representative surface areas: 200 m²; 400 m² and 800 m². Similarly, the number of plants has been simplified with three representative values: 4
plants; 7 floors; and 10 plants. The height between floors considered is always 3 m.

**Construction features**

Differentiated by the year of construction, four different types of building envelopes have been evaluated in each climatic zone. As an example, Table 2 shows the limit values of the overall heat transfer coefficient of each component of the building envelope for the three climatic zones evaluated (C1, D1 and E1).

Table 2: The limit values of the overall heat transfer coefficient of the building envelopes in the climatic zones.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>2.17</td>
<td>1.20</td>
<td>0.41</td>
<td>0.23</td>
</tr>
<tr>
<td>Exterior wall</td>
<td>2.38</td>
<td>1.60</td>
<td>0.73</td>
<td>0.29</td>
</tr>
<tr>
<td>Ground floor</td>
<td>1.00</td>
<td>1.00</td>
<td>0.73</td>
<td>0.29</td>
</tr>
<tr>
<td>Partition wall</td>
<td>2.25</td>
<td>1.62</td>
<td>0.73</td>
<td>0.73</td>
</tr>
<tr>
<td>Roof</td>
<td>2.17</td>
<td>1.20</td>
<td>0.38</td>
<td>0.22</td>
</tr>
<tr>
<td>Exterior wall</td>
<td>2.38</td>
<td>1.60</td>
<td>0.66</td>
<td>0.27</td>
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<tr>
<td>Ground floor</td>
<td>1.00</td>
<td>1.00</td>
<td>0.66</td>
<td>0.27</td>
</tr>
<tr>
<td>Partition wall</td>
<td>2.25</td>
<td>1.62</td>
<td>0.66</td>
<td>0.73</td>
</tr>
<tr>
<td>Roof</td>
<td>2.17</td>
<td>1.20</td>
<td>0.35</td>
<td>0.19</td>
</tr>
<tr>
<td>Exterior wall</td>
<td>2.38</td>
<td>1.60</td>
<td>0.57</td>
<td>0.25</td>
</tr>
<tr>
<td>Exterior wall</td>
<td>1.00</td>
<td>1.00</td>
<td>0.57</td>
<td>0.25</td>
</tr>
<tr>
<td>Partition wall</td>
<td>2.25</td>
<td>1.62</td>
<td>0.57</td>
<td>0.25</td>
</tr>
</tbody>
</table>

The windows are characterized by the type of glass and frame that compose it according to the building regulations [9]. Types of glazing modelled are: simple, double, low-emission I double and low-emission II double. Types of frames modelled are: PVC, wood, metal (with and without thermal break).

**Internal gains**

Set point temperatures are fixed in summer and winter for thermal conditioning. Internal loads are defined by their occupancy, lighting and equipment values [9]. A differentiation is made in the occupation between workdays and holidays.

Ventilation and infiltration are the two types of air changes modelled. Ventilation depends on the occupation regardless of the infiltration value. Constant infiltration values are proposed according to the typology and year of construction of the building. Detailed information is shown in Table 3.

Additionally, different percentages of shade are defined in each main orientation: 100%, 75%, 50%, 25% and no shade.

### Table 3: Ventilation and infiltration values for the energy performance models of residential buildings.

<table>
<thead>
<tr>
<th>Occupancy</th>
<th>Before 2006</th>
<th>After 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>1.2</td>
<td>0.2</td>
</tr>
<tr>
<td>No</td>
<td>0.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Single</td>
<td>0.24</td>
<td>0.24</td>
</tr>
<tr>
<td>Block</td>
<td>0.24</td>
<td>0.24</td>
</tr>
</tbody>
</table>

# 4. DYNAMIC SIMULATION ENVIRONMENT

The dynamic simulation program TRNSYS is used to evaluate the impact of passive measures in the energy performance of residential buildings. Simulation matrices have been developed to create the inlet databases of the platform. These matrices are fed by the input variables and the parameters defined above, providing as outputs the energy savings of all the proposed cases. The energy improvements have been calculated through the coupling between TRNSYS and GenOpt [10].

The methodology used to create the retrofitting databases of this platform is described as follows:

- **Creation of building models.**
  The representativeness of the building stock has been chosen through a parametric matrix that characterizes the residential buildings stock of the area.

- **Creation of the simulation environment.**
  Eight building models have been developed with TRNSYS to characterize the energy performance of residential buildings. The representative building models are detailed in Table 4. Different input variables of these models have been modified to carry out a multi-parametric study. Batteries of simulations have been executed using GenOpt to automate the TRNSYS runs (Figure 2). Climatic files, building regulations, surface area of blocks and percentage of shade for the main orientations (south, north, east and west) have been modified to obtain the databases that fed the platform.
Post-processing and creation of the analysis matrices.

The output variables of the simulation batteries are used to develop the analysis matrix of the platform. A post-processing evaluation has been done to create the databases of the platform. Heating, cooling and annual loads have been assessed to calculate the theoretical retrofitting potentials of each configuration.

Table 4: Representative building models developed in TRNSYS

<table>
<thead>
<tr>
<th>Representative Models (Case)</th>
<th>Family house</th>
<th>Block</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single (Case 1)</td>
<td>Four-storey Isolated (Case 3)</td>
<td></td>
</tr>
<tr>
<td>Semi-detached (Case 2)</td>
<td>Linear (Case 4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Seven-storey Isolated (Case 5)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Linear (Case 6)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ten-storey Isolated (Case 7)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Linear (Case 8)</td>
<td></td>
</tr>
</tbody>
</table>

5. RESULTS

The Principado de Asturias is a region characterized by high heating needs and low cooling needs. This situation is highlighted in the annual contributions reached by the seasonal loads of the studied cases. Figure 3 shows the percentages of thermal needs reached by the eight building models proposed. These charts differentiate the heating contribution (blue bars) and the cooling contribution (green bars) of the annual loads. The cases represented in this figure correspond to the eight building models (Case 1-8 of Table 4), with no shades on the facades and the climatic zone D1. The surface area of the block shown in these graphs are 400 m².

The heating contributions vary from: 91 to 94% for the regulation before 1979, 90 to 93% for the regulation 1979-2005, 81 to 90% for the regulation 2006-2013 and 74 to 88% for the regulation after 2006. As it can be seen, the regulations before 2006 show similar seasonal contributions both for houses and blocks. Nevertheless, these contributions are little bit different for regulations after 2006. In these cases, the cooling contribution gains more weight in houses than in blocks.

When the surface area of blocks are 200 and 800 m², similar trends have been achieved in the thermal load percentages. When the climate is different from D1, the heating percentages are slightly lower for C1 and slightly higher for E1.

In all the building models studied, the configurations that reach the lowest heating contributions of the total thermal needs are the single-houses and the isolated blocks.

The first output of the platform is the maximum retrofitting potential reached by each municipality of Principado de Asturias (Figure 4). These potentials are calculated with respect to the minimum value of thermal loads, which corresponds to the Spanish regulation defined after 2013. So higher annual thermal loads produce higher maximum retrofitting potentials.

Figure 4 shows different potentials based on the climate, the type of building and the year of construction, reaching very different values. For example, the maximum retrofitting potentials are obtained for the single-family houses that vary between more than 200%, for regulations before 2006, to 25%, for the regulation after 2013. In the case of blocks, the maximum potentials have been reached for isolated blocks with four-storey plants. Regarding the surface area of blocks, lower potentials have achieved when the area is higher.

As an example of different cases studied by this platform, Figure 5 shows the retrofitting potential (%) obtained by a single-family (upper part) and an isolated four-storey block with 400 m² floor area (lower part) in the three climatic areas studied. This Figure represents the annual retrofitting potentials obtained with the Spanish regulations: before 1979 (purple colour), 1979-2005 (blue colour) and 2006-2013 (green colour), for the three climatic zones C1,
D1 and E1. As expected, the highest potential has been reached by the oldest normative (before 1979) in all cases, being more remarkable for a single-family house.

Regarding the retrofitting potential demanded by a single-family house (Figure 5 upper part), the percentages for the houses built before 2006 are very similar in all climatic zones. A potential of about 268% is achieved by the regulation before 1979 while a potential of about 184% is obtained for the regulation 1979-2005. The regulation 2006-2013 shows differences between the climate zones. The highest value is reached in zone C1 (45%) while the lowest is reached in E1 (36%). The zone E1 represents areas with more severe winter weathers in which the heating demand are higher.

In the isolated four-storey blocks (Figure 5 lower part) the pattern observed in single-family homes is repeated. Very similar percentages of the retrofitting potential are obtained in all climatic zones in the case of blocks built before 2006. A potential of about 195% is achieved by the regulation before 1979 while a potential of about 137% is obtained for the regulation 1979-2005. Stricter regulation leads to differences between the climate zones. The highest potential is reached in zone C1 (27%) while the lowest is reached in E1 (22%).

Starting from the first output based on the climate, type of building and year of construction, three upgraded measures can be selected: surface area, type of windows and shadows on the south, north, east and west façades. More specific building models can be defined by this platform (Figure 6). The obtained outputs are the heating, cooling and total retrofitting potentials achieved. These potentials are calculated with respect to the minimum value of the thermal loads obtained with the regulation after 2013.

This platform allows the impact assessment of climate, building shape and external shading on building behaviour. Users can modified the input variables in order to quantify the retrofitting potentials for specific building configurations. As an example of these evaluations, the annual needs for a single-family house (two storey and 100 m² of floor area) and an isolated block (four-storey and 400 m² of floor area) are represented in Figure 7 and Figure 8, respectively. In both cases the climate zones C1 (upper part), D1 (middle part) and E1 (lower part) are analysed. Four building regulations are studied: before 1979, 1979-2005, 2006-2013 and after 2013. And finally, five percentages of shade on the main façades are analysed: 100% (purple bars), 75% (grey bars), 50% (blue bars), 25% (green bars) and no shade (orange bars). The shadowing factor is modified jointly for all exterior façades.

The influence of the shadowing factor on the annual thermal demands of houses and blocks follows a linear behaviour (with a coefficient R² of about 0.96 for single-houses and 0.95 for blocks). The greatest slopes are obtained with strictest building regulations (before 2006), being more remarkable in the climate zones E1.
The energy savings produced by the shading factor on the façades are greater for single-family houses than for blocks, reaching the highest percentages of savings in zone C1 and the lowest in zone E1. In all cases, higher savings percentages are obtained in regulations after 2006 compared to regulation before 2006. The annual energy savings are shown in Table 5.

Table 5: Energy savings comparing annual thermal loads without shades and with shades on the façades for regulations before and after 2006 for the studied climate zones.

<table>
<thead>
<tr>
<th>Climate</th>
<th>Annual Energy savings (%)</th>
<th>Before 2006</th>
<th>After 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Single-Family House</td>
<td>2-7</td>
<td>4-23</td>
</tr>
<tr>
<td></td>
<td>Isolated four-storey block</td>
<td>1-6</td>
<td>3-15</td>
</tr>
<tr>
<td>D1</td>
<td>Single-Family House</td>
<td>1-6</td>
<td>4-20</td>
</tr>
<tr>
<td></td>
<td>Isolated four-storey block</td>
<td>1-5</td>
<td>3-13</td>
</tr>
<tr>
<td>E1</td>
<td>Single-Family House</td>
<td>1-6</td>
<td>4-18</td>
</tr>
<tr>
<td></td>
<td>Isolated four-storey block</td>
<td>1-5</td>
<td>3-11</td>
</tr>
</tbody>
</table>

### 6. CONCLUSIONS

A new platform is developed to quantify the energy-savings obtained through the implementation of retrofit measures in residential building models placed in the Principado de Asturias. This region is characterized by high heating loads and low cooling loads.

This platform shows the theoretical high retrofitting potentials for the oldest Spanish regulations (before 2006). These potentials are higher in houses than in blocks, being more remarkable in single or isolated building configurations. In the case of blocks, the retrofitting potentials are higher for four-storey plants in comparison with seven and ten-storey plans. If the surface area of blocks is higher, the energy-savings obtained are lower. The highest energy-saving potential is reached in warmer climates (zones C1) while the lowest is reached in colder zones (zones E1).

Analysing the influence of external shades on facades, this platform obtains higher impact on buildings constructed according to stricter regulations and in single-family vs blocks. Regarding the climate impact, the annual thermal load increases in colder climates due to the higher heating requirements. On the contrary, the impact of shading is greater in warmer climates where the cooling demands are higher.

### ACKNOWLEDGEMENTS

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### REFERENCES

Daylight performance evaluation in a modern Brazilian heritage building
Analysing daylight assessment tools

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ABSTRACT: This paper reports results from research investigations and simulations conducted in a Brazilian modern architecture icon: University of São Paulo’s Faculty of Architecture and Urbanism (FAUUSP). Due to its heritage-listed status, much needed retrofit and changes to the indoor configuration of workspaces have been limited. Current workspaces have seen a significant reduction of the overall amount of daylight available indoors and there is anecdotal evidence from occupants’ dissatisfaction. Although prior research has documented the environmental performance of this building, little has been done in regards to capturing daylight performance and occupants’ feedback. This paper contributes to this gap by reporting results from Post-Occupancy Evaluation (POE) surveys and daylight performance simulation. The sample of 33 occupants reported a high level of satisfaction on visual comfort and connection to outdoor environment-related questions, they also complained about spaces being too dim/bright, glare from light and reflection on screen. Further, simulation results showed that orientation, depth of the floorplan, colours and materials greatly affected the reflectance and light distribution within the space. While colours are protected by restrictions posed by the heritage status, other changes proposed here, such as indoor partitions could address reported sources of dissatisfaction with light and daylight reported by occupants.

KEYWORDS: Workspace, Post-Occupancy Evaluation, Daylight, Modern Architecture

1. INTRODUCTION

In heritage buildings, it can be particularly challenging to marry inherently conservation limitations of the building envelope and changes in interior design configurations that happens through long-term occupancy and repurpose. Ill designed and/or implemented solutions on how the space is reconfigured to accommodate new demands of occupants may impact how daylight is distributed within indoor spaces as well as its availability to be visually accessed by occupants. Environmental variations, including window heights, distances between workstations and windows, have significant impacts on occupant satisfaction with daylighting [1].

The overall quality of light in workspaces has been found to have a positive correlation with productivity [2], ability to work [3], and health [4]. Appropriate lighting in workspaces influences office occupant’s satisfaction and consequently improve their job performance [5]. Proper indoor lighting can also decrease complaints about eye symptoms, tiredness and motivational difficulties [6,7]. Research also indicates that for every 10% increase in daylight illuminance, there was a 0.45% increase in short-term memory performance of the occupants [8]. The availability and access to an outside window plays an important role on occupants’ satisfaction with lighting than only having access to daylight [9,10]. Having a window also plays an important role on having an outside view. The mental stimulation or relaxation achieved from having an outside view has a positive influence on mental function, and having a workstation with a better view can increase performance by 8% to 16% [8]. It also brings health benefits - occupants with access to windows slept 46 minutes more per night, when compared to occupants in offices without windows [4].

Despite the fact that seating next to a window can improve productivity, daylight and view satisfaction, it can also expose the occupants to unwanted glare [9,10]. Discomfort from glare can vary depending on the quality of the view outside, as well as the distance from the window and on the task taken by the occupant [11]. Although we know that glare exposure can vary by orientation and many other design aspects, and that distance from a window and the level of glare can lead to higher level of dissatisfaction by its occupants [5], research also shows that some occupants are willing to tolerate glare in exchange for the view and access to daylight [12].

This paper reports results of occupant’s satisfaction and daylight performance evaluation at a
heritage-listed building. The Faculty of Architecture and Urbanism of the University of São Paulo (FAUUSP) is recognized as one of the most representative icons of the Brazilian modern architecture [13]. In 1982 the building was heritage-listed [14] and since then, any intervention must consider the architect’s original design and conservation code regulations. Survey results from the pilot study conducted here are targeted at identifying key sources of occupants’ satisfaction/dissatisfaction with daylight and connection to the outdoor environment of the current building. Later simulation was used in order to explore minor physical interventions that can help improve occupant’s satisfaction. The first parameter is color, which is under severe heritage-related restrictions, which prohibits painting the exposed concrete ceiling and/or blue walls. The second parameter is the introduction of indoor partitions, a minor modification of the physical configuration of the space, which is not covered under current heritage-related restrictions. Finally, the study will be able to inform future changes on workspaces implemented in this building may have an impact, if at all, on the quality of daylight made available indoors.

2. METHODOLOGY
Conducted at three different workspaces, this study has two distinct and complementary parts: (i) deployment of Post Occupancy Evaluation (POE) surveys in order to understand occupants’ satisfaction; and (ii) computational performance simulation of workspaces.

2.1 The case study building and workspaces
FAUUSP was designed by the architect Villanova Artigas and Carlos Cascaldi between 1960 and 1961, and its construction was completed in 1969. The Brazilian modern architecture had a remarkable development in the 20th century and Artigas’s designs constitute a significant legacy for understanding the history of São Paulo and modern architecture of this era in particular [14].

The building structure is characterized by a 110mx66m block formed by a large concrete wall supported by trapezoids shaped columns (Fig. 1). From inside the block the spatial continuity is determined by a large central atrium and ramps that connect all eight floors (Fig. 2). The roof is designed as a concrete grid, which carries a series of translucent fiberglass domes. The adoption of large structural spans, open plan spaces, the use of exposed fair-faced concrete finishes and glass are trademarks of Brazilian modern architecture, and São Paulo’s Brutalist Architecture in particular. The exposed concrete and yellow epoxy flooring designed by Artigas are protected from any interventions. As part of his practice and main concept, Artigas also implemented passive environmental strategies to his projects. The use of a ‘floor to ceiling’ glass windows allowed the access to natural light and outside views throughout, while as extended concrete slab works as a horizontal shading along two main facades, protecting them from excessive solar radiation (Fig 2). Changes in the interior layout were carried out 2000 and 2010. Removable partitions were used to split the space up, making room for administrative and academic staff and research students.
The three workspaces analysed here present an open plan configuration (Fig. 02, 03 and 04). Similar furnishings are observed: partitions are made of pressed wood fibre or drywall panels, yellow epoxy for the floors on an exposed concrete slab. All workspaces have 3 meters height from floor to ceiling. An extended concrete slab works as shading device, allowing natural light into the space, and reducing the direct solar radiation - common strategies seen in Brazilian modern buildings.

Workspace A (LABAUT) is located on the half-underground floor, northeast orientation and it is designed as an open plan office with a partition dividing the space into two rooms. Room 01 does not have direct access to the outdoor environment; it has 12 desks, which are shared by research students. Room 2 has fixed 6 desks allocated for academic staff (Fig. 5), that are located nearest the window.

Workspace B (AUT) is located on the fourth floor, northeast orientation and it is designed as a small open plan office with fixed desks (Fig. 6) that accommodates a maximum of 4 people at time. This office has windows from floor to ceiling (3m height).

Workspace C (Admin/Library) is located on the third floor, southwest orientation, and it is designed as an open plan office with fixed desks, accommodating a maximum of 10 people (Fig. 7).

2.2 Post-Occupancy Evaluation survey
For this study, the BOSSA (Building Occupants Survey System Australia) Time-Lapse survey was used. Time-Lapse asks occupants to assess physical environments on key IEQ (Indoor Environmental Quality) parameters (thermal comfort, Indoor Air Quality, lighting and acoustics), perceived productivity and health. Further the survey also collects basic demographics. Details about BOSSA have been outlined elsewhere [15].

This study is only concerned about occupants’ assessment of overall lighting conditions indoors as such, only results from questions about the connection with the outdoor environment, access to daylight and visual comfort are reported. The pilot study collected 33 responses from all three different offices. Overall, respondents included 24 females (73%) and 9 males (27%). The majority of participants were below the age of 30 (45%), another 39% were between the age of 31-50.

2.3 Performance simulation
Computer simulations conducted with Dialux Evo software are in accordance with EN12464 ISO 8995 [16] and validated according to CIE 171:2006 [17]. Simulations were performed for two periods of the year: summer (December 21) and winter (June 21) solstices. Clear and cloudy sky conditions were also considered. The range of 250 to 300 lux was used as the minimum performance criteria for lighting levels, as recommended by research [18] for building with natural lighting and no direct solar radiation. Table 1 and 2 shows the scenarios simulated for each workspace.

<table>
<thead>
<tr>
<th>Sim.</th>
<th>Partitions</th>
<th>Ceiling Color</th>
<th>Wall Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>As original</td>
<td>Concrete as original design</td>
<td>One blue and one white, as original</td>
</tr>
<tr>
<td>B</td>
<td>Removed</td>
<td>Concrete as original design</td>
<td>One blue and one white, as original</td>
</tr>
<tr>
<td>C</td>
<td>As original</td>
<td>Painted in White</td>
<td>Painted in White</td>
</tr>
<tr>
<td>D</td>
<td>Removed</td>
<td>Painted in White</td>
<td>Painted in White</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sim.</th>
<th>Ceiling Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Concrete as original design</td>
</tr>
<tr>
<td>2</td>
<td>Painted in White</td>
</tr>
</tbody>
</table>

3. RESULTS AND DISCUSSION
3.1 POE Surveys
As depicted in Figure 8, occupant survey results from workspace A suggest a high level of satisfaction regarding visual comfort and connection to outdoor environment. Workspace A outperformed B and C on question regarding satisfaction with the amount of light, control over shading devices and connection to the outdoor environment. Workspace B presented the lowest performance of all questions, with exception of views. Workspace C outperformed the others on questions regarding daylight and view.

The highest level of satisfaction for all workspaces is regarding the “outside view”, as shown in Figure 8. This result can contribute to occupants’ satisfaction with lighting, as suggested by other studies [9,10], and can also be related to the size of the windows, which is greater than 1,80m X 2,40m [11] for all workspaces. As shown in Figure 9, 25% of the occupants reported “too dim” environment as being the reason for their dissatisfaction for workspace A. The blinds can also support this result, once the occupants can control it during the day.

Dissatisfaction regarding shading is also reported by the occupants in workspaces B and C (Fig. 8), and it might be because of the absence of blinds or any personal controlled shading device in both workspaces. The horizontal concrete shading of the building might not be effective in both orientations and floors, and can influence the reason of dissatisfaction reported on workspace B as being a “too bright” environment (Fig. 9). On the other hand, for workspace C, the “connection to outdoor environment” dimension showed a level of satisfaction up to 100% for both questions regarding outside view and access to daylight. It might be related to the fact that workspace C has a shallower space, with a depth of 4.24m, allowing the desks distribution to be lined up parallel to the windows, so all occupants have direct access to daylight and outside view, a factor that plays an important role on occupant satisfaction with lighting than only having access to daylight [9,10].

3.2 Performance simulations

Workspace A
As shown in Table 3, when removing the partition on simulation B, workspace A had an increase on the illuminance level of 50% on room 1 which is furthest from the window. Near the window, results show a reduction of about 5% of the illuminance level, which can be related to reflections on the high partitions. For simulation C, results show an increase of illuminance level of 10% in room 2 near the window, and 30% in room 1. For simulation D, when removing the partitions, and applying a white ceiling and wall colour, the distribution and intensity of the daylight reaches up to 4.5m inside the room, increasing the lighting conditions by 65% in locations furthest from windows, when compared to simulation C. For any modification proposed, it is possible to achieve an increase of 10% to 50% of the daylight illuminance level, which can help improve the occupant’s performance by 0,45% [8].

Table 3: Summer solstice simulation (9am) for workspace A.

<table>
<thead>
<tr>
<th>With partition</th>
<th>Without partition</th>
<th>With partition</th>
<th>Without partition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sim. A</td>
<td>Sim. B</td>
<td>Sim. C</td>
<td>Sim. D</td>
</tr>
<tr>
<td>Eₘ₉ = 4215 lux</td>
<td>Eₘ₉ = 4124 lux</td>
<td>Eₘ₉ = 4805 lux</td>
<td>Eₘ₉ = 4618 lux</td>
</tr>
<tr>
<td>Room 1</td>
<td>Room 2</td>
<td>Room 1</td>
<td>Room 2</td>
</tr>
<tr>
<td>Eₘ₉ = 78 lux</td>
<td>Eₘ₉ = 168 lux</td>
<td>Eₘ₉ = 141 lux</td>
<td>Eₘ₉ = 302 lux</td>
</tr>
<tr>
<td>5 15 30 100 300 650 1200 2300 5000 17000 lux</td>
<td>5 15 30 100 300 650 1200 2300 5000 17000 lux</td>
<td>5 15 30 100 300 650 1200 2300 5000 17000 lux</td>
<td>5 15 30 100 300 650 1200 2300 5000 17000 lux</td>
</tr>
</tbody>
</table>

For workspace A, the ideal solution is simulation D, where results showed an increase of the level of daylight illuminance level by more than three times when compared to simulation A, which can consequently help increase the level of occupants’ satisfaction [5]. Reported dissatisfaction levels regarding the room being “too dim” shown in Figure 9, can probably be related to the occupants of room 1, where the desks are located furthest from the window. Near the window, and for any simulation presented on Table 3, the level of illuminance achieved might cause glare and/or contrast within the workspace, which can be related to the reason of dissatisfaction regarding “contrast”, reported by 25%
of the occupants of workspace A, as shown in Figure 9. Contrast can be reduced when using the existing blinds until 11:00am, as a result of all simulations. After this time, the blinds could be opened because the illuminance level starts to become more evenly distributed. Teaching occupants about how to use the building and its features can also help improve satisfaction. Simulation D is also the only scenario where the workspace could achieve the range between a 250 and 300lux [18].

Workspace B
For workspace B, two simulations were carried out, as shown in Table 4. For both simulations, during winter solstice and equinoxes, in the morning time, the illuminance reaches 1000lux near the window. Also, with a depth of eight meters, spaces furthest from the window do not receive much daylight, reaching up to 150lux on simulation 2, possibly because of the influence of the concrete horizontal shading of the building in this floor. In contrast, as shown in Figure 9, occupants reported dissatisfaction with too much ‘glare from light’, ‘too bright environment’, and ‘reflection on screen’. It might be assumed that layout distribution of the desks, the design aspects of the workspace [5], the distance between workstations and windows, and seating orientation can cause the occupants dissatisfaction regarding lighting conditions [1,11].

Table 4: Summer solstice simulation (9am) for workspace B.

<table>
<thead>
<tr>
<th>Concrete ceiling - Sim 01</th>
<th>White ceiling - Sim 02</th>
</tr>
</thead>
<tbody>
<tr>
<td>E_m = 107 lux</td>
<td>E_m = 132 lux</td>
</tr>
</tbody>
</table>

For the variation on simulation 2 with a white colour slab, results show that the distribution of daylight became more homogeneous at a 4.5-meter depth and the illuminance increased by 19% (Table 4). None of the simulations achieved the minimum performance criteria of 250-300 lux [18]. However, simulation 2 showed an illuminance increase of 19%. To further improve lighting conditions of workspace B, it is suggested to change the desks arrangement to avoid “glare from lights” and “reflection on screens” as reported by occupants. Because of the depth of the room, it is necessary to add artificial lighting and diffusers as a supplement during all office hours, allowing greater comfort for occupants.

Workspace C
As shown in Table 5, simulation 1 showed an illuminance of 296lux on the summer solstice. For simulation 02, with the white slab, the illuminance reached 367lux at 17:00h, which represents an increase of 19% of the illuminance level, and which exceed the maximum performance criteria of 300lux [18] established for this study. Workspace C is the shallowest space, allowing greater homogeneity of light distribution in all workstations. No modification here is needed to achieve the minimum criteria established for this study [18], probably because of its shallow configuration. Also, occupants can work for some periods without using artificial light, which can be related to the satisfaction level regarding the “overall lighting conditions” of the work area, the “outside view” and the “access to daylight”, as shown in Figure 8. Allowing a workspace to work for some periods of the day without using artificial lighting can also help save energy.

Table 5: Summer solstice simulation (5pm) for workspace C.

<table>
<thead>
<tr>
<th>Concrete ceiling</th>
<th>Simulation 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>E_m = 296 lux</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>White ceiling</th>
<th>Simulation 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>E_m = 397 lux</td>
<td></td>
</tr>
</tbody>
</table>

4. CONCLUSION
This study contributes to the knowledge gap in Brazilian heritage buildings by providing evidence about the environmental performance of FAUUSP through a combination of POE surveys and performance simulation of daylight.

For workspace A, the overall distribution of light improved when high partitions were removed and wall and ceiling were painted white. These modifications increased illuminance levels by more than three times when compared to the current workspace, allowing furthest spaces from window to achieve a minimum of 250 to 300lux. Those results could address reported dissatisfaction results from the POE survey about the room being too dim.

Workspace B, attracted the lowest levels of satisfaction by its occupant for all questions with
exception of views, probably because of the ‘floor to
celling’ glass windows. Occupants also reported a
dissatisfaction regarding room being too bright (40%),
glare from lights (40%) and reflections on screens
(20%). Neither existing conditions nor modifications
simulated here achieved the minimum performance
criteria. Both dissatisfaction results from surveys and
performance simulations can probably be related to
the design aspects of the space, the distance between
workstations and windows and seating orientation, so
a more detailed study should be carried out.

Workspace C, is the only office that achieved the
minimum criterion for light distribution in its
current/existing configuration. In addition, when
modifying the ceiling color on the performed
simulation 2, workspace C exceeded the maximum
performance criteria by up to 65lux. In regards to the
POE survey, workspace C outperformed the other
workspaces on questions regarding daylight and
views. Reported dissatisfaction was linked to “glare
from lights”, which can be related to the layout
distribution and design aspects of the space.

Combined, modifications proposed here helped
increase the illuminance level by 10% to 65% within all
workspaces. These results bring out the discussion of
how architects should propose modifications on
heritage buildings in order to improve occupant’s
satisfaction, and how important is the combination of
a POE surveys and performance simulation of daylight
studies for existing buildings.

The concrete ceiling of FAUUSP’s building is
protected from any intervention, because of the
heritage-related restrictions reflecting the design of an
era. However, this study showed that for specific
orientations, floors, color of the materials and space
configurations, any modification within the
workspace, such as painting the ceiling in white, is
required to achieve minimum performance, increase
the performance of a space, as well as the level of
satisfaction of occupants. Further studies should be
conducted to address the limitations of the current
study in terms of sample size and demographics.

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Assessment of Thermal Comfort Conditions in Public Spaces of a Densifying Urban Business District

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ABSTRACT: A newly introduced master plan in the metropolitan area of Tel Aviv, Israel calls for the extreme densification of an intensively renovated business district. The present study aims at assessing the existing thermal comfort conditions experienced by pedestrians in this urban district during the hot humid Mediterranean summer season, and predicting future conditions under various construction scenarios. Microclimatic monitoring was conducted in the summer of 2019, and collected data served as the basis for an evaluation of the thermal environment using the Index of Thermal Stress (ITS). Future scenarios were modelled by conducting a series of sensitivity analyses. Findings from the modelling study highlight the complex and often contradictory effects of high-rise buildings, which deeply shade the narrow streets between them and thus lower surface temperature and overall radiant heat gain, but may also increase air temperature and restrict ventilation by reducing wind speed. Outdoor summer conditions are therefore expected to be thermally stressful, and limited space for green infrastructure suggests the need for creative solutions. Assisting planners and decision-makers with such challenges in densifying business districts is vital, since a more amenable outdoor environment is one of the keys to sustaining urban life within a destabilized global climate.


1. INTRODUCTION

The combination of global warming and local urban heat island effects¹, together with economic pressure and planning considerations leading to urban densification, have created unprecedented challenges for planners in many large cities; improving thermal comfort (TC) is amongst them.

Extensive research efforts have been carried out in different climatic regions around the world regarding the factors that influence TC²–⁴, and the mitigation strategies which are most effective for improving it by reducing heat stress in cities⁵–⁷. Solar radiation, air and surface temperature, relative humidity (RH) and wind regime are the key meteorological variables affecting TC, and numerous studies have examined ways of modifying them – particularly by leveraging the beneficial effects of urban green infrastructure⁶–⁷. Mitigation strategies also include the use of ‘cool’ paving materials, aiming to reduce surface and even air temperature⁴–⁵. Street shading by high-rise buildings has been examined as a moderator of air temperature, mainly in hot climates⁶–⁸. Wind attenuation in the urban canopy has also been studied extensively, due to the important role of air flow in easing heat stress.

In this study, we evaluate the microclimatic characteristics and TC conditions in an intensively built, mixed-use, business district located at the heart of the Tel Aviv metropolitan area, where municipal authorities are promoting a master plan that could triple the existing built floor area. We analyzed the thermal characteristics and TC conditions in a number of representative street canyons on typical summer days, and assessed future changes for a series of possible design scenarios, which vary in terms of their proposed building heights, finish materials and green infrastructure. Our aim was to provide a robust quantitative evaluation of the current situation, along with a credible forecast, representing ‘business-as-usual’ and ‘climatically optimal’ planning approaches to the anticipated renewal of the district.

2. STUDY AREA

2.1 The urban district

The study area comprises approximately 30 hectares consisting mainly of office and commercial buildings – many of which are converted workshops, since the district was originally a world center of the diamond industry. The district is located about 3.5 km from the Mediterranean coast and is adjacent to a major transportation artery in the metropolitan area of Tel Aviv, which is the largest in Israel.

In terms of Local Climate Zones⁹, the high-rise, campus-like southern part of the district can be defined as LCZ1 and the northern block-structured section (with building heights of 2–13 stories, and most typically 5 stories) as LCZ2. Future implementation of the promoted master plan...
(assuming a 50% buildout of the maximum allowable volume) would result in both parts being defined as high-density cases of LCZ1 (see Figure 1).

The new master plan allows for high-rise towers (up to 60 stories) with very high floor area ratios (up to 3,000%). Given that street canyon widths are expected to remain in the range of 12-25 meters, maximum H/W ratios may therefore exceed from about 0.5-1.8 to 6-9. The district is active during daytime hours, and the master plan envisions it becoming a vibrant mixed-use urban center.

Figure 1: An aerial photograph of the case study site (district boundaries marked with dark blue line). Selected streets (1-4) marked in red, with representative cross-sections in yellow; Local Climate Zone classification areas (light grey); “a” – site of approved high-rise plan (see section 4.4 below).

2.2 Regional climate

The study region is characterized by a Mediterranean climate (Csa according to the Köppen classification). Typical midday temperatures in summer reach approximately 30°C, with RH of about 70%. Minimum daily temperatures are close to 25°C with RH as high as 80%, implying that significant heat stress prevails during the entire day. The summer season is characterized by small inter-diurnal variations, with persistent sultry conditions for at least three months of the year. Moreover, the Mediterranean basin is affected by long-term warming that is more intensive than the average global rate, and is thus defined as a climate change ‘hot spot’, while in addition, the city of Tel-Aviv exhibits a pronounced UHI.

3. METHODOLOGY

3.1 Site selection

Four urban street canyon segments were selected (see Figure 1) according to pre-defined criteria; each segment has a length of at least 60 meters with continuous building facades on both sides, and is relatively homogenous in terms of the height of the buildings (mostly 4-12 stories). The linear axes of two of the streets are approximately North-South, and the other two are aligned in a roughly perpendicular (WNW-ESE) direction. Two of these streets are pictured in Figure 2, together with illustrations of their H/W and SVF.

Figure 2: Existing street view + sky view factor, and current + predicted street section and H/W in Habonim St. (left) and HaYetsira St. (right), 1 & 2 in Fig. 1, respectively.

3.2 Measurements

Measurements were taken on two typical summer days. On Day 1 (28 June 2019), we used a FLIR B350 thermal imaging camera for measuring the radiant temperature of all surfaces facing the canyon, i.e., vertical building facades and horizontal street paving. FLIR QuickReport 1.2 SP2 software was used to process the image data. A hand-held IR thermometer (Martellato 50t002) and a portable thermometer/hygrometer were also employed, both on Day 1 and on Day 2 (19 July 2019). Ambient air temperature (Ta), RH and wind speed (WS) were taken from two stations of the Israel Meteorological Service (IMS), one located 5 km SW of the study area on the coast, and the other located downwind of the city (~7 km from the coast). Global radiation was taken from the inland IMS station. WS within the urban street canyons was estimated as a function of the measured data at the coastal station, using empirical attenuation factors derived from previous experimental work.

3.3 Index of Thermal Stress

The Index of Thermal Stress (ITS) was used to quantify the balance of radiative and convective energy exchanges between the human body and the urban surroundings, expressing the rate of cooling (in watts) by sweat evaporation that is required for the
body to maintain thermal equilibrium under warm conditions. ITS values have been previously correlated with subjective thermal sensation in a number of climatic contexts including for the area of Tel Aviv, and the index has been shown to reliably reflect the average level of TC experienced by pedestrians12.

The quantification of ITS includes solar geometry calculations by latitude, date and time of day, accounting for the particular street direction and average height of the buildings. Long-wave irradiation was based on the measured surface temperatures of shaded and exposed street canyon facets (e.g., Figure 3), and their distinct view factors in both current and projected scenarios. Heat loss from the human body by convection was calculated as a function of the skin-air temperature difference and the estimated WS within the street canyon. Sweat efficiency was based on the measured RH, and metabolic heat production was adjusted according the level of physical activity. Computed values of ITS are presented here together with corresponding categories of thermal sensation, based on previously derived correlations12.

Figure 3: Thermal IR image of a bicycle path, highlighting the "thermal memory" of asphalt and concrete, and the cooling effect of white paint (left); and corresponding visible image (right).

3.4 Basic assumptions

Basic factors defined for the ITS calculations included: albedo of street paving (0.2), of building walls (0.3), of glazing (0.08 for normal incidence and 0.09-0.52 for 40-80° incidence) and skin/clothing (0.35); diffuse radiation ratio (0.3); skin temperature (35°C); "human cylinder" head height (1.6m) and body area (1.6m²); metabolism (100 W/m²) for a stationary pedestrian; sweat evaporation was based on light summer clothing (1 clo) and the person referred to is in the middle of the street.

3.5 Sensitivity analyses

Sensitivity analyses were performed to quantify the impact of projected changes in individual and in combinations of parameters on the level of TC, in order to better evaluate the implications of several future scenarios. The parameters included in the analyses were building height, Ta, WS attenuation, RH, street surface temperature, percentage of tree cover and of glazing of facades and metabolic activity.

4. RESULTS AND DISCUSSION

4.1 Thermal comfort in the existing situation

Figure 4 shows the dominance of 'warm' conditions during typical summer daytime hours in the four street canyons studied. It can be seen that in the N-S street (HaYetsira), thermal stress is highest at noon due to direct solar exposure, and it drops sharply by mid-afternoon, when the canyon is deeply shaded due to the low-angle sun from west. Such a sharp reduction is not seen over a similar time increment in HaBonim Street, whose axis is closer to E-W. It should thus be stressed that even in the existing situation, with medium-density low-rise construction (H/W on the order of 1.0), street geometry – which defines the depth and duration of shade – plays a significant role in the variation of pedestrian thermal stress.

Figure 4: ITS and thermal sensation results for the four examined streets on 28 June 2019, reflecting existing conditions in the urban district.

4.2 Future scenarios

Results for future scenarios are presented for one street aligned on a N-S axis (HaYetsira) and one aligned WNW-ESE (HaBonim), and include several building heights (10, 20 and 40 stories). In lieu of empirical data or reliable simulations for such a complex urban context, we calculated the ITS for these future scenarios using a "rational speculation" research approach. The physical and meteorological parameters of these future scenarios are described in Table 1 (with estimated values, based on previous studies, indicated in light blue).

Figure 5 shows the predicted thermal stress under these scenarios, taking into account the future increases in building height, Ta and WS attenuation. In general, increasing the height of the buildings leads to an overall moderation of thermal stress, due to the dominant effect of deeper and longer-lasting shading within the street canyon and despite the amplified attenuation of WS and raised Ta. This shading effect is a combination of reduced solar heating of the human body, directly as well as indirectly through
reflected short-wave radiation and emitted long-wave radiation from the surrounding built surfaces.

The differences between the N-S and WNW-ESE streets are clearly seen at noon for building heights of ~20 stories; the N-S street will have higher thermal stress. In the afternoon, only for the present conditions, i.e. building heights lower than ~8 stories, the N-S street has lower thermal stress, but will have higher stress under future scenarios.

Table 1: Basic Future Scenario

<table>
<thead>
<tr>
<th>no. of stories</th>
<th>height [m]</th>
<th>wind attenuation of IMS Ta-beach</th>
<th>wind speed m/s</th>
<th>air temp. increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>16 (HaBonim) 18.7 (HaYetsira)</td>
<td>0.5 of 4.3 and 4.4/4.5</td>
<td>2.15 and 2.2-2.25</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>20</td>
<td>0.25</td>
<td>~2.1</td>
<td>0.5</td>
</tr>
<tr>
<td>20</td>
<td>82</td>
<td>0.15</td>
<td>~0.99</td>
<td>3.0</td>
</tr>
<tr>
<td>40</td>
<td>150</td>
<td>0.005</td>
<td>~0.975</td>
<td>2.0</td>
</tr>
</tbody>
</table>

4.3 Effects of individual parameters

In order to better understand the causes of future changes, we analyzed the influence of each separate factor on the overall ITS. It should be stressed that such an influence is hypothetical since most factors are actually inseparably connected to others.

Raising of the building height (without any concurrent changes in Ta or WS) lowers thermal stress during the hot season due to deeper shading, with the extent of this improvement dependent on the street direction and width and the hour of the day, as illustrated in Figure 6. The sharp reduction in thermal stress with building height confirms the dominant effect of shading in determining outdoor TC in hot climates. Note that the N-S street at 14:40 PM is already shaded under present conditions (with a 5-story height), and thus any further reduction in thermal stress is minimal. For the perpendicular street at this hour, such shading (and sharp reduction in ITS) only occurs at 7 stories and above. Earlier in the day (around noon) the sun angle is much higher and thus shading is only achieved with heights of 20-30 stories depending on street orientation.

The effect of wind attenuation is slightly non-linear; as the WS decreases, thermal stress increases exponentially (see Figure 7). It should be noted that WS was taken here to be the same for both street orientations, assuming that attenuation of the westerly sea breeze results from the overall densification of the district. However, the actual wind flow in these almost-perpendicular streets could vary, and this is a subject that needs further examination.

Obviously, an increase in Ta results in higher thermal stress (Figure 8). However, the scale of this impact depends on street direction (it is larger in the N-S street than in the WNW-ESE one) and on the time of day. Reductions in street surface temperature were found slightly more effective for moderating TC around noontime than in the afternoon hours, due to their rapid response to maximal radiation (not shown). Trees were found almost non-effective due to their small contribution to street shading.

Street surface temperature, the metabolic activity, human body size and Ta have more extreme effect in N-S street than in WNW-ESE one on the human TC.
No significant influence of changes in the surface temperature or percentage of wall surface glazing of the building facades was observed, probably because of the high solar incidence angles around noon hours when radiation is at its highest intensity (700-1,000 W/m²). Incremental changes in RH only had a significant impact on thermal stress when humidity was already very high.

4.4 Combined effects

We applied two sensitivity tests combining the three climatic factors determining the TC in Mediterranean climate in summer: Ta, WS and RH (Figure 9). The left graph refers to Ta of 32°C (i.e., ~1°C higher than actually measured) and the right, to 35°C; both graphs show three levels of wind attenuation (0.5, 0.25 and 0.05). It is seen that RH increasingly affects TC as it reaches higher levels (80%), and the combined impact of higher air temperatures, RH and reduced wind speed results in a ‘very hot’ level of thermal sensation.

4.5 Future scenario with thermal stress mitigation

Though increasing building height can moderate TC in the summer due to deeper shading, still there is a need to quantify the potential contribution of mitigation strategies for regions such as the Mediterranean, that suffer from thermal stress. This is especially important in light of the ongoing global and localized warming trends that have been observed, with further aggravation in thermal stress predicted for the future. Moreover, the effects of impaired ventilation cooling due to WS attenuation (Figure 7) are expected to be exacerbated by extreme cases of approved high-rise construction (such as that marked "a" in Figure 1), which are expected to further block the sea breeze penetration.

Figure 10 quantifies the effects of deliberate interventions aimed at mitigating thermal stress, and shows the influence of added tree shade (with 25% canopy cover, the maximum potential) and of cooler pavement and asphalt materials (4°C reduction in surface temperature when exposed to the sun and 1°C when shaded), exemplified for the two case-study streets. In HaBonim St. (WNW-ESE) these strategies are beneficial at noon time for buildings lower than ~20 stories, and in the afternoon – only for buildings lower than ~10 stories. Results for the N-S street (HaYetsira) are even more significant, with mitigation strategies improving TC around noon for building heights of even ~20 stories. Note that in the afternoon hours the street is shadowed even by relatively low buildings, and no added value for these strategies is found in terms of improving TC.
Equivalencies may be found between different factors influences. In HaBonim St, for example: additional physical activity of 20W/m² is equivalent to additional Ta of 1°C; ~20% trees shade cover - to Ta 2°C higher; WS with no attenuation (4.3 m/s) is equivalent to reduced 2°C, etc.

5. CONCLUSION
Increasing building height in densifying business districts is being promoted due its potential for exploiting valuable real estate and revitalizing urban life. Even to the extent that these motivations are desirable – economically, socially, politically or environmentally – the effects of extreme densification on pedestrian TC should be closely examined, since a well-functioning commercial and civic space implies walkability for its users.

The present work quantifies the existing TC conditions during the summer in an intensive business district in a Mediterranean climate that is undergoing extreme densification, and the changes in TC that may be anticipated due to this process. It was found that deep street shadowing is likely to be the main factor determining future TC, though higher Ta and weaker WS are side-effects from the buildings’ heightening that could change this balance. Accordingly, TC could in fact improve on summer days in a more compacted three-dimensional urban fabric – but such a future scenario could deteriorate due to sharply reduced WS as a result of additional nearby construction, which is expected to further obstruct penetration of the sea breeze. In addition, higher Ta could result from increased anthropogenic heat sources, amplifying other urban heat island and global warming trends.

Sensitivity analyses of mitigation strategies including increased tree canopy coverage (as a percentage of street area) and lowered street surface temperatures indicated noticeable reductions in thermal stress for pedestrians who would otherwise have high exposure to solar radiation. Though its contribution to TC is in this case limited, the contribution of trees and plants to human well-being as well as to other environmental impacts should be taken into account.

The impact of incremental changes in RH on TC were found to be minor, though this influence increases when RH is very high (~80%) and is combined with rising Ta. Therefore, since trees and other plants can reduce temperate through evaporative cooling, planting on walls, between the buildings and in public spaces is recommended even if it’s shading effect on TC is small.

The combined analysis of various factors clearly illustrates their interdependence. Thus, if the activity taking place in the street is walking, dancing or repairing automobiles, rather than sitting, the predicted increase in thermal stress could change substantively; similarly, good ventilation with air flow similar to that at along the coast would improve TC in a tangible way.

Further research is needed to more precisely characterize the wind regime in such a complex urban district, through on-site measurements as well as simulation based on numerical modelling. Moreover, the potential effect of extreme wind gusts resulting from high-rise construction, especially during the winter season, should be studied in detail.

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Retrofitting actions to convert a building into net-zero energy
The case study of the itdUPM headquarters

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ABSTRACT: The objective of this work is to show the several energy saving strategies required to convert a code-compliant building into a Zero-Energy Building (ZEB). The case study is a real building located in Madrid whose energy consumptions have been monitored for three years. In the first step of the study, the current state was modelled in detail using the official software Unified Tool Lider-Calener, and annual energy consumption was obtained. In the next stage, the model was validated comparing the results of the simulation with the experimental data coming from the monitoring system, showing a good match with a difference lower than 3%. Next, the annual on-site renewable energy generated by a photovoltaic pergola that will be installed on the building’s roof was estimated using PVSyst software tool. At this point, several energy saving strategies were defined and combined to reduce the building energy consumption to the local generation. Results show that the net-zero energy balance is technically viable even in buildings with a limited on-site energy generation potential. However, this study highlights that the energy self-sufficiency is a hard goal to reach in retrofitting projects, requiring the implementation of a long list of energy-saving strategies.

KEYWORDS: Energy, ZEB, Retrofitting, Efficiency, Simulation

1. INTRODUCTION

The trend of the building sector is very far from the Sustainable Development Scenario defined by the International Energy Agency [1], which indicates the global direction that should be followed to simultaneously meet the three main Sustainable Development Goals related to energy [2]. The energy policies implemented in many regions in the last decade are managing to reduce the energy intensity per built square meter, but this improvement is not being fast enough to compensate for the growth of the built park, which globally has doubled in just 30 years. The objective of the sector seems to be to achieve zero-energy buildings (ZEB). Between the several definitions of NZEB and ZEB energy buildings [3], a possible definition, adopted in this study, is that the actual annual consumed energy is less than or equal to the on-site renewable energy generated [4].

This work shows a case study of building energy renovation toward the ZEB target. The case study is a real building located in Madrid that already meet the requirements of the national Technical Building Code. Starting from the current situation, this work shows the energy saving strategies required to cover the annual energy consumption with the electricity locally generated by a photovoltaic pergola that will be installed on the roof.

2. MATERIALS AND METHODS

The objective of this work is to point out the energy saving measures necessary to convert the headquarters of the Centre for Innovation in Technology for the Human Development (itdUPM) into a ZEB. The building has a rectangular floor plan and a North-South orientation, is surrounded by trees, and located on the hearth of the University Campus of Moncloa in Madrid, Spain. The ubication has an elevation of 664 m and a Hot-summer Mediterranean climate (Csa) in a Köppen-Geiger scale [5].

The building consists of two stories (one of them underground), with global dimensions of 21.4 m by 9.3 meters, and a total built area of 399.8 m². The upper floor, with a total net area of 195.8 m², houses the headquarters of the itdUPM of the Technical University of Madrid [6] and consists of multipurpose rooms for meetings, workshops, conferences, exhibitions and classes, articulated around a large central hall. The underground floor used as a maintenance garage and has not been considered in this study, since no retrofitting of this space was foreseen. There is not vertical communication between the two stories and each one has a separate entrance. Thus, this work focuses on the upper floor only (Figure 1), which is the space that needs improvements to achieve better thermal comfort.
reducing energy consumption for heating, cooling and lighting. On top of the entrance hall stands a rectangular skylight that provides daylight. In terms of structure, the building has metal pillars and 30cm prestressed concrete slabs.

To carry out the study, the following steps have been followed.

2.1 Building’s energy consumption simulation in the current state

The first step of the study was modelling the building in the current state to assess the building energy demand. To that end, the building was defined in detail in the official software Unified Tool Lider-Calener (HULC) [7], that is used in Spain to check the compliance of the buildings with the energy-related requirements of the Technical Building Code [8]. To carry out the simulation, both ground and first floors were defined in the tool, since the thermal properties of the ground floor deeply influence the thermal behaviour of the building. Thus, both floors were simulated but only the energy consumption of the first floor was considered in the further steps of the study. Each building element was defined by means of its thermal properties such as specific heat, density, and conductivity. The thermal transmittance of the main building envelope enclosures is summarized in Table 1.

Table 1. Thermal transmittance of the building envelope in the current state.

<table>
<thead>
<tr>
<th>Enclosure</th>
<th>Thermal transmittance [Wm⁻²K⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab in contact with the ground</td>
<td>0.33</td>
</tr>
<tr>
<td>Walls in contact with the ground</td>
<td>2.92</td>
</tr>
</tbody>
</table>

The windows, placed in the west and east facades only, and covered by the continuous sheet metal that encloses all the façades, are made of a double glass (6+12+6 acoustic COOL-LITE, thermal transmittance 3.30 Wm⁻²K⁻¹, solar factor of 0.75), and a metal frame without thermal break (thermal transmittance 5.70 Wm⁻²K⁻¹, absorptivity 0.70 and air permeability 27 m³h⁻¹m⁻² at 100 Pa). The skylight windows have the same characteristics.
Figure 3. HVAC ducts and lighting system.

The lighting system is made up of conventional fluorescent T8 lamps installed on suspended luminaires, with a power density of about 16 Wm\(^{-2}\) and a power density per 100 lx of about 5.6 Wm\(^{-2}\)100lx\(^{-1}\).

2.2 Model validation with experimental data

The next step was the validation of the model and with this purpose the simulated data were compared with the actual data coming from the monitoring system installed in the building. It is based on an ad-hoc designed embedded system connected through an RS-485 serial bus to several distributed nodes. These nodes are directly connected to several sensors such as thermocouples, pyranometers, heat flux sensors, meteorological stations, and electric power meters. The nodes are running a real-time operating system which acquires data coming from all the sensors every 10 ms. Next, every second the monitoring node performs the mean of the last 100 measurements and stores it internally to be acquired by the main controller, that acquires all measurements stored on the nodes and accumulates them on an internal SD card every minute. Moreover, every five minutes the main controller sends the data stored to the monitoring server, which oversees uploading them to a monitoring database. A monitoring website has been created to allow researchers and general public observe the behaviour of the building in real time [9].

2.3 Building’s on-site PV production estimation

To reach a net-zero energy building, technologies to locally produce energy are mandatory. Regarding this aspect, the installation of a photovoltaic pergola on the building’s roof consisting of 36 monocrystalline silicon PV modules was analysed.

Figure 4. 3D model of the PV pergola.

This system covers only one third of the roof surface since the remaining part must be kept free of shadows to be used in other experimentations, such as the development of microalgae photobioreactors for biomass production. To estimate the annual energy generation, PVSyst software tool [10], considered one of the reference software in PV engineering, was used.

2.4 Definition of energy-saving strategies

The following energy saving strategies have been analysed:

- Improvement of the thermal insulation
- Removal of perforated metallic double skin
- Improvement of window and skylight glazing
- Improvement of window and skylight frame
- Improvement of the lighting system efficiency
- Improvement of the heat recovery units efficiency

A wide range of parameters has been simulated for each strategy, to fully characterize the effect of each of them on the overall energy consumption of the building.

2.5 Combination of energy-saving strategies

The analysis of the effect of each strategy allowed the definition of the most effective ones in terms of energy saving. The next step was studying the compatibility between them, by defining six final models in which several solutions were combined, as shown in Table 2. Based on this analysis, the most efficient combination was pointed out.

3. RESULTS

3.1 Energy balance in the current state

In the current state, the simulated and measured annual electricity consumptions of the floor of the building under test (the first floor with a net area of 195.8 m\(^2\)) are 132 kWh m\(^{-2}\) and 135 kWh m\(^{-2}\), respectively. Being the difference lower than 3%, the model may be considered validated and can be used to assess the effects of the energy saving strategies proposed. Regarding the distribution of the consumptions, lighting is the most intensive energy use with 66.6 kWh m\(^{-2}\), heating is the second one with 44.2 kWh m\(^{-2}\) and cooling requires 21.3 kWh m\(^{-2}\).
Concerning the on-site energy generation, about 67 kWh m\(^{-2}\) of AC electricity (standardized with respect to net surface) can be locally generated by the PV system. This means that the local generation would cover about 50% of total electricity consumption, staying halfway to be a self-sufficient building on an annual basis. Accordingly, it is necessary to reduce 50% of energy consumption by implementing energy-efficient measures to achieve this goal.

3.2 Thermal insulation improvement effect

The implementation of an ETICS (External Thermal Insulation Composite System) is usually one of the first measures to be considered in an energy rehabilitation. In this study, the effects of several insulation thickness were simulated to find out a good compromise between performance in winter, in summer, economic feasibility and space issues. By increasing the thickness of the expanded polystyrene (EPS) insulation layer, the energy for heating is reduced to more than the energy for cooling is increased, so the overall effect is that the consumption for HVAC lowered. (Figure 6). In particular, the reduction of heating energy ranges between 7% (4 cm thickness) and 20% (40 cm thickness), whereas the increase of cooling energy for the same thicknesses varies between 3% and 6%. However, although using thicker layer would be energetically more efficient, the feasibility of the application of EPS thermal insulation with a thickness above 20 cm is reduced by both economic and space issues.

3.3 Removal of the metallic double skin effect

The effect of removing the metallic perforated double skin, completely or just in front of the windows, was analysed. Simulations show that in both cases, heating energy consumption is reduced by 12%. On the other hand, cooling consumption is increased by 17% when the perforated metal sheet is completely removed, while this increase is reduced to 11% when the sheet is removed in front of the windows only. The overall effect is that removing all the double skin or in front of the windows only produces 3% and 5% energy savings for HVAC respectively.

3.4 Windows and skylight quality improvement effect

To analyse the impact of improving the thermal properties of the glazing surfaces, four options including double and triple glazing were considered. In combination with the glazing substitution, the replacement of the existing aluminium frame without thermal break by one with a thermal break of 12 mm was evaluated. As shown in Figure 7, using a double glazing with a thermal transmittance of 1.5 Wm\(^{-2}\)K\(^{-1}\) and a very low g-value of 0.11, increases about 17% the heating consumption and reduces 8% the consumption for cooling, mainly because the solar gains through the skylight are drastically reduced, being the overall effect an increase in HVAC consumption. It should be noted that the energy behaviours of the double glazing (thermal transmittance of 1.5 Wm\(^{-2}\)K\(^{-1}\), g-value 0.63) and the triple glazing (thermal transmittance of 0.6 Wm\(^{-2}\)K\(^{-1}\), g-value 0.54) are practically equivalent, with an overall reduction of HVAC consumption of about 7%.

Figure 6. Annual HVAC energy consumption of the current state (CS) and as a function of the insulation thickness. Heating in red and cooling in blue.

Figure 7. Annual HVAC energy consumption of the current state (CS) and as a function of the thermal properties of the glasses. Heating in red and cooling in blue. Units of the thermal transmittance (U-value) are Wm\(^{-2}\)K\(^{-1}\).
3.5 Lighting system efficiency improvement effect

Lighting is the most intensive energy use of the building and accounts for about the half of the total electricity consumption. To improve the efficiency of the system and minimize the overall energy consumed by lighting, four main solutions have been considered: i) replacing the T8 fluorescent lamp (with a luminous efficacy of about 80 lm W⁻¹) for LED tubes with a luminous efficacy of about 140 lmW⁻¹; ii) introducing an automatic lamps dimming system to make the most of the natural lighting provided by the skylight; iii) using clear colours on both interior surfaces and furniture to maximize the utilization factor; iv) bring the luminaires closer to the working plane by slightly lowering the suspended luminaires. With these measures, consumption for lighting is reduced by 44%, with a final value of about 37 kWh m⁻².

3.6 Improvement of the heat recovery units efficiency

The building in its current state has two heat recovery with an efficiency of about 70%. The effect of replacing them with units with 85% efficiency was analysed, finding that this operation could reduce the HVAC energy by 10%.

3.7 Combination of the best performing energy-saving strategies

Once the effects of the energy saving strategies have been individually determined, they have been introduced in different combinations in 6 new models, with the aim of determining their compatibility and the most energy efficient package of measures for the building (see Table 2. Combinations of energy saving solutions in the six final models analysed.).

4. DISCUSSION

In all simulated models, there are significant reductions in energy consumption (Figure 8). However, looking for an energetically self-sufficient building, the most efficient combination corresponds to the model 6, in which about 47% reduction of the energy consumption of the building is achieved.

To obtain these results, several energy saving solutions are combined, such as a:

- Improvement of the thermal insulation with a 20 cm thick (ETICS)
- Removal of the metallic double skin in front of the windows to get solar gains and daylighting
- Triple glass windows (4-16-6-16-4) with U=0.6 Wm⁻²K⁻¹ and solar factor of 0.54
- Frames with thermal bridge breakage
- Solar protection of the south face of the skylight with horizontal slats (10 cm width, tilt 65°)
- Solar protection of the east and west faces of the skylight by vertical slats (20 cm width, perpendicular to the glass surface)
- Solar protection of the windows in the ground floor by vertical slats (20cm width, perpendicular to the surface of the glass)
- Improvement of the lighting system efficiency using LED lamps, dimmer, clear colour surfaces and furniture and ac closer position of the luminaires to the working plane.

In particular, the demand for heating is reduced by 56%, mainly thanks to the ETICS, high performing windows and the use solar gains in winter. At the same time, the demand for cooling is reduced by 32% thanks to the improvement of the lighting system efficiency and the lower solar factor of the glazing used in the skylight and in ground floor windows. Combinedly, all these measures generate a reduction of about 48% in the HVAC consumption. Moreover, a 44% reduction in lighting consumption is obtained thanks to a significant improvement of the lighting system efficiency.

With the application of all these solutions, an energetically self-sufficient building has been reached.
Table 2. Combinations of energy saving solutions in the six final models analysed.

<table>
<thead>
<tr>
<th></th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
<th>Model 5</th>
<th>Model 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETICS thickness</td>
<td>20 cm EPS</td>
<td>20 cm EPS</td>
<td>20 cm EPS</td>
<td>20 cm EPS</td>
<td>20 cm EPS</td>
<td>20 cm EPS</td>
</tr>
<tr>
<td>Opaque envelope transm. [Wm⁻¹K⁻¹]</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Metallic double skin covering windows</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Windows glasses</td>
<td>Triple</td>
<td>Triple</td>
<td>Double</td>
<td>Double</td>
<td>Triple</td>
<td>Triple</td>
</tr>
<tr>
<td>Glasses transm. [Wm⁻¹K⁻¹]</td>
<td>0.60</td>
<td>0.60</td>
<td>1.50</td>
<td>1.50</td>
<td>0.60</td>
<td>0.60</td>
</tr>
<tr>
<td>Glasses solar factor</td>
<td>0.54</td>
<td>0.54</td>
<td>0.11</td>
<td>0.11</td>
<td>0.54</td>
<td>0.54</td>
</tr>
<tr>
<td>Windows frames thermal break length</td>
<td>&gt;12mm</td>
<td>&gt;12mm</td>
<td>&gt;12mm</td>
<td>&gt;12mm</td>
<td>&gt;12mm</td>
<td>&gt;12mm</td>
</tr>
<tr>
<td>Lighting system</td>
<td>LED</td>
<td>LED</td>
<td>Current T8</td>
<td>LED</td>
<td>LED</td>
<td>LED</td>
</tr>
</tbody>
</table>

5. CONCLUSION
This paper shows that net-zero energy is a goal difficult to achieve, especially in retrofitting projects in which the on-site energy generation potential is limited. To reach this goal, it is necessary to minimize the energy needs of the building by combining several energy saving strategies. In short, despite the satisfactory results obtained, it can be noted that reaching energy self-sufficiency in retrofitting projects, by improving the thermal envelope, the lighting system and implementing local renewable energy generation systems is technically possible but not an easy task at all, mainly because actuations on several components of the building are required. For this reason, new initiatives promoting energy self-sufficiency both in the new and retrofitting projects must be considered very positive.

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The impact of kinetic facades on building occupants
Psychological state and cognitive performance

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ABSTRACT: Kinetic facades combine passive design techniques with smart active features to improve the energy performance and indoor climate in buildings. However, kinetic facades also affect visual aesthetic aspects. Research has indicated that the form and composition of a facade can influence building occupants, visually, psychologically, and physiologically. The design of kinetic facades, therefore, requires a more human-centred approach to make it truly sustainable. In this paper, we report on a study that used a new experimental tool, immersive Virtual Reality (iVR), to analyse the effects of the dynamic behaviour of kinetic facades on human psychological comfort and cognitive performance. The results indicated that the state of kinetic facades affects the psychological state and the cognitive performance of building occupants. The magnitude of the impact depended on the kinetic concept and the surroundings of the building.

KEYWORDS: Kinetic facade, Psychological effect, Cognitive performance, immersive Virtual Reality, Human experiment

1. INTRODUCTION

In recent years, the notion of "intelligent" buildings has become increasingly popular. An intelligent building is a dynamic and responsive architecture that provides occupants with productive, cost-effective and comfortable conditions through a continuous adaption of its basic elements: places (fabric; structure; facilities); process (automation; control; systems); people (services; users) and management (maintenance; performance) and the interrelation between them [1].

Kinetic facades are a means to realise the features of an intelligent building. A kinetic façade seeks to maintain indoor thermal and visual comfort for the user through shape-changing. Allowing movement of the building façade also has a strong influence on the exterior architectural expression of the building. During the design process, the ability of a kinetic façade to facilitate indoor activities and its implication on architectural expression should, therefore, be evaluated. For example, its ability to provide thermal comfort can be assessed by evaluating output from thermal simulations. Similar exercises can be done for other aspects that affect the comfort of occupants such as visual (lighting) comfort. However, little is known about the effect of kinetic façades on psychological factors.

In this paper, we report on a study that investigated the effects of the dynamic behaviour of kinetic facades on the psychological state and cognitive performance of building occupants and the methodology developed to perform this psychological analysis. The study was originally reported in [2].

An investigation of the following two questions was made as to the basis for developing the methodology to analyse the effect of kinetic facades on human psychology:

1. Which psychological factors can be influenced by architecture/facades and how?
2. What methods can be used to analyse these psychological factors in an architectural environment?

1.1 Psychological factors – visual and non-visual

The discovery of the intrinsically photosensitive retinal ganglion cells (ipRGCs) has led to a new understanding of how light affects human physiology and health and introduces a new dimension for architectural lighting design and engineering in buildings. The non-visual system adapts its response to changes in light intensity and spectral composition over a longer period, than the visual system. Current responses depend on past exposure and can extend over several hours, or even days. At the same time, it provides new challenges in lighting performance evaluation, because these novel photoreceptors are the primary mediators of non-visual physiological and neuro-behavioural responses to light but can also function independently of classical photoreceptors. This means that the human eye plays a dual role in detecting light and existing methods must be revised for the assessment of our lighting environment to meet the requirements of the non-visual system [3].
It is also responsible for many cognitive processes, such as attention, executive functions and memory [4]. Moreover, daylight has been associated with improved mood, with an enhancement of morale, lower fatigue and reduced eyestrain [5]. Furthermore, studies indicate that daylight enhances mental performance and decreases aggressive behaviour, as well as depression [6]. Another important psychological aspect is accommodating the need for contact with the outside world through openings in buildings [7]. In this regard, daylight can enhance the feeling of connectivity to nature and directly improve the mood of the building occupants [8]. Therefore, daylighting strategies, for instance: the orientation of the building, the proportion of windows, the depth of the rooms, the design of shading devices, the reflective surfaces and the colouring of the enclosing components (walls, doors, and soffits) are all important design features [9]. Table 1 sums up the psychological factors that can be related to kinetic facades and should consequently be considered in a psychological analysis of their performance.

Table 1. Psychological factors related to kinetic facades

<table>
<thead>
<tr>
<th>Visual comfort</th>
<th>Non-visual comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perception of space and time</td>
<td>Emotional state (mood)</td>
</tr>
<tr>
<td>Quality of view</td>
<td>Feeling of privacy</td>
</tr>
<tr>
<td>Dynamic behaviour</td>
<td>Connectivity to the outside</td>
</tr>
<tr>
<td></td>
<td>Level of concentration</td>
</tr>
<tr>
<td></td>
<td>Cognitive performance</td>
</tr>
</tbody>
</table>

1.2 Methods for performing psychological analysis

A review of the literature identified a range of methods that can be used to analyse the psychological factors listed in Table 1:

1. Full-scale mock-up,
2. 3D model and immersive Virtual Reality (iVR),
3. Computer simulation software,
4. Numerical analysis,
5. Human experiment,
6. Surveys,
7. Personal interviews,
8. Gaze recording with a camera,
9. Rendered simulations,
10. Augmented Reality (AR)

Based on this review, the methods: iVR, human experiment, and personal interviews were chosen for setting up the methodology.

Immersive Virtual Reality (iVR)

iVR has been demonstrated to be a reliable method for psychological analysis as the immersive effect provides a sense of realness to the user [10-12]. Furthermore, iVR is an effective experimental tool as it allows researchers to expose human subjects to specific environments and within a short period. This has led to increased use of iVR as a research tool across many psychological domains, such as psychotherapy [13, 14], sports psychology [15], and social interaction [16]. Virtual environments can present a range of complex stimulus conditions that would not be easily controllable in the real world and enabling the examination of both cognitive processes (e.g. attention) and functional behaviours (e.g. planning and initiating a series of required actions) [17]. iVR research studies now include varying levels and combinations of multimodal sensory input, allowing audio, haptic, olfactory, and motion to be experienced simultaneously to the graphically rendered environment or objects. This greatly increases the user’s sense of immersion in the virtual environment and allows the experimenter to create protocols that would not otherwise be possible.

Human Experiment

The need for subjective assessments from humans is self-explanatory. Data can be collected using questionnaires or interviews. Numerous examples of this method can be found in the literature, often in combination. Combining iVR with subjective assessments has been demonstrated to be a reliable method for psychological analysis since its immersive effect can provide a sense of realness to the user.

Personal interviews (oral questionnaires)

Using personal interviews in the form of an oral questionnaire for collecting subjective data is suitable for 2 reasons: 1. it is a commonly used method by psychologists and therapists to evaluate the psychological state of a human, and 2. the participants can evaluate facades while being in the virtual environment instead of filling in a questionnaire afterward, i.e. introducing bias as they would have to evaluate based on memory.

Consequently, the following methodology for the psychological analysis of kinetic facades was chosen: human experiment using immersive Virtual Reality (iVR) and personal interviews (oral questionnaires). The implementation of the methodology is elaborated in the following section.

2. METHOD

The steps for the psychological analysis were:

Step 1: The creation of a realistic virtual environment in which the goal is that the participants perceive the same psychological stimuli as in real life.
Step 2: The creation of the façade/surrounding scenarios.
Step 3: The preparation of the questionnaire, designed for collecting data for statistical psychological analysis.
Step 4: Set up an experimental protocol, including randomization of participants, scenarios, and formulation of questions.

2.1 Creating the virtual environment

This process required considerations about the suitable computational tools, in terms of modelling speed, hardware and software compatibility, graphic quality and flawless integration, to create a realistic virtual environment, in which the participants can immerse themselves. Immersive environments are better remembered by participants [18], elicit more intense emotional responses [19], and replicate more successfully the anxiety associated with real-life stressful situations [20]. For a realistic experience, a fully immersive environment, the feeling of presence and visual realism (authenticity) are key factors.

Visual realism

Visual realism can be regarded as the degree to which a simulated, artificial world resembles a corresponding real world. The degree to which an object resembles its real-world counterpart can be assessed based on the following properties:

- The geometric aspect defines whether the shape of the object is similar to the corresponding real object. In computer graphics, complex curved objects generally need a higher number of polygons than simple rectangular objects.
- Material properties define whether the surface of the object looks natural.
- The virtual light is simulated correctly, and thus the overall visual realism of the virtual environment. This depends on the mathematical implementation of the light structuring process, as well as the geometric and material realism of the object that receives the light.

To achieve the above properties, the virtual indoor environment of this experiment was created in Autodesk Revit, using the plugin Enscape. In Revit, it is possible to create complex geometries, assign realistic material properties to the objects, and use real geographical data (via Enscape), so that the geometry, materials, and light resemble a real-life environment.

3D modelling and automatization

For this study a high-rise office building with two different types of kinetic façades was modelled:

- For a complex façade geometry, the facade of the Al Bahar towers was used as inspiration (Fig. 1).
- For a simpler geometry, the Kiefer Technique Showroom was used as inspiration (Fig. 2).

Both kinetic façade types were created as a parametric Revit family, which then was automatized by using a Dynamo script. This allowed the panel movements to happen, being able to open and close, simulating their dynamic behaviour from real life.

The type of building was chosen to be a high-rise office building (see Fig. 3) and the analysed office space was placed on the 15th floor. The offices were placed in two different surroundings with different characteristics (Fig. 4.):

- “Nature”, i.e. surrounded by mountains, characterized by calmness, relaxation, intimacy, etc.
- “Urban”, surrounded by buildings, characterized by intensity, density, potential lack of privacy, etc.

These environments were defined in Enscape, by converting the images into "skyboxes". When a skybox is used, the images are projected onto a cube’s faces using a technique called cube mapping, creating the illusion of a three-dimensional space.
The skybox is then placed in the 3D model in Revit and adjusted to the building model. Examples of the final virtual environments are depicted in Figure 5 and 6.

2.2 Creating façade/surrounding scenarios

Space, time, and panel movements were considered in the development of specific façade/surroundings scenarios for the psychological analysis. Space and time are defined by the context of the surrounding environment, while the positions of the kinetic panels were selected according to the different stages of movement: 0% closed panels, 25% closed panels, 50% closed panels, 75% closed panels and 100% closed panels.

These static positions affect the light levels, the position of the shadows, the quality and amount of view, and the amount of privacy in the offices and therefore - also the psychological state of the human subjects. Furthermore, a dynamic scenario was added with the use of Dynamo, where psychological factors were assessed during a continuous movement between completely open and completely closed. Consequently, two environments (Space A with expanding panels and Space B with sliding panels) with five scenarios each were created, leading to a total of ten scenarios to be evaluated by the human subjects.

2.3 Preparing the interview questions

Two types of questions were used to collect information: 1. Structured (fixed response) questions, using an 11-point bipolar Likert scale from -5 to +5 and 2. Non-structured (open questions) with an additional short-term memory exercise, where the participants needed to perform a simple cognitive task. Table 2 shows an overview of the category of questions asked during the experiment.

<table>
<thead>
<tr>
<th>Question</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Question 1-3</td>
<td>Perception of space and time</td>
</tr>
<tr>
<td>Question 4</td>
<td>Quality of view</td>
</tr>
<tr>
<td>Question 5</td>
<td>Feeling of privacy</td>
</tr>
<tr>
<td>Question 6</td>
<td>Emotional state (mood)</td>
</tr>
<tr>
<td>Question 7</td>
<td>Connectivity to the outside</td>
</tr>
<tr>
<td>Question 8</td>
<td>Level of concentration</td>
</tr>
<tr>
<td>Question 9</td>
<td>Aesthetic influence</td>
</tr>
<tr>
<td>Question 10</td>
<td>Short-term memory exercise</td>
</tr>
</tbody>
</table>

First, three introductory questions were asked to understand how well the participants were immersed into the virtual environment and to calibrate them to the virtual environment by enhancing their feeling of presence and to have an initial similar state of mind before the psychological analysis.

Next, six questions related to the psychological state of the participants were asked.

Finally, a cognitive performance test (a short-term memory exercise) was performed. The task was to memorize 15 names written on a piece of paper, lying on the table in the virtual environment in 30 seconds and repeat as many as they could. This task was performed in the scenario with completely open and static panels, and the scenario with moving panels. The number of names repeated by the participants was registered both times to test whether their cognitive performance has dropped when the panels were moving, compared to when they were static.

2.4 Experimental protocol

The experimental protocol was designed using randomization, which is a reliable method for creating homogeneous treatment groups, without involving any potential biases or judgments [21]. In a
randomized experimental design, objects or individuals are randomly assigned to an experimental group. In this experiment, the exposure to Space A (expanding panels) and Space B (sliding panels), and the order of questions was randomised, but the order of the scenarios was planned. Instead of showing a stepwise panel movement from open to closed, the following order was created in both spaces:

- Scenario 1: 0% closed panels
- Scenario 2: 75% closed panels
- Scenario 3: 25% closed panels
- Scenario 4: 100% closed panels
- Scenario 5: 50% closed panels

The order of scenarios was planned for creating the feeling of randomness, to avoid a carry-over effect from one scenario to the next one.

3. RESULTS
A total of 70 subjects participated in the experiment. Figure 7 illustrates the mean ratings of the participants for each question and cognitive tests in all scenarios in the two environments.
Figure 7: Mean votes of the 70 participants for each psychological factor and cognitive performance

4. CONCLUSION

The study indicates that the state of kinetic facades affects the psychological state and the cognitive performance of building occupants. The magnitude of the impact depended on the kinetic concept and the surroundings of the building.

Furthermore, iVR seems to be a useful tool for analysing the psychological effect of kinetic facades on the building occupants.

REFERENCES

Analysis of materials to evaluate their environmental impact in the manufacture of thermoplastic parts. Case study: AutoBioGen.

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2 General direction of industrial Technology education, Secretary of Public Education, México City, México

ABSTRACT: Currently the use of software in the architecture and design of products has allowed the development of products to be competitive and efficient to meet the diverse needs of human beings, likewise it has developed software options that evaluate the production with the plastic in its potential environmental impact. The main purpose of this research is to evaluate the environmental impact when manufacturing a piece of the AutoBioGen (Air conditioning system for a four person housing) study case, with thermoplastic using software. The Autodesk Inventor 2018 software was used specifically in the Eco Materials Adviser option, which takes little time to simulate the amount of material that will be used, to evaluate the environmental impact in the manufacture of the AutoBioGen part. With the aforementioned software, the thermoplastics used were compared, high density polyethylene (HDPE), low density polyethylene (LDPE) and polypropylene (PP), comparing with respect to the energy consumed in mega joules (MJ), the carbon footprint in kilograms (kg), the liters (l) of water consumed and the cost in dollars (USD). The best thermoplastic for the construction of the part of the AutoBioGen required is the PP, since it needs 6% less energy, emits 5% less carbon dioxide (CO2), needs 37% less water, but being its price is 14% higher compared to HDPE. The PP uses 2.68% less energy, emits 2.40% less CO2 and uses 49.64% less water than the LDPE.

KEYWORDS: Architecture, product design, environmental impact, AutoBioGen, thermoplastic, high density polyethylene, low density polyethylene, polypropylene, Eco Materials Adviser.

1. THEORETICAL FRAMEWORK

Plastics have become a key element in almost all industrial activities, are among the industrial materials of greatest growth in the industry of the twentieth and twenty-one centuries. The basic raw material for the production of resins or polymers are the monomers and most of them come from petroleum [1].

- Plastics are organic polymers, which can be molded by heat and pressure. These polymers are large groups of monomers linked by a chemical process called polymerization, which mainly contain carbon and hydrogen. Plastics provide properties that can’t be achieved with other materials, for example: color, light, weight and resistance to environmental and biological degradation [1].

- Thermoplastics are resins with a linear molecular structure, which during hot molding don’t undergo any chemical modification. Their behavior derives from the properties and the molecular structure of the polymer itself. It is estimated that of all the plastics used in the world more than 75 percent are thermoplastic [1].

The reaction to obtain the raw material for thermoplastics is called Polymerization, which is carried out by addition polymerization, in which two or more similar monomers have a direct reaction to form long chain molecules, such as PE and PP [1].

Currently, the use of plastics in Mexico has diversified by using garbage bags, pipes, door frames, ceilings, moldings, among other items, because of their convenience and economic value [2], due to the above the consumption of thermoplastics has increased year by year. In 1997, 1,893,845 tons (ton) were used, while in 2002 it was 2,566,599 tons, which represents an increase of 35% [3].

The consumption of HDPE, LDPE and PP has increased from 1997 to 2002, as shown in Table 1 [2].

<table>
<thead>
<tr>
<th>Thermoplastic/year</th>
<th>1997</th>
<th>2001</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDPE</td>
<td>418,839</td>
<td>552,915</td>
</tr>
<tr>
<td>LDPE</td>
<td>515,300</td>
<td>649,852</td>
</tr>
<tr>
<td>PP</td>
<td>367,939</td>
<td>575,616</td>
</tr>
</tbody>
</table>

The risk to the environment from the use of thermoplastics in Mexico has increased the contamination of water, air and soil by the large volumes of waste from thermoplastics that are generated daily, which receive little or no treatment, in addition to Mexico from 2000 has implemented few policies in the reduction, reuse and recycling of thermoplastics. "Although the characteristics of
danger most synthetic plastics do not represent a risk to the environment, if they are a major problem because they can’t be degraded by the environment. Contrary to what happens with wood, paper, natural fibers or including metal and glass, plastics do not oxidize or decompose with time” [3].

The HDPE and LDPE are simple polymers, obtained from the polymerization of ethylene (CH2=CH2), which is carried out by the opening of the double bond, through a mechanism of chain reaction by effect of temperature and pressure, as well as by the help of catalysts such as triethylaluminium. The pressure during polymerization will determine whether the PE will be low or high density [4].

- The HDPE is a heavy and very resistant material. It is used in containers for food and industrial use, bags, appliance housings, toys and pipes [1].
- The HDPE is a non-renewable resource, it can be recycled from five to seven times, exceeding the previous number of recycled HDPE begins to lose its physical properties [4].
- The LDPE is light and flexible and is mainly used for bags, wraps, toys and household items [1].

The PP is a thermoplastic that is produced by polymerizing propylene molecules, which are the monomer units, in very long molecules or polymer chains. The main properties of the PP in the melting state are derived from the average length of the polymer chains and the amplitude of the distribution of the polymer chain lengths in a given product. In the solid state, the main properties of the PP material reflect the type and quantity of crystalline and amorphous regions formed from the polymer chains [5].

- The PP is a rigid and resistant material. It is used in industrial parts, electrical and electronic components, packaging, helmets, toys, among others [1].

Depending on the manufacturing process there is a preliminary operation to condition the thermoplastic (HDPE, LDPE, PP, among others) before using it, but most thermoplastics are in granular form (pellets) or in powder form (Fig 1a, b) [1].

The case study to be evaluated is a piece that is part of a climate control system using a biodigester (AutoBioGen) for a house where four people live in the municipality of Texcoco, State of Mexico. The system uses the heat generated within the AutoBioGen, transferring this heat to a hose. The hose carries water, which is heated in order to be used in a thermal socket that air-conditioned the dining room. The methane (CH4) produced in AutoBioGen by anaerobic fermentation is used as fuel for the stove, it also helps to recycle the water and to generate biofertilizer. The methane monitoring generated in the AutoBioGen was carried out using an electronic device known as Arduino uno [8].

The AutoBioGen was designed in the software Autodesk-Inventor 2018. The piece called cylinder with capacity of 300 l, has two enclosures, each with a capacity of 68 l, with the following functions: In the cylinder the excrement is fermented in order to generate methane, the first box is where the excrement is separated from the soapy water, while in the second box it is used to separate the fermented excrement from the water. The pipe inside the cylinder contains water which is heated by the temperature of the fermentation of the excrement. (Fig. 2) [8].

![Figure 1 (a). PP in granular form](image)

![Figure 1 (b). PP in powder form](image)

![Figure 2. Part of cylinder with a capacity of 300 l](image)
The designed piece is proposed to be produced using the rotational molding method because the costs would decrease compared with other processes used in the manufacturing of products with thermoplastics, such as plastic injection, blow molding, among others [8]. Currently rotomolding is very used by the company Rotoplas (This mexican company uses PE to mass-produce its products), which within its main activities are the assembly of water tanks and biodigesters [10]. One advantage and benefit of rotomolding is to manufacture very large parts at reduced costs.

Which type of thermoplastic (HDPE, LDPE or PP) has a lower environmental impact for the production of the cylinder part with a capacity of 300 l of the AutoBioGen?

If the 300 l cylinder part of the AutoBioGen is produced with the HDPE, LDPE or PP, then which of the three materials has a lower environmental impact.

The general objective is to select the least polluting material for the 300 l cylinder part of the AutoBioGen with the use of the Eco Material Adviser.

The Autodesk Inventor 2018, is a software that allows you to simulate and analyze the designs made with the computer. Its purpose is to optimize its development, to obtain the desired product. The software is used in the design of new products or existing ones, to improve their performance and verify that the proposed design is suitable for its production following the specifications of the client; this computer model is also used to certify the product [11].

The Autodesk Inventor 2018 specifically the Eco Materials Adviser option calculates the environmental impact of HDPE, LDPE and PP for the manufacture of a prototype [11].

The Eco Materials Adviser calculates the forecast of key environmental indicators, such as [11]:

- Amount of CO₂ associated with the creation of the product.
- Amount of energy that is used in the production and elimination of the product.
- Amount of water that is used in the extraction of the material to be used in the product.
- Estimated cost of materials used in a product.
- If the materials used in a product comply with the European legislation on Restriction of Hazardous Substances (RoHS) [10].
- If the materials used in a product are available in food contact qualities (FDA, UE, BFR, NSF) [11].
- Material useful life (for example: recycling, downcycling, buried and combustion) [11].

These environmental indicators can be displayed at the Eco Materials Adviser control center or as a detailed report that can be printed or saved as a PDF.

Eco Materials Adviser is displayed in a panel that appears in the right part of the Autodesk Inventor window by default. The commands are available in the panel toolbar or from the homepage of Eco Materials Adviser.

2. INVESTIGATION METHODOLOGY

The methodology for the design and construction of the AutoBioGen is described below:

- Define the materials to be used.
- Get characteristics of the materials.
- Analysis of the cylinder part with a capacity of 300 l of AutoBioGen through the use of the Autodesk Inventor 2018 software in the Eco Material Adviser option.
- Breakdown of environmental indicators of materials.
- Comparison between materials.
- Analysis of the result obtained.

2.1 Experiment with HDPE

The piece to be evaluated was designed in the Autodesk Inventor 2018 software and the HDPE material was selected (Table 2).

Table 2. Physical characteristics of the HDPE

<table>
<thead>
<tr>
<th>Basic thermal</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity</td>
<td>2.11 E-01 with (m-K) (meter per degree kelvin)</td>
</tr>
<tr>
<td>Specific heat</td>
<td>2.859 J/(g°C) (joule per gram per degree centigrade)</td>
</tr>
<tr>
<td>Coefficient-thermalon</td>
<td>150.000 mm/(m°C) (milimeter per meter per degree centigrade)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechanics</td>
<td></td>
</tr>
<tr>
<td>Behavior</td>
<td>Isotropo</td>
</tr>
<tr>
<td>Young module</td>
<td>0.911 GPa (gigapascal)</td>
</tr>
<tr>
<td>Poisson’s coefficient</td>
<td>0.39</td>
</tr>
<tr>
<td>Cutting module</td>
<td>320.000 MPa (megapascal)</td>
</tr>
<tr>
<td>Density</td>
<td>0.952 g/cm³ (gram per cubic centimeter)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistance</td>
<td></td>
</tr>
<tr>
<td>Yield point</td>
<td>20.670 MPa (megapascal)</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>12.780 MPa (megapascal)</td>
</tr>
</tbody>
</table>

The cylinder piece with capacity of 300 l of AutoBioGen using the HDPE material, has the following environmental impacts [12]:

- Amount of energy: 3,820 MJ.
- Amount of CO₂ not emitted: 299 kg.
- Amount of water used: 4,430 l.
- Estimated cost: 144 USD.
- The material complies with European RoHS legislation.
- The material is available in food contact qualities (FDA, UE, BFR, NSF).
- The material if it is recyclable.
2.2 Experiment with LDPE

The LDPE material was selected (Table 3).

Using LDPE, it has the following environmental impacts [12]:
- Amount of energy: 3,720 MJ.
- Amount of CO₂ not emitted: 291 kg.
- Amount of water used: 5,600 l.
- Estimated cost: 167 USD.
- The material complies with European RoHS legislation.
- The material is available in food contact qualities (FDA, UE, BfR, NSF).
- The material if it is recyclable.

2.3 Experiment with PP

Then the PP material was selected in the Autodesk Inventor 2018 software (Table 4).

Using the PP, it has the following environmental impacts:
- Amount of energy: 3,620 MJ.
- Amount of CO₂ not emitted: 284 kg.
- Estimated cost: 166 USD.
- The material complies with European RoHS legislation.
- The material is available in food contact qualities (FDA, UE, BfR, NSF).
- The material if it is recyclable.

3. ANALYSIS OF RESULTS

The environmental indicators included in this analysis are based on detailed and quantitative studies of the natural resources and energy needed to:
- Produce a material.
- Process that material in manufacturing operations.
- Manage that material at the end of its useful life.

These studies allow predicting how much energy is consumed or the amount of CO₂ that is released into the atmosphere to produce, process and manage 1 kg of a material.

The base version of Eco Materials Adviser focuses on the analysis of the material production, product manufacturing and end of life phases of the product life cycle.

Figure 3 compares the impacts of HDPE, LDPE and PP using only the material.

4. DISCUSSION AND REFLECTIONS

The software Autodesk Inventor 2018 has been used specifically in the application Eco Materials Adviser to simulate the amount of thermoplastic that should be used in the production of the piece of AutoBioGen mentioned.

Three types of thermoplastics were evaluated, in order to choose the one that best suits the
production of the AutoBioGen part. The comparison is made when using the HDPE, LDPE and PP.

When comparing HDPE with LDPE:
- The HDPE uses 2.61% more energy.
- The HDPE emits 2.67% more CO2.
- The HDPE uses 26.41% less water.
- The HDPE is 15.97% less expensive.

When comparing PP with HDPE:
- The PP uses 6% less energy.
- The PP emits 5% less CO2.
- The PP uses 37% less water.
- The PP is 14% more expensive

When you compare PP with the LDPE:
- The PP uses 2.68% less energy.
- The PP emits 2.40% less CO2.
- The PP uses 49.64% less water.
- The PP is 0.59% less expensive.

The simple matrix (Table 5) shows the impact levels of the analyzed materials.

Table 5. Manufacturing and environmental impact on thermoplastic materials for AutoBioGen

<table>
<thead>
<tr>
<th>ROTATION MOLDING</th>
<th>Product production and disposal</th>
<th>Product creation</th>
<th>Extraction of the material to be used in the product</th>
<th>Cost of the material used in the product</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENVIRONMENTAL IMPACTS</td>
<td>Amount of energy (MJ)</td>
<td>Amount of CO2 (kg)</td>
<td>Water amount (l)</td>
<td>Cost (USD)</td>
</tr>
<tr>
<td>HDPE</td>
<td>Red</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>LDPE</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>PP</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

Obtaining the cost manually the process is very laborious, because you must find a distributor of the polymer in specific HDPE, and then calculate the total cost of the piece to produce, which takes an approximate time of two days, while designing the piece and using the Eco Materials Adviser takes a few minutes.

The piece designed in the Autodesk Inventor 2018 is useful to observe the aesthetics and shape of the piece, as well as, to meet a good part of the mechanical requirements that the piece would have in short, in this case it offers the possibility of testing functional and even homologation. In the software Autodesk Inventor 2018 the size and type of the materials that will be used for its design and manufacture were determined.

5. CONCLUSION

The design of an optimal product for the architecture comes from an exhaustive investigation, from the observation, to formulate the problem. You must experiment to test new materials, techniques and compile the knowledge to put it into practice, in order to develop a solution tailored to the architecture where each detail of the product is exactly adapted to the required needs. To be able to do the above, we must work on sustainability, materials, environmental impact of the product to be developed.

The products are an intrinsic part of the architecture, the smallest details from the form, the ergonomic qualities must be related to obtain the best sustainable product design. The following aspects should be considered:
- Functionality.
- Ergonomics.
- Quality of materials and usability.

As in this case, the AutoBioGen, which is an air conditioning system using a biodigester for housing where four people live. The system uses the heat generated in the AutoBioGen, transferring it to a hose inside it, which heats the water that is transported to a thermal base that climatizes the living room of the house. Furthermore, the biogas produced in AutoBioGen is used as fuel for the domestic stove; It also helps to recycle water, as well as to generate organic fertilizer and electrical energy.

Due to the above, AutoBioGen was chosen as the case study because it was designed as a sustainable product, this was achieved through its function as it saves water, reduces atmospheric pollution and transforms clean energy, in addition to its function, in this research analyzed the use of materials for its construction and the impact they have on the environment, made through a methodology that can be used both in design and development of products for architecture.

The analysis and understanding of the use of materials to build a product or architectural spaces is of vital importance nowadays, since, in most cases they can be non-renewable resources and generate a large environmental pollution in their life cycle. This project proposes the methodology to learn how to analyze and choose the least polluting materials.

The best material is the PP according to the data obtained in the Autodesk Inventor 2018 software, given that it has the least environmental impact in comparison with the HDPE and the LDPE.

The environmental impact on the use of HDPE, LDPE and PP is considered in the emission of the carbon footprint as well as the use of water for the production of the AutoBioGen part, but the use of thermoplastics will continue to increase, so that Mexico should implement a program for the proper management of this type of waste, which should include several economic, educational and regulatory strategies. The cost of the virgin raw material is lowest cost than that of the recycled material,
therefore there are few incentives for its reuse. The manufacturing industry must assume the shared responsibility with the consumer and the regulatory entities. An example of the above mentioned is that in Belgium since 2010, when a plastic product contains more than 50% of recycled material, there is a greater reduction of the environmental pollution tax produced by use and handling, this does not happen in Mexico, where new environmental regulations of the Chamber of Deputies of Mexico City restricts the massive use of all types of plastics from June 2019. The recycling of thermoplastics is an effective method to reduce both consumption and its environmental impact [13].

The advantages that can be mentioned when obtaining in a fast way, a three-dimensional simulation of the AutoBioGen prototype, is to avoid the production of expensive prototypes, besides increasing the quality of the developed part, which generates considerable savings of all kinds. The project is proposed from the perspective of sustainable development.

ACKNOWLEDGEMENTS

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REFERENCES


Influence of the Form of the Perforation of the Perforated Block in the Loss by Acoustic Transmission

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ABSTRACT: The openwork blocks known in Brazil as Cobogós are widely used in hot-humid areas including Colombia and around the world to improve natural ventilation and lighting conditions inside buildings. But in turn, allow outside noise to pass through spaces. Evidence of the acoustic behavior of these openwork blocks is lacking in most of the information available on the subject to determine specific uses or improvements in their design. Through a deductive comparative analytical methodology and using a scale reverberation chamber, transmission losses (TL) were analyzed and compared for a 2000 Hz signal from six types of openwork blocks used in Colombia. The results show indications that the size of the perforations of the openwork blocks is the factor that most affects acoustic insulation for a frequency of 2000 Hz.

KEYWORDS: Tropical architecture, Openwork walls, Cobogó, Architectural acoustics, Acoustics attenuation.

1. INTRODUCTION

Throughout the history of architecture, the need to illuminate and ventilate interior spaces led to the development of perforated facade devices used in warm humid regions [2,15]. Openwork walls are one of the most economical methods of solar control, which in turn allow free circulation of ventilation [16] and use of natural light in addition to the recognized aesthetic qualities [6,11].

Derived from the latter, the openwork blocks have generated great interest in the impact on the sustainability of passive design tools in architecture or in situ evaluations of thermal qualities [12] and lighting of the spaces with facades built with openwork blocks.

However, the exploration and development of walls built with openwork blocks do not indicate their behavior on acoustic transmission losses [7], since the direct incidence of noise on the wall involves the implementation of materials and geometries that can reflect sound and redirect sound waves [9].

Some research has proposed the possibility of building openwork blocks with a noise reduction close to 34dB, revealing that the main design factor is the geometry of the block and not the addition of insulating or absorbent elements [3].

Although, it has only been achieved through the introduction of metamaterials, super light, and open structures that can be stacked to make a permeable wall that cancels up to 94% of the noise emanating from a source [10]. Nevertheless, these new metamaterials could prove to be an unfeasible alternative in the context of Colombia’s tropical vernacular architecture.

The absence of parameters for the acoustic design of the openwork blocks justifies, as a preliminary phase, the exploration of the acoustic behavior of some commercial industrial openwork blocks offered in Colombia.

2. METHODOLOGY

Using a deductive comparative analysis approach, six commercial openwork blocks offered by the Colombian industry were evaluated.

For evaluations of acoustic transmission loss (TL), it was used a scale reverberation chamber adjusted to the UNE EN ISO 140-1:1997 [13], a calibrated BK 732 precision sound level meter and a loudspeaker which transmit frequencies of 500 Hz, 1000 Hz and 2000 Hz [14], it allowed evaluating the value in dBA of reduction of the sound pressure in a receptor space separated by a partition in which each type of openwork block was located.

Subsequently, the data were tabulated and analyzed, considering the procedure described by ISO 16283-3: 2016 for the evaluation of acoustic insulation with the in-situ method. However, the volumetric requirements of the room established was not considered since the study is performed under the behavior of an isolated openwork block and not a set of these.

2.1. Types of openwork blocks

Six commercial blocks were selected and identified with a code (Fig. 1).

The openwork blocks C01, C02, and C05 with a single perforation are appreciated, while C03, C04,
and C06 have more than one perforation and are considered complex.

Since it is common to use the openwork blocks in two positions, two types of evaluations were made, on one of their faces (90°) and on one of their edges (45°) and in two orientations concerning the sound source, face front (a), and back face (b).

<table>
<thead>
<tr>
<th>Block</th>
<th>Weight (Kg)</th>
<th>Openings (%)</th>
<th>L1</th>
<th>L2</th>
<th>L3</th>
</tr>
</thead>
<tbody>
<tr>
<td>C01</td>
<td>3.5</td>
<td>50</td>
<td>0.18</td>
<td>0.19</td>
<td>0.19</td>
</tr>
<tr>
<td>C02</td>
<td>6.0</td>
<td>40</td>
<td>0.17</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>C03</td>
<td>4.6</td>
<td>40</td>
<td>0.17</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>C04</td>
<td>3.4</td>
<td>40</td>
<td>0.17</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>C05</td>
<td>5.3</td>
<td>35</td>
<td>0.22</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>C06</td>
<td>5.3</td>
<td>35</td>
<td>0.22</td>
<td>0.20</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Figure 1: Technical sheet of the selected openwork blocks.

2.2. Tools used for measurements

The tools, devices and software used measurements were:
- Scale reverberation chamber adjusted to the UNE EN ISO 140-1: 1997 standard (Fig. 2).
- Calibrated BK PRECISION 732A sound level meter arranged in the geometric center (C) of the acoustic tunnel outlet 20cm from the openwork block.
- Diffuse field speaker (F) to reproduce three signals at 500 Hz, 1000 Hz, and 2000 Hz at 90 dBA.
- Revit modeling software from the Autodesk platform for the two-dimensional graphic analysis of the generated waves selected.

Figure 2: Axonometric with the dimensions of the reverberation chamber: Sound source in F, openwork block in opposite end in H.

2.3. Description of the experiment

The speaker is located at one of the ends of the chamber (F) and at the opposite end the openwork block to be evaluated coupled to a light frame sealed with an elastic material in its mass-air-mass perimeter with an STC of 50 (Fig. 3).

Figure 3: The coupling frame and openwork block at opposite end have the source of the reverberation chamber. The block C03 in a 90° position with the front face (a) was ubicated. The block code for investigation is C03p90a.

Figure 4: Coupling frame and openwork block on the opposite end to the source of the reverberation chamber. The block C03 in 45° position with the front face (a) was ubicicated. The block code for investigation is C03p45a.

To determine if the camera's modes affected the performance of any frequency, the signals emitted by the speaker were at frequencies of 500 Hz, 1000 Hz, and 2000 Hz at 90 dBA [13].

It began with the measurements of the support frames without the openwork blocks to determine the acoustic attenuation on behalf of the camera, considering that the sound level is attenuated as the sound propagates, between the source and the receiver, to along a certain trajectory [8] and the
losses of the support framework that was designed for an STC of 50.

The dBA values of these evaluations without the openwork blocks were called reference, from which the evaluation values with the installed blocks are subtracted and the difference in dBA is obtained for each orientation and frequency studied.

Figure 5: Measurement process of the C02 openwork block in the 90° position. Block code for research is C02p90.

2.4. Treatment of results

The data obtained in the scale reverberation chamber were tabulated to establish relationships between the sets of openwork as a function of the frequency analyzed and the position and orientation in the chamber.

To recognize the performance of each openwork block, they were grouped comparatively according to their position (45° or 90°) and their orientation concerning the source. For openwork blocks with complex geometries (C03, C04, and C06) additional letters were used, (a) for evaluations on the front face and (b) for evaluations on the back face.

3. RESULTS

Table 1 summarizes the measurements taken, expressing the positions and orientations evaluated. These data were averaged and validated with statistical correlation tests, Pearson, and R² linear regression.

The correlations between the mean of all the frequencies and each one of them indicated that for the frequencies of 500 Hz and 1000 Hz they are medium and low, respectively. Behavior caused by the camera’s modes and will not be taken into consideration, while the correlation for the frequency of 2000 Hz is high and positive. For this reason, the subsequent analyzes were only made with that frequency.

3.1. Evaluation by position

in order to know the incidence that could have the way to place the openwork blocks, transmission loss behaviors were evaluated in each case, placed on one of its faces (90°), and on one of its edges (45°).

Table 2: Isolation values in dBA obtained from the subtraction of the reference value and the sound pressure level measured in each openwork block.

<table>
<thead>
<tr>
<th>TESTING PERFORATED BLOCK BY POSITION</th>
<th>90°</th>
<th>DIFFERENCE (dBA)</th>
<th>45°</th>
<th>DIFFERENCE (dBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C01p90a</td>
<td>4.10</td>
<td>C01p45a</td>
<td>0.70</td>
<td></td>
</tr>
<tr>
<td>C02p90a</td>
<td>4.80</td>
<td>C02p45a</td>
<td>-1.50</td>
<td></td>
</tr>
<tr>
<td>C03p90a</td>
<td>5.20</td>
<td>C03p45a</td>
<td>4.40</td>
<td></td>
</tr>
<tr>
<td>C03p90b</td>
<td>6.90</td>
<td>C03p45b</td>
<td>3.70</td>
<td></td>
</tr>
<tr>
<td>C04p90a</td>
<td>5.30</td>
<td>C04p45a</td>
<td>1.60</td>
<td></td>
</tr>
<tr>
<td>C04p90b</td>
<td>4.90</td>
<td>C04p45b</td>
<td>1.10</td>
<td></td>
</tr>
<tr>
<td>C06p90a</td>
<td>5.80</td>
<td>C06p45a</td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>

| MEAN | 5.29 | 1.57 |
| CORRELATION | 0.54 | 0.29 |

The rhombic position of the drafts (45°) compared to the straight position (90°) has a lower soundproofing effect (Table 1), which apparently has to do with the greater length of the opening towards the sides, up and down, and must be analyzed in-depth on another occasion since the correlation data does not allow assuring it because they are very low.

The correlations between the data according to the position do not conclude that this condition affects transmission losses.

4. DISCUSSION

4.1. Evaluations by internal geometry

Since some of the openwork blocks have complex elements in their design (C03, C04, and C06) and others have simple elements (C01, C02, and C05), these were grouped into these two categories to determine how much this characteristic influences the acoustic insulation.
Greater soundproofing efficiency was detected in those openwork blocks that have barriers in their internal composition that deviate the direct path of the sound wave.

The sloping walls inside the openwork block and the decrease in the area as the sound enters, also represents a factor that seems to have an impact on the C03 openwork that presents better performance.

The results indicate that the most complex geometries are related to the increase in transmission losses. In the case of the openwork blocks evaluated, the transmission losses of those with complex geometries is twice that of those with simple geometries.

4.2. Statistical evaluations of attenuation averages vs the perforated area and weight of the openwork blocks.

Table 4: Isolation values in dBA obtained from the subtraction of the reference value and the sound pressure level measured in each complex block according to its mass and perforated area.

<table>
<thead>
<tr>
<th>TYPE</th>
<th>WEIGHT (Kg)</th>
<th>OPENING AREA(%)</th>
<th>DIFFERENCE (dBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C01</td>
<td>3.36</td>
<td>53.00</td>
<td>2.40</td>
</tr>
<tr>
<td>C02</td>
<td>6.02</td>
<td>42.70</td>
<td>1.70</td>
</tr>
<tr>
<td>C03</td>
<td>4.60</td>
<td>31.00</td>
<td>5.10</td>
</tr>
<tr>
<td>C04</td>
<td>3.28</td>
<td>42.50</td>
<td>3.20</td>
</tr>
<tr>
<td>C05</td>
<td>5.30</td>
<td>50.50</td>
<td>0.70</td>
</tr>
<tr>
<td>C06</td>
<td>3.38</td>
<td>54.00</td>
<td>3.40</td>
</tr>
<tr>
<td>MEAN</td>
<td>4.32</td>
<td></td>
<td>2.75</td>
</tr>
</tbody>
</table>

CORRELATION WEIGHT/DIFFERENCE -0.44

R² WEIGHT/DIFFERENCE 0.19

CORRELATION OPENING/DIFFERENCE -0.60

R² OPENING/DIFFERENCE 0.36

Table 4 shows a trend that would indicate that the lower the weight of the openwork block, the greater the soundproofing. (contrary to the theoretical foundations of mass law), but the data are not conclusive because they have other variables included that it has not considered, much less controlled.

The statistical evidence indicates that the opening percentage has a higher incidence by transmission than the weight, behavior that conforms to the theoretical bases. However, in the analyzed blocks, this behavior is not always met, which indicates that in addition to the opening percentage there are other factors involved.

4.3. General Evaluations

Some indications would show that the aperture area of an openwork block does not allow more noise to pass if it is greater, which may be related to the type of geometry of the aperture and the frequency analyzed.

Three clues can corroborate the hypothesis that the geometry of the openwork block perforation is the variable that most affects its ability to acoustically isolate at 2000 Hz.

The first evidence is a greater correlation (0.60) between the acoustic insulation of the blocks and their perforated area, while the correlation on account of weight is only 0.44. It means the size of the perforations has more incidence in the insulation than the mass of the perforations.

On the other hand, it can be seen that when the geometry of the perforations of the complex openwork blocks is changed by modifying their way of position in the camera (90° or 45°), the isolations at 2000 Hz in the first option are 2.5 times greater than when placed at 45°.

Lastly, the overall results show that the blocks with complex perforations and geometries insulate on average 3.99 dBA against 2.03 dBA of the blocks with simple perforations, even with similar perforation areas.

To ratify the results, it must be verified if the protocol used for the measurements in a reverberation chamber at scale is the most appropriate to know the losses due to acoustic transmission in a perforated wall, given that this type of chamber is used to generate a diffuse field that makes vibrate the element to be evaluated, but this vibration is not homogeneous when the wall has a hole.

On the contrary, if the chamber is absorbent (anechoic), the diffuse field would be eliminated and the direct field would be increased, which would be made to coincide with the perforation of the wall, the direct effect on the transmission of sound could be
known due to the shape and position of that hole in the wall.

Although the results indicate transmission losses of up to 6.9 dBA for 2000 Hz shown in the block C03p90 at 90° (Table 2). These values are very low for the acoustic requirements that a perforated wall constructed with these elements may need in certain types of buildings such as educational, which points to the importance of expanding the range of characteristics of these elements to their acoustic performance.

5. CONCLUSIONS

Finding evidence that admits the possibility of controlling the acoustic insulation of a wall with the geometry of its perforations, expands the technical and constructive possibilities of this type of high-use product in hot and humid climates.

The percentages of sound reduction found in the experimentation (in no case greater than 10% of the sound pressure of the source), are very low compared to those obtained by Ghaffarivardavagh [10], close to 90%, which also presents metamaterials and advanced techniques that are possibly not applicable in our local context. Nevertheless, their statements support some aspects discovered in this work and will serve as a guide in the future development of this research, on the use of cheap and low-tech materials as the basis for the development of these openwork blocks.

The theoretical foundations and common sense establish that, the higher the mass, the sounder insulation. However, it was possible to verify that the incidence of the mass in the openwork blocks is relegated to a less important factor, being essential the geometry of the element, the size of the opening and the complexity of the geometry in the perforation that increase the reflected field of incident waves.

This research continues in the search for an easily reproducible process in the context, which also determines acoustic parameters that allow its correct classification considering the performance of these openwork blocks for each spatial situation. In turn, the formal and geometric aspects of these openwork blocks can be transformed in search of the required performance.

6. RECOMMENDATIONS

The question remains whether the results can be extrapolated to those obtained in an absorbent chamber (anechoic), since the latter eliminates the diffuse field and works with the direct field, a characteristic more compatible with acoustic geometric analyzes belonging to wave acoustics.

The methodology will possibly demand adjustments, such as greater precision in future measurement and a greater amount of data to compare and to verify the conclusions established here, in addition to considerations about the properties of the material such as its roughness.

Furthermore, it is necessary to evaluate the behavior of the geometry of the perforations at low-frequency ranges. It has to do with the size and shape limitations of the reverberation chamber.

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REFERENCES


Daylight Performance Comparison of Openwork Walls in the Facades for Interior Spaces

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ABSTRACT: The lighting of interior spaces through the implementation of openwork walls in facades is one of the most widespread passive control strategies in the humid tropics. Despite this, there is little research focused on the individual characterization of this element to determine its lighting qualities. The present research aims to compare the illuminance performance of 6 commercial openwork models, applied to interior spaces in the city of Cali-Colombia (Latitude: 3.42 North, Longitude: 76.5 West). First, the performance of the 6 openwork models in terms of illuminance was compared to determine their effectiveness at different hours (9:00 am and 3:00 pm) and months (June 21, September 21, December 21). The second step was to compare the performance of the 6 openwork blocks throughout the year using UDI (Useful Daylight Illuminance) metric. To achieve this, the Diva for Rhino plugin was used. Thanks to an exhaustive analysis of the data it is possible to evidence the impact of the geometric and morphological configuration of the openings on the specific and general light performance of the openwork walls.

KEYWORDS: Architecture, Bioclimatic, Openwork Wall, Daylight Performance, Daylight Simulations

1. INTRODUCTION

Natural Daylight, both as a physical phenomenon and in its poetic sense, significantly affects the experience or performance of interior spaces users [1]. Architecture, in its role as a mediator between interior and exterior, has the responsibility of providing the right amount of natural light to interior spaces through so-called passive control strategies, such as windows, skylights, or perforated surfaces, according to their lighting requirements [2].

The implementation of perforated surfaces on facades is one of the most widespread passive control strategies in the humid tropics since they allow lighting and ventilation of interior spaces at low cost [3]. The openwork wall is one of the most common variations of perforated surfaces, especially in buildings with traditional construction systems [4]. It can be defined as a vertical enclosure system composed of modular elements called openwork blocks. The openwork block itself is a piece of masonry made of clay or concrete with a series of openings that allow air and natural light to pass through.

The illuminance performance of interior spaces with openwork walls on the facade is an issue that has not been explored enough, and in which it is possible to find research on the performance of perforated surfaces in a general overview, however, there is not enough evidence to determine the illuminance performance of a specific openwork block.

Several authors agree that the implementation of openwork walls in facades represents a thermal control strategy that allows the creation of more comfortable interior spaces for the potential user [5,6]. Additionally, its qualities as an element of architectural composition are exalted, which allows mitigating the negative effects of sunlight in the humid tropics [4].

The present research aims to compare the illuminance performance of 6 commercially available openwork blocks in the Colombian market. These comparisons were made for the city of Cali (Latitude: 3.42 North, Longitude: 76.52 West) which according to the Köppen scale is classified as a city with a tropical climate, with an average annual temperature of 24°C, which is why the use of this type of elements in facades prevails.

2. METHODOLOGY

A deductive comparative analytical methodology was used, based on simulations made with the Diva for Rhino plug-in. 6 Colombian commercial openwork blocks were selected, each of which was used on an entire facade option for a hypothetical evaluation space, and its illuminance performances were compared using static and dynamic metrics in the west and south orientations.

Firstly, the illuminance performance was compared by the time of the year (June, September, and December) and by hours (9:00 am and 3:00 pm) using static simulations. Subsequently, the
performance of the 6 models throughout the year was compared using dynamic simulations with the UDI (Useful Daylight Illuminance) metric. Finally, the data were tabulated, and the corresponding comparative graphs were made.

Due to the proximity of the chosen location with the equator line and the similarity of the lighting conditions between the east-west and north-south orientations, it was decided to omit the data corresponding to the east and north orientations.

2.1. Openwork models

Figure 1 shows the 6 commercial openwork models selected for the research, their dimensions, opening percentage, and the code by which they were identified.

2.2. Experiment description

The experiment was conducted in a hypothetical evaluation space, 3m high, 3m wide, and 3m deep (Fig. 2), on which 6 different facade options were built using the 6 openwork block models selected for the research, using exclusively one model for each facade option. It is important to mention that the experiment was carried out by orienting the respective openwork wall facade options to both the south and the west.

2.3. Simulations

2.3.1. Static simulations

72 static simulations were made in the Diva for Rhino plugin, 36 simulations for south orientation and 36 simulations for west orientation, from which it was possible to determine the admission and distribution of the floor level illuminance in the hypothetical evaluation space, with the different facade options at specific dates and hours.

The following parameters were used: Location: (Cali, Colombia), materials with absorption coefficient number: (GenericInteriorWall_50, ceiling: GenericCeiling_70, Floor: GenericFloor_20), unit: lux, radiance parameters: (-ab5 -ad 1000 -as 20 -ar 300 -aa 0.1), dates: (June 21, September 21, December 21), time: (9:00 am and 3:00 pm).

To verify one of the most unfavorable conditions from the light point of view, a partially cloudy sky with sun was used. The results were processed according to the percentage of the floor area that has illuminance levels between 300-700 lux according to the Colombian technical standard [7], additionally, it covers the required illuminance levels for reading and writing activities in indoor spaces according to the Technical Regulation of Lighting and Public Lighting [8] given by the Colombian government which is from 300 to 750 lux.

2.3.2. Dynamic simulations

Twelve dynamic simulations were made using the Diva for Rhino plugin using UDI (Useful Daylight Illuminance) metric. From there, the annual illuminance performance was obtained in terms of useful illuminance, which is the yearly percentage of occupation hours in which the hypothetical evaluation space will have levels between 300 and 3000 lux.

The simulations were carried out for the previously mentioned orientations under the following parameters: Location: (Cali, Colombia), materials with absorption coefficient number: (GenericInteriorWall_50, ceiling: GenericCeiling_70, floor: GenericFloor_20), unit: lux, radiance parameters: (-ab5 -ad 1000 -as 20 -ar 300 -aa 0.1), occupancy schedule: (SG_8to5noDST.60min.occ.csv).

2.4. Treatment of results

2.4.1. Treatment of static simulation results

The results of the static simulations were compiled and the percentages of the illuminated area in the chosen range (300-700 lux) were tabulated. The results obtained in the south orientation were used to evaluate the illuminance performance by time of the year since this orientation is not exposed to direct solar radiation at a certain time of year due
to the proximity of the chosen location to the Equator line. The results show the monthly illuminance performance of the interior spaces with openwork walls on the facade. These percentages are the result of averaging the data provided by the static simulations of each openwork wall at the previously mentioned hours for each month evaluated at the southern orientation (Table 1).

On the other hand, the simulations carried out in the west orientation were used to evaluate the illuminance performance of the openwork blocks by hours (9:00 am and 3:00 pm), given that this facade does receive direct solar exposure and, therefore, it is possible to evidence changes in the illuminance behavior between one hour and another. These percentages are the result of averaging the data provided by the static simulations of each openwork block of all the months evaluated for the previously mentioned hours in the west orientation (Table 2).

Finally, bar graphs were made to estimate which of the 6 selected openwork blocks obtain higher illuminance performances according to the time of the year or the hour of the day, being this a very relevant data for decision making when implementing openwork blocks in educational or academical architectural projects.

2.4.2. Treatment of dynamic simulation results

The data corresponding to the UDI percentages of the 6 selected openwork blocks in the south and west orientations were collected. Subsequently, data were tabulated, and the corresponding bar charts were made. In this way, the results show the annual illuminance performance of the 6 openwork blocks in the previously mentioned orientations (Table 3).

3. RESULTS

3.1. Comparison of static simulations

Table 1: Specific comparisons by the time of year (south orientation).

<table>
<thead>
<tr>
<th>MODEL</th>
<th>% Illuminated Area from 300 to 700 lux</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>JUNE</td>
</tr>
<tr>
<td>C01</td>
<td>14,8</td>
</tr>
<tr>
<td>C02</td>
<td>0,1</td>
</tr>
<tr>
<td>C03</td>
<td>0,0</td>
</tr>
<tr>
<td>C04</td>
<td>0,1</td>
</tr>
<tr>
<td>C05</td>
<td>13,4</td>
</tr>
<tr>
<td>C06</td>
<td>0,0</td>
</tr>
</tbody>
</table>

Table 1 shows the percentage of the illuminated area in the 300-700 lux range per season for interior spaces with an openwork wall on the facade.

Table 2: specific comparisons by the time of day (west orientation).

<table>
<thead>
<tr>
<th>MODEL</th>
<th>% Illuminated Area from 300 to 700 lux</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9:00 a.m.</td>
</tr>
<tr>
<td>C01</td>
<td>3,5</td>
</tr>
<tr>
<td>C02</td>
<td>0,0</td>
</tr>
<tr>
<td>C03</td>
<td>0,0</td>
</tr>
<tr>
<td>C04</td>
<td>0,0</td>
</tr>
<tr>
<td>C05</td>
<td>2,6</td>
</tr>
<tr>
<td>C06</td>
<td>0,0</td>
</tr>
</tbody>
</table>

Table 2 shows the percentage of the illuminated area in the 300-700 lux range per hour of interior spaces with an openwork wall on the facade.

Figure 3: Bar graph comparing light performance by time of year.

Figure 3 and Figure 4 shows the relationship between the percentage of the illuminated area in the 300-700 lux range (Y-axis) and the month or the hour depending on the case (X-axis).

It is demonstrated that the single opening openwork blocks (C01, C02, and C05) manage to obtain higher performances than those with multiple openings (C03, C04, and C06) shown in Figure 3, in which a clear tendency to the null performance is observed with results equal or smaller than 2.9% of the illuminated area for the selected 300-700 lux range.

The specific case of C01 and C05 models, both with the same opening percentage (50%) and similar morphological configurations, allows to speculate about the incidence that the angle of entry has on the monthly performance of the openwork walls, given that the results of the first one (C01) are in all instances higher than those of the second one (C05), especially in the month of September, where the difference reaches 30.9% (Fig. 3).
Figure 4: Bar graph comparing illuminance performance by time of day.

The comparison by hours shows that the openwork blocks with a single opening (C01, C02, and C05) manage to obtain higher performances than those with multiple openings (between 17% and 54% more).

It is important to mention that the performance of the C01 and C05 models at 3:00 pm is quite disparate (Fig. 4), with a 16.5% difference in favor of the C05 model, despite having the same opening percentage. This information strongly contrasts with what was seen in the results by the time of the year, in this case, the oblique entry angles positively affect the performance of the openwork walls in the afternoon (3:00 pm), taking into account a partially cloudy sky with sun condition.

On the other hand, the C06 model presents null performances both at 9:00 am and at 3:00 pm, positioning itself as the least viable option (Fig. 4). This pattern also repeats in the performance by time of the year (Fig. 3).

3.2. Comparison of dynamic simulations

Table 3: Dynamic comparisons by orientation.

<table>
<thead>
<tr>
<th>ANNUAL LIGHT PERFORMANCE BY ORIENTATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODEL</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>C01</td>
</tr>
<tr>
<td>C02</td>
</tr>
<tr>
<td>C03</td>
</tr>
<tr>
<td>C04</td>
</tr>
<tr>
<td>C05</td>
</tr>
<tr>
<td>C06</td>
</tr>
</tbody>
</table>

Table 3 shows the annual percentage of occupancy hours in the 300 to 3000 lux range for interior spaces with openwork wall on the facade using the UDI (Useful Daylight Illuminance) metric.

The comparison of the annual illuminance performance shows that the single opening openwork blocks (C01, C02, and C05) have quite similar general performances in both orientations, while the multiple opening openwork blocks (C03, C04, and C06) show higher performances in the west, the orientation that receives the solar radiation directly.

It is important to mention that most of the illuminance contribution of these openwork blocks are located in the 100-300 lux range (Fig. 5), which allows to determine that although their performance is not optimal for spaces dedicated to reading and writing activities, they can be used in spaces with lower illuminance requirements such as corridors, rooms for automatic processes and occasional workspaces exposed in the Technical Regulation of Lighting and Public Lighting RETILAP [8].

4. DISCUSSION

The first reflection that arises from the study has to do with the used methodology, although it is true that dynamic simulations allow to observe the general performance of interior spaces with openwork walls on the facade since they cover a much wider time spectrum they do not allow to differentiate other determining characteristics of this element, such as performance by hours or by the time of the year (factors that influence performance by up to 38%), which are indispensable for a complete understanding of the phenomenon, especially for locations quite close to the equator line, where orientation significantly affects the illuminance performance of indoor spaces with differences of up to 26% between one orientation and another. Therefore, it is possible to state that subsequent studies carried out along the same line of work should implement static simulations and make an exhaustive analysis of them.
The second section of the discussion has to do with the effectiveness of openwork walls as a passive control strategy in the humid tropics. For this purpose, an additional analysis was carried out in which the annual performance of openwork walls against 6 windows was compared using the UDI Metrics.

The area of each window was calculated according to the percentage of the opening of each facade option. For example, the C01 model has an opening percentage of 50%, which in the complete facade of the hypothetical evaluation space (3m x 3m x 3m) is equivalent to 4.5m² of perforated area (Fig. 6), a dimension that will be assigned to its corresponding window for the comparative purposes mentioned above.

The study shows that most of the openwork walls do not exceed the performance of their corresponding window (whose values vary between 49.8% and 79.9% in the UDI metric), excepting the C01 and C05 models, which have higher useful illuminance percentages (20.6% and 12.4% more respectively), this is because the illuminance values presented by the above-mentioned windows exceed 3000 lux, the upper limit of useful illuminance. Although, indeed, most of the selected openwork blocks (C02, C03, C04, and C06) have lower percentages of useful illuminance, their capacity to uniformly distribute the illuminance levels of the space should be highlighted, especially for their capacity of minimizing adverse conditions such as glare.

The opposite case can be seen in the windows, which have a clear tendency to generate glare, therefore it is intuited that future research on the same subject should address the problem, not only from the intention of determining the light output of the openwork blocks but also from their ability to generate shade and avoid glare.

Table 4: Correlation between opening percentage and UDI for single and multiple opening openwork.

<table>
<thead>
<tr>
<th>MODEL</th>
<th>% Opening</th>
<th>WEST</th>
<th>SOUTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>C01</td>
<td>0.50</td>
<td>0.82</td>
<td>0.86</td>
</tr>
<tr>
<td>C02</td>
<td>0.43</td>
<td>0.40</td>
<td>0.39</td>
</tr>
<tr>
<td>C05</td>
<td>0.50</td>
<td>0.75</td>
<td>0.76</td>
</tr>
<tr>
<td>Multi-opening openwork wall</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MODEL</td>
<td>% Opening</td>
<td>WEST</td>
<td>SOUTH</td>
</tr>
<tr>
<td>C03</td>
<td>0.33</td>
<td>0.34</td>
<td>0.22</td>
</tr>
<tr>
<td>C04</td>
<td>0.54</td>
<td>0.33</td>
<td>0.22</td>
</tr>
<tr>
<td>C06</td>
<td>0.42</td>
<td>0.27</td>
<td>0.01</td>
</tr>
</tbody>
</table>

In order to determine the equivalent relationship between the opening percentage and illuminance performance, it was identified that single-opening openwork blocks (C01, C02, and C05) maintain a higher correlation coefficient between both variables, of 0.981 in west and 0.988 in the south, while those with multiple openings (C03, C04, and C06) present coefficients of 0.27 in the west and 0.114 in the south (Table 4), due to the fact that the partitions and internal geometries limit the entry of natural light.

5. CONCLUSIONS

The analysis of the static simulations in the 300-700 lux range, allowed the identification of important patterns in the behavior of the interior spaces with openwork walls in the facade, such as the scarce incidence that factors like the time of the year or the hour of the day have on the illuminance performance of the multiple openings openwork blocks (C03, C04, and C06) when a partially cloudy sky with sun is considered. On the other hand, the study of the dynamic simulations allowed to identify that the orientation has a remarkable influence on the illuminance performance (UDI) of the openwork with multiple openings (C03, C04, and C06) with differences of up to 96.3% between one orientation and another.

Following the same line, the different comparisons made, allow to speculate on the incidence of the geometric and morphological configuration of the void of the openwork blocks in the specific and general illuminance performance of them, obeying the following patterns:
The openwork blocks with a single perforation (C01, C02, and C05), present higher performance, both in specific and general comparisons, positioning themselves as the most viable alternative for interior spaces with requirements above 300 lux, whose locations are close to the equator line.

In contrast to the previous point, the models with internal geometries of concave or convex character (C04, and C06) are positioned as an ineffective strategy, with specific results (illuminance) lower than 29.2% and general results (UDI) lower than 33%. It is important to mention that they do not present notorious changes before factors like the time of the year, in which the maximum variation between months is 2.6%.

The implementation of oblique planes in the interior, as is the case of the C05 model, is a resource that diminishes the general illuminance performance (UDI) and by the time of the year up to 30%, at the same time that promotes the performance in the afternoon hours (3:00 pm), turning it into a little profitable strategy in general terms, with a certain degree of utility for very precise aspects.

The direct comparison of the C01 and C05 models in both instances (static and dynamic), allows to determine the high impact that the angle of entry has on the specific and general performance of the openwork walls. The results establish that the disposition of oblique surfaces facing the light source is a resource that diminishes the general illuminance performance of the openwork walls (UDI), limiting the entrance between a 7% and a 10% at the same time that it influences negatively in the illuminance performance by time of the year restricting the light entrance up to a 30%. In this manner, it is positioned as a resource of doubtful effectiveness, which should be studied in depth.

Finally, it was evident that the thickness of the openwork blocks can significantly influence the results, as it is estimated that the differences between the C01 and C02 openwork could be due not only to the opening area but also to the additional obstructions generated in the latter due to its greater thickness.

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REFERENCES
GLOBAL SENSITIVITY ANALYSIS OF PASSIVE SOLAR SYSTEMS
A case study in cold equatorial climate conditions

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ABSTRACT: This research aims to define the most important parameters in the design of a passive solar heating system that can be attached to existing buildings, in order to improve the indoor thermal performance conditions of projects located in high mountain climates at tropical latitudes. To determine the relative importance of the different variables that influence the solar heating system, the “Morris’ improved sensitivity analysis” method was used. This study involved 165 dynamic thermal simulations using R and Python coupled with EnergyPlus for building energy simulation with Honeybee plugin for Grasshopper 3D. The simulations were performed on a typical room model, with results based on the adaptive comfort model established by ASHRAE 55. Preliminary conclusions of the research indicate that the most sensitive variables to change for the design of the solar collection systems in low latitude climates are the people’s internal gains, width and height of the solar collection system and roof insulation of the conditioned space. In low latitude climates the orientation variable in a solar heating system is not the most important variable for ensuring indoor temperatures within the hygrothermal comfort range.


1. 1. INTRODUCTION
Construction culture in Colombia is such that the buildings are not climate responsive, which results in poor thermally habitable built spaces. Additionally, communities located in cold high mountain climates at tropical latitudes, do not consider the acquirement of mechanical equipment to improve indoor temperature conditions. The population has become habituated to the discomfort generated by low temperatures. Consequently, heating systems are not used, leading to low comfort conditions for most of the inhabitants.

The development of real estate projects is based solely on the financial gains that can be obtained and seek only the highest profit possible. Thus, orientation and selection of materials, amongst others are not variables to be considered. Projects are built using hollow brick, sheet metal tiles, and single pane glass across the whole country without considering the location, site and climate conditions. Therefore, comfort is considered as a minor problem.

Base on the premises of passive solar architecture, the authors propose creating a greenhouse-type prosthetic device than can be readily assembled onto existing constructions. Improving therefore the indoor comfort conditions. For determining which of the design variables of the device has the greatest impact on indoor thermal comfort for homes located in high mountain climates at tropical latitudes, the “Morris’ improved sensitivity analysis” method was used. This study involved dynamic thermal simulations using R and Python coupled with EnergyPlus for building energy simulation with Honeybee plugin for Grasshopper 3D. A total of 10 design variables were studied, which were: (i), (ii), (iii) greenhouse dimensions along its three axes (x, y, z), (iv) size of the collector wall attached to the existing wall, (v) orientation of the solar collection system, (vi) number of occupants in the place, (vii) greenhouse glazing U-coefficient, (viii) collector wall material, (ix) thickness of collector material, and (x) thickness of thermal insulation on the roof.

A case study was conducted in the city of Bogota, Colombia. Involving the development of a parametric base model room with typical constructions, geometry, and spatial arrangement based on examples in the studied area. The study area was chosen due to its climatic conditions and opportunity to improve hundreds of homes with comfort problems.

2. METHODOLOGY
2.1 Sensitivity Analysis
Sensitivity analysis is a method that helps recognize the most effective optimization strategy applied to a specific context [1]. In this study, a global sensitivity analysis was performed to determine the impact of key design parameters (X) on different outputs (Y). Applying the enhanced Sensitivity Analysis Method of Morris [2] using the “sensitivity” package for R, coupled with custom Python code.
Morris [3] proposed an efficient parameter screening method along with a factorial sampling strategy. Allowing the examination of changes in an output that are unequivocally attributed to changes in individual inputs. It is based on random OPAT (one factor at time) analysis, but the baseline changes in every step. This method requires a total number of simulations of n=r(k+1), with r being the number of iterations of the OAT experiment and k, the number of parameters [3]. This number is very efficient compared to other methods of global sensitivity analysis, enabling its use in the analysis of high-cost computer models such as building dynamic thermal simulations [4].

The “sensitivity” package for R [5] was used to generate the input vector through the factorial sampling method proposed by Morris [3]. After defining the ranges of values for each design parameter (Table 2), a normal probability density function was assigned to each continuous variable. For every design parameter, the discrete number of values (p-levels) has been set as four (p = 4). Randomly selected values on a standard grid with p-values were used to construct the sampled points. The procedure was repeated fifteen times (r = 15) for ten input variables (k = 10). Therefore, the total number of simulations performed was 165.

After running all simulations, the method of Elementary Effects (EE) [3] was used to assess the influence of each design parameter over the output. According to Campolongo [2], the absolute mean and standard deviation of the elementary effects were calculated to assess the results. The absolute mean value (μ*) determines the importance of each design parameter and the standard deviation (s) measures the interactions with other factors and possible non-linear effects. Low values of both indicate therefore a non-influential input, while high values indicate the main variables [4].

Figure 1 shows a general outline of the methodology applied integrating sensitivity analysis programs with parametric tools for energy simulation in buildings.

**Figure 1** General methodology for sensitivity analysis coupling R, Python, Grasshopper and EnergyPlus.

### 2.2 Energy Modelling Tools

To perform the thermal simulations, a custom algorithm was developed on the Grasshopper 3D platform (a complement to the Rhinoceros software) using custom Python code coupled with Honeybee plugin, that allows translation of parametric geometry into OpenStudio format, which in turn allows simulations with the EnergyPlus calculation engine.

Figure 2 illustrates the thermal simulation algorithm on the Grasshopper 3D platform, composed of 5 main groups: (a) Inputs, section where the definition of the geometrical parameters and the thermal properties of the materials of the solar collection device are controlled. This section reads the simulation cases from an external file, wrote in R defining the sampling used for the “Morris sensitivity analysis”; (b) Definition and creation of thermal properties, where it is possible to sort and apply thermal properties to geometry coming from Rhino through the Honeybee plug-in; (c) Export of the IDF files native to EnergyPlus containing all the necessary information to perform the thermal simulations, and then simulated externally; (d) Import and post-processing of the results, where the performance metrics are calculated and visualized in terms of percentage of comfort time, operating temperature, among others; (e) Results, where the performance metrics and images are written to an external file that collects all the analysed variations.

**Figure 2** Thermal analysis algorithm on the Rhino / Grasshopper platform. Lines between components represent the data flow.
2.3 Study location and climate Conditions
The Savannah of Bogotá has nearly constant weather conditions as a result of its low latitude (~4.5°N) and mean temperature of ~13.1 °C given its elevation above sea level (i.e., ~2640 m). Figure 3 shows that the outdoor temperatures in the Savannah stay below comfort conditions most of the time; with lower temperatures during the night and at dawn when houses are normally fully occupied. The average minimum temperature is close to 5°C, although on some nights in the months of December, January and February, where it can drop to values below 0°C.

Figure 3 Annual outdoor temperature for the city of Bogotá, Colombia. Authors. Climate data from NREL [6].

2.4 Building Modelling
For the development of the parametric study a base model room with typical constructions (Table 1), geometry, and spatial arrangement based on examples in the studied area. The thermal model consisted of a box with dimensions 3.0 m x 3.0 m x 2.5 m (width, length and height, respectively), with a single pane window of 1 m². To this main zone, a greenhouse device with variable sizes were attached, as seen in Figure 4. In the simulation, the floor surfaces and two walls of the space are set as adiabatic surfaces in order to simulate a corner room scenario on an upper floor. Thermal losses attributed to infiltration through interior doors or windows were not considered.

Figure 4 Typical 3D room model. In this case, including an attached greenhouse with dimensions 2.0 m x 2.0 m which projects 0.5 m with respect to the plane of the facade. These measurements will vary during the simulation process. The collector wall is shown in red.

Table 1 Physical properties of the building envelope. Materials that consider some variation in some of their physical properties are indicated with var.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness [mm]</th>
<th>Thermal Conductivity [W/m·K]</th>
<th>Density [kg/m³]</th>
<th>Specific Heat [J/kg °C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>200</td>
<td>0.600</td>
<td>1000</td>
<td>800</td>
</tr>
<tr>
<td>Walls</td>
<td>120</td>
<td>0.320</td>
<td>770</td>
<td>1000</td>
</tr>
<tr>
<td>Roof Insulation</td>
<td>var</td>
<td>0.032</td>
<td>30</td>
<td>837</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness [mm]</th>
<th>U Value [W/m²K]</th>
<th>SHGC [k]</th>
<th>Visual Transmittance [vT]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window Glass</td>
<td>4</td>
<td>5.8</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Green House Glass</td>
<td>var</td>
<td>var</td>
<td>0.9</td>
<td>0.9</td>
</tr>
</tbody>
</table>

2.4.1 Gains and Schedules
Based on the purpose of this work, only the internal loads due to occupancy were considered. Therefore, discarding any variation coming from the use of diverse types of lights and equipment inside the space. The loads per person were defined in terms of persons per area, considering two cases, single room (1 person) and shared room (2 people). The weekly occupancy schedules were generated based on the ASHRAE 90.1 (Table G-I) schedules for apartments occupancy.

2.4.2 Input Variables (X)
In previous studies, the optimal design parameters of a passive solar heating system were defined for a specific case study using computational optimization algorithms [7]. For this research, the authors use the same variables seeking to find the relative influence of each one of them in the thermal performance of the passive solar collection systems in the study area. Table 1 shows the input variables defined for the analysis including: (i,ii,iii) size of the greenhouse in its three axes, understanding that it is fundamental to know the behaviour of different formal configurations, in length, width and height of the solar collector element; (iv) size of the collector wall attached to the existing wall, since defining the size of this material will allow us to evaluate if it is necessary to add additional thermal storage wall or if the system would work without it, reducing the system’s cost; (v) orientation of the solar collection system, to determine the importance of whether or not the device needs direct solar radiation or it can be used with diffuse radiation; (vi) number of occupants, since at night this is one of the largest sources of heat available in the room; (vii) U-coefficient of the glass used for the greenhouse, to determine if it is necessary to further reduce greenhouse’s thermal loss at night, or if simple float glazing could work just as well, reducing costs in the
proposed system; (viii) collector wall material, in which three materials were evaluated to determine which would be the most efficient in high mountain equatorial climate conditions; (ix) collector wall material thickness, which, combined with the size of the accumulator wall, will allow us to define the need for additional thermal accumulation wall; and finally, (x) thickness of thermal insulation on the roof, with the goal of determining the magnitude of thermal loss caused by this element. We propose insulation just on the roof since it is the element that generates the greatest thermal loss at night. In order to acknowledge the budget variable, we do not consider thermal insulation on the exterior walls, since we are trying to avoid increasing significantly the cost required to condition the space.

Table 2 Building design parameters studied in the sensitivity analysis.

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Unit</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>X axis Green House</td>
<td>%</td>
<td>0 to 95</td>
</tr>
<tr>
<td>Y axis Green House</td>
<td>%</td>
<td>0 to 95</td>
</tr>
<tr>
<td>Z axis Green House</td>
<td>%</td>
<td>0 to 95</td>
</tr>
<tr>
<td>Collector wall size</td>
<td>%</td>
<td>0 to 95</td>
</tr>
<tr>
<td>Orientation</td>
<td></td>
<td>0 to 345</td>
</tr>
<tr>
<td>Number of people</td>
<td>People</td>
<td>0 to 2</td>
</tr>
<tr>
<td>U coefficient of the glass</td>
<td>U&lt;sub&gt;t&lt;/sub&gt;</td>
<td>2.8 to 5.6</td>
</tr>
<tr>
<td>Collector wall material</td>
<td></td>
<td>Water, solid brick, concrete</td>
</tr>
<tr>
<td>Collector wall thickness</td>
<td>mm</td>
<td>100 to 3000</td>
</tr>
<tr>
<td>Thickness roof thermal insulation</td>
<td>mm</td>
<td>0 to 50</td>
</tr>
</tbody>
</table>

The size variations of both greenhouse and collector wall are analysed in a percentage ratio in order to generate a representative study for spaces of various dimensions and, furthermore, to avoid generating errors in the simulation. The latter is because if these variables are not related to the wall to which the greenhouse is attached, then larger greenhouses than its base wall or accumulation walls larger than greenhouse could be created, leading to modelling errors in the simulation.

2.4.3 Measured Outputs (Y)

The outputs of interest for the sensitivity analysis, listed in Table 3, include percentage of time in the comfort zone, and operative temperature (minimum, maximum and average) between night hours (6:00 pm to 8:00 am). To assess the thermal comfort inside the space, the adaptive comfort ranges recommended by ASHRAE 55 of 2017 were used. In the study area, depending on the season the range were between 19.6°C and 24.6°C.

Table 3 Measured output for sensitivity analysis.

<table>
<thead>
<tr>
<th>Outputs(Y)</th>
<th>Abbreviation</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of night hours within the comfort zone</td>
<td>PTC</td>
<td>[%]</td>
</tr>
<tr>
<td>Average Night Operative Temperature</td>
<td>AvgOT</td>
<td>[°C]</td>
</tr>
<tr>
<td>Minimum Night Operative Temperature</td>
<td>MinOT</td>
<td>[°C]</td>
</tr>
<tr>
<td>Maximum Night Operative Temperature</td>
<td>MaxOT</td>
<td>[°C]</td>
</tr>
</tbody>
</table>

3. Results and discussion

Table 4 shows the parameters ranked based on their values of absolute elementary effects (µ*), the top four highly-sensitive parameters identified using Morris method are, in descending order: (a) Number of people in the place, (b) length of the greenhouse, (c) thermal insulation of the roof, (d) height of the greenhouse. These four parameters are therefore the basic variables to consider in the design of a passive solar heating device for homes located in high mountain climates at tropical latitudes.

Table 4 Ranking orders of design parameters based on Morris Sensitivity Analysis. The parameters in bold and italic are identified as the highly sensitive parameters.

<table>
<thead>
<tr>
<th>Input Variable</th>
<th>PTC</th>
<th>AvgOT</th>
<th>MinOT</th>
<th>MaxOT</th>
<th>Average Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>N° People</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>1.8</td>
</tr>
<tr>
<td>X axis GH</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2.3</td>
</tr>
<tr>
<td>Roof insulation</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>3.3</td>
</tr>
<tr>
<td>Z axis GH</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>4.0</td>
</tr>
<tr>
<td>Orientation</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>1</td>
<td>4.3</td>
</tr>
<tr>
<td>Collector wall size</td>
<td>6</td>
<td>7</td>
<td>5</td>
<td>5</td>
<td>5.8</td>
</tr>
<tr>
<td>U coefficient GH</td>
<td>7</td>
<td>6</td>
<td>7</td>
<td>7</td>
<td>6.8</td>
</tr>
<tr>
<td>Y axis GH</td>
<td>8</td>
<td>8</td>
<td>10</td>
<td>9</td>
<td>8.8</td>
</tr>
<tr>
<td>Collector Thickness</td>
<td>10</td>
<td>9</td>
<td>9</td>
<td>8</td>
<td>9.0</td>
</tr>
<tr>
<td>Collector Material</td>
<td>9</td>
<td>10</td>
<td>8</td>
<td>10</td>
<td>9.3</td>
</tr>
</tbody>
</table>

The difference in ranking position of the solar heating device’s height (z axis) in relation to its width (x axis), can be due to the fact that both parameters were evaluated separately in a percentage ratio (Table 2) relative to the wall’s differing height and width dimensions meaning that the same percentage in both variables are different dimensions in the analysed device.

Figure 5 shows the resulting percentage of night hours in comfort, were the variable with the greatest variation are the people internal gains, with an average variation of 30% and a standard deviation of 6%. This may be due to the size of the simulated space, since a small volume means the interior temperature is more sensitive to change by internal gains generated by occupation.
temperature. The number of people is still the most important variable, with an impact of 2.6°C with a standard deviation of 0.2°C. In this case, the main ranking change is in the thermal insulation of the ceiling, rising to a second place of relative importance with an impact of 1.9°C on the minimum temperature, with a standard deviation of 0.6°C. This might be because reducing thermal losses mitigates the low temperatures on peak hours on night hours.

Figure 7 Sensitivity analysis results by Morris method in relation to minimum operative temperature during the night. Black line shows standard deviation D.

For this metric the orientation has a slight loss of importance, this can be due to the latitude the place of analysis. Since the project is located in the city of Bogota, all four façades receive high levels of radiation, which vary their intensity in relation to the different months of the year, but always with levels higher than 1.4 kWh/m²-day (Figure 8), for which the minimum temperature is not affected as much, since the solar heating device always has solar contributions.

Figure 8 Total daily solar radiation by facade in the city of Bogota. Liu-Jordan’s method, GEOSOL software. Remark: The east and west radiation lines overlap.
Figure 8 shows the relative influence of each variable in relation to the maximum internal temperature of the space under analysis. In this case, the orientation is the most important variable, with an impact of 2.2°C with a standard deviation of 1°C.

This might be because with a given orientation it is possible to receive much more radiation by increasing the temperature progressively until the maximum possible temperature is reached. This is confirmed by the radiation levels received by the south facade in December, reaching 5 kWh/m²-day, more than 3 times the radiation levels received by the north facade in the same period, or 38% more than what is received on average by the east and west facades. These increases in incident solar radiation can generate peaks in the maximum temperature of the space.

![Figure 9 Sensitivity analysis results by Morris method in relation to maximum operative temperature during the night. Black line shows standard deviation.](image)

4. CONCLUSION

It is important to mention that in the process of designing a passive solar heating system, the objective is not to have the maximum temperature possible, but to take advantage of solar energy to maintain indoor temperature levels close to the comfort zone. An efficient design would have the highest minimum temperature possible and the lowest maximum temperature while maintaining the temperatures between comfort range, decreasing the temperature difference and retaining the heat inside the space.

According to the results of the sensitivity analysis, we conclude that for climate conditions in Bogota and its surroundings, the variables with a relative effect greater than 10% of the percentage of comfort during night time when designing greenhouse prosthetic devices are, in descending order: (a) number of occupants, (b) height and (c) width of the greenhouse and (d) presence of roof thermal insulation. Also, due to the high sensitivity to change from internal gains, the design of the solar device for shared rooms will be different than for single rooms.

In addition, it’s feasible to conclude that a Trombe wall works better than a greenhouse as a solar system for this area, as evidenced by the lesser importance of the greenhouse depth variable. Moreover, it is also possible to achieve comfort conditions during the night in this space regardless of orientation, which is favourable for the scope of this work considering that homes already built in the study area have different orientations.

5. ACKNOWLEDGEMENTS

This contribution shows preliminary results of the project “Sistemas de captación solar en las tipologías de viviendas en clima ecuatorial frío”, developed for the masters program in Architecture and Sustainable Habitat at the Universidad Nacional de La Plata, Argentina, between 2017 and 2020.

6. REFERENCES

Influence of Gaze Direction and Time on the Glare Assessment: A Case Study in an Office Space

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ABSTRACT: Recent studies in visual comfort have embraced the users’ dynamic nature, pointing out new parameters and measurement methods to minimize the existent gap in the understanding of the visual experience. This research aims to test the influence of visualization time and gaze direction on the glare probability assessment of dynamic users in a work environment. Data collection was performed in an experimental environment, where volunteers were monitored while performing pre-defined office tasks. The gaze movements were recorded with an Eye-Tracker device. Through High Dynamic Range images (HDR), luminance from surfaces were mapped and the glare probability index (DGP) was calculated for each scene. Finally, the DGP index for each visual field was examined under a temporal approach. It was found that when performing a task, the user keeps his/her eyes fixed on the work plan regardless of the luminance from the surfaces. When asking for a break or when talking on the phone, users tended to have their gaze more dispersed, varying the visualized areas. From the results, it was possible to conclude that the time spent by the users looking at a specific direction was the variable that most influenced the results, being directly connected to the task executed.

KEYWORDS: Visual Comfort, Glare, Eye-Tracker, User Satisfaction

1. INTRODUCTION
Visual discomfort is usually related to the inability of the visual system in adapting to lighting dynamism – usual under daylight conditions - and the brightness of the visual scene, generating user’s behavioral responses [1] that are difficult to be determined. To propose models that incorporate the caused visual sensations on the glare assessments, some researchers have been investigating the responses of the visual system to lighting [2–8]. Hamendani et al. [7] identified larger differences in the physiological responses when increasing the visual discomfort levels.

Besides physiological responses, glare assessment involves subjective aspects relating to users’ dynamism, a characteristic sometimes neglected by considering the users as static in the space [9], which is contrary to reality. Recent studies have incorporated users’ dynamism, understood as the body and head movements, approximating us to the visual experience that they might have [10–16]. Through the adaptive zone model, the prediction of glare discomfort was perceived as more accurate, according to [10]. On the other hand, when considering shifts in the view direction the differences in glare assessments were significant [13–15], while the time with the gaze in one direction could be another factor for improving the visual sensation [16].

The content of the view, visual contact with the exterior, and the visual task are also parameters that affect the visual comfort assessment [17]. The interest in visual content is another aspect that can mitigate the effect of glare on visual sensation [18,19]. Sarey Khanie et al. [15] found users looking through the window during the tasks’ brakes.

Due to the diverse and multiple variables that might be taken into account in visual comfort studies, the techniques used for data collection are also diverse [20–22]. Field studies on visual comfort are a valuable source of information since the users’ behavior cannot be obtained through computer simulation. This research aims to test the influence of the visualization time and gaze direction on the daylight glare probability of users in a work environment.

2. METHOD
Data collection was conducted through field studies in an office space located in Florianópolis, Southern Brazil (Latitude: 27°S; Longitude 48°W) throughout the summer season of 2017. The methods used in the survey campaign involved measuring eye movement (eye-tracking); luminance mapping (HDR images) and questionnaires to assess the subjective glare sensation.

The participants, 26 volunteers with an average age of 27 years, were in four different spots within the analyzed space (P01, P02, P03, P04). Thus, from each position, the window occupied different portions in the visual field (Figure 1). The studied environment had two windows: W01 with 2.20m² (w=1.12 m; h= 1.98 m) and W02 with 5.93m² (w= 2.30 m; h= 2.58 m). The blinds
remained partially open as this was the typical condition of use, according to the regular users of the space. The four light fixtures, each with two T8 lamps, were turned on after 17h. The general features of the environment are shown in Figure 1.

![Image of environment features](image)

**Figure 1- Participants’ location and environment features.**

### 2.1 Eye-tracking

The participants’ gaze movements were recorded during a sequence of typical office activities, previously defined and divided into three phases (Table 1). Fixations and saccades were recorded using the SensoMotoric Eye-Tracker glasses and the software iView ETG 2.6. Data analysis was performed using the software Be Gaze 3.6 based on the focal points and the time spent by the participants looking to certain surface. A picture of the visual field for each participant was taken and used to overlap with the gaze movements. In the same image were marked off the surfaces involved in the visual tasks, walls, ceiling, and windows (Figure 2a). A second image was created, delimiting in its three-view directions: left, central, and right (Figure 2b).

![Image of view directions](image)

**Figure 2- a) Surfaces of interest and b) View directions**

### 2.2 Luminance mapping and DGP

The luminance from the surfaces in the visual field was mapped, considering the three-viewing directions, by using HDR photography. Each view direction was defined from the central direction by an angle of 60° to each side. For each view direction, eight low dynamic range images (LDRi) were taken using a Canon_EOS60D equipped with an EX Sigma-Circular Fisheye 4.5mm1-2.8 lens. Table 2 presents the camera settings used. Before (initial values) and after (final values) each sequence of LDRi was measured the luminance from a reference surface (a gray sheet of paper) and the vertical illuminance on the camera lens.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Setting</th>
<th>Feature</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Balance</td>
<td>Natural light</td>
<td>Image Size</td>
<td>3456 x 2304 pixels</td>
</tr>
<tr>
<td>Focus</td>
<td>Automatic</td>
<td>Sensitivity</td>
<td>ISO100</td>
</tr>
<tr>
<td>f-stop</td>
<td>f/11</td>
<td>Lenses</td>
<td>Fisheye</td>
</tr>
<tr>
<td>Shutter Speed</td>
<td>Variable</td>
<td>Format</td>
<td>RAW and JPG</td>
</tr>
</tbody>
</table>

The average luminance from the reference surface was calculated based on the initial and final values measured. This value was used to calibrate the HDR image and luminance map, calculated in the software Aftab Alpha v.2.1 [23]. The DGP index for each visual field was calculated using the same software.

### 2.3 Effect of time on glare assessment

For each participant, the DGP index for each visual field was examined under a temporal approach [16]. Aiming to incorporate the vision’s natural dynamism, the DGP values were weighted by the time spent by the participant in each view direction (Equation 1). Thus, the new DGP value would be representative of the participant’s position (DGPw).
\[ DGP_w = (DGP_{vdL} \times %t_{vdL}) + (DGP_{vdC} \times %t_{vdC}) + (DGP_{vdR} \times %t_{vdR}) \] (1)

Where: 
- \( DGP_{vdL} \) - DGP for "Left" view direction; 
- \( DGP_{vdC} \) - DGP for "Central" view direction; 
- \( DGP_{vdR} \) - DGP for "Right" view direction; 
- \( %t_{vdL} \) - time percentage looking at the "Left"; 
- \( %t_{vdC} \) - time percentage looking at the "Central"; 
- \( %t_{vdR} \) - time percentage looking at the "Right".

2.4 Glare subjective assessments

The questionnaire used in this study was based on [24,25]. The participants needed to assess the glare perception during the tasks as imperceptible, perceptible, disturbing, or intolerable, and were asked about the satisfaction with the visual environment, by answering the level of agreement for each statement below, as Strongly disagree; Disagree; Nor agree or disagree; Agree; Strongly agree:

- I am satisfied with the visual appearance of the office;
- I am satisfied with the walls and windows brightness;
- I am satisfied with the amount of light for computer work;
- I am satisfied with the amount of light for reading/writing on paper;
- The computer screen is legible and does not have reflections;
- The light is well distributed.

3. RESULTS

Analyses between the study variables were performed to verify the association with participants’ behaviour. Gaze mapping data, luminance in participants’ visual field, and subjective assessment were evaluated according to participants’ positions in the environment, and dominant vision directions. Three participants were excluded from some analysis due to problems related to data archiving. Except for P02, all positions had at least six participants.

3.1 Surfaces of visual interest and luminous characteristics

For each participant, the Eye-tracker glasses recording activities lasted approximately 14 minutes. The participants’ fixations on the task’s surfaces showed that the monitor, paper, and keyboard were the most viewed surfaces. However, those participants located in P01 frequently looked through the windows. Participants located at P02 had the most limited visual field due to their proximity to the wall. This fact made their interaction with the window to be the lowest ones (0.6%).

As expected, the areas of the visual fields with the highest luminance values were the windows and regions around them. Peak luminance values from ceiling and walls were around 850 cd/m². Areas distant from the windows had luminance around 400 cd/m² while the luminance from the common task surfaces was between 50 and 150 cd/m² (Figure 3).

3.2 DGP

The measured DGP values varied between "Imperceptible" (89.58%), "Perceptible" (6.25%) and "Disturbing" (4.16%), with no "Intolerable" situation.
recorded. As expected, the view direction affected the participants’ DGP values \(H(3) = 21.41; p< 0.001\) (Figure 5a). When the participants were looking to the left, the glare sensation was higher than in the other two view directions \(\text{DGP}_{\text{avg}} = 0.24\), corresponding to an "imperceptible" sensation. In this view direction, from the four positions of the participants, at least one of the windows was viewed.

Although the variations in the DGP were small between the participants’ positions (Figure 5b), these differences were statistically significant \(H(3) = 82.28; p< 0.001\). Statistically significant, negative and weak differences were identified between position P01 and P02 \((U= 1456; p < 0.001; r=-0.37)\), P01 and P03 \((U= 1344; p < 0.001; r=-0.32)\), and P02 and P04 \((U= 1536; p < 0.001; r=-0.35)\). Between positions P03 and P04 \((U= 1088; p < 0.001; r=-0.42)\), and P01 and P04 \((U= 304; p < 0.001; r=-0.76)\) the effect size was moderated.

3.3 Impact of visualization time on DGP

For the three directions of view of each participant, the DGP index was weighted \(\text{DGP}_w\) by the visualization time through Equation (1). Despite little variation in DGP values between participants’ locations, were identified differences statistically significant \(p<0.05\).

In the "Right" and "Left" view directions, the differences between the values were higher due to the lower time spent by participants in these directions. Because the visualization time was higher for the "Central" direction, the differences between \(\text{DGP}_w\) and \(\text{DGP}_{\text{vdC}}\) were smaller. For all the participants, the calculated values indicated that, if considered the time in the glare evaluation, the reductions on the glare index would lead to imperceptible glare (up to 0.3), as presented in Figure 6.

![Figure 5 - DGP differences per: a) View direction and b) Position. The sensation produced by the DGP was plotted by color: gray ("Imperceptible"), green ("Perceptible"), and orange ("Disturbing").](image)

3.4 Subjective environmental assessments

After finishing the tasks, the participants’ sensation of glare was evaluated through the questionnaire. During most of the tasks, the sensation of glare was considered "imperceptible" (80.43% of the votes). Only 18.48% of the votes indicated "Perceptible" brightness during the activities, and only 1.01% of the votes indicated a "Disturbing" brightness when "reading on the monitor" (this was reported by the participants in position P01). It was found that the activity performed had a significant but weak effect on the brightness perception \(\chi^2 (3)=29.93; p< 0.001; \text{Cramer’s V}= 0.33\).

The votes of the level of satisfaction with the visual environment, surveyed through six affirmations, are presented in Figure 7. Except for the affirmation "The light is well distributed", with 36% of the participants in disagreement, most votes revealed users’ satisfaction with the visual environment. Regarding the satisfaction with the visual appearance, 48% of the participants agreed with the statement. The participants in positions P01 and P02 presented the majority votes in disagreement with the statements. None of the participants pointed "Strongly disagree" in his/her answers.
3.5 Differences between DGP and the subjective glare assessments

When analyzing the differences in the DGP values in the three categories of subjective assessment performed by the participants, no significant differences were found between the means of the groups [H(2)= 5.81; p = 0.06]. When the measured DGP indicated that the glare sensation would be "Imperceptible", 72.46% of the participants also considered the brightness "Imperceptible". However, when DGP indicated a sensation of "Disturbing" brightness, the participants evaluated the sensation as "Imperceptible" (3.62%) and "Perceptible" (0.72%), with no relation between the variables [χ² (4) = 7.69; p= 0.09].

Differences statistically significant were identified between the degree of satisfaction and the DGP scene value [H(3)= 12.62; p = 0.006]. The visual appearance had greater participants acceptance when the DGP values were higher (DGPaverage= 0.22; DGPMdn= 0.23 for "I agree" and DGPaverage = 0.21; DGPMdn= 0.22 for "I totally agree") (Figure 8).

4. CONCLUSION

Although the visual process is dynamic, the results found could help in the development of behavioral patterns, regarding the office’s visual environment. Several factors may influence the decision to permanently maintain the vision in each direction, such as the activity, the interest in the visual content and the access to external environment, attitudes that may be conscious and unconscious by the user. With the data collected in a work environment, we investigated the influence of the visualization time and gaze direction on the daylight glare probability reduction.

From the results, we conclude that the participants’ location within the environment was more relevant than view direction since the performed task defined the view directions while the space location defined the user relationship with the windows. We confirmed that during the breaks between tasks, talking at the phone, as well as during thinking processes, the participants looked through the windows. These findings agreed with the findings of a previous study [15]. Despite the high luminance from the windows, the visual search for these elements could support the hypothesis of higher luminance thresholds when the user is interested in the visual content [18,19]. However, in this study, the participants avoid looking through the window when it was necessary a greater movement of the body or head.

The time spent looking at a specific direction was the quantity that most influenced the results, being directly connected to the type of task executed. In this paper, the results found for the weighted DGP indicated a reduction of up to 100% in the static DGP. The subjective data, obtained through the application of questionnaires, were closer to the weighted DGP by the time of visualization in each direction, emphasizing the importance of including the user’s dynamism in studies of visual comfort.

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ABSTRACT: In light of the rising energy consumption awareness in the Architecture, Engineering and Construction (AEC) industry and the built environment, retrofitting design offers benefits towards achieving higher sustainability and performance standards. Building retrofitting opens up opportunities for the AEC industry to modify existing infrastructure towards more efficient solutions regarding energy performance. Technological advancements in building performance, design and data management provide a promising potential in promoting our objectives for energy efficiency, by allowing for the integration and analysis of sophisticated data structures and more seamless collaboration between different stakeholders. However, despite the abundance of tools and available data, professional practice is in search of an integrated approach to maximize the benefits of the available technologies at hand and improve decision-making processes. This paper analyses the literature related to the level of ‘real-world’ data integration, representation and exchange methods, and how these define user comprehension in the context of energy retrofitting. Finally, it proposes a framework for integrating existing building envelope data to a Linked Building Data (LBD) model, taking advantage of methods for structuring building data as Resource Description Framework (RDF) graphs and linking them into a semantic BIM model.

KEYWORDS: Building Retrofitting, Building Information Modelling (BIM), Energy Performance, Data Management, Semantic Web

1. INTRODUCTION
The built environment embodies large amounts of data, and our current tools aim for maximizing our capacity to collect, analyze and understand these data, with the aspiration to improve the efficiency and performance of our designs. The purpose of using sophisticated tools is to create readings of the buildings we could not have produced otherwise and to structure the relationship between all members of the Architecture, Engineering and Construction (AEC) industry. As awareness around building energy consumption increases, architects are encouraged to increase their consideration of the energy performance aspects regarding the built environment and to find ways to improve its efficiency. As a large portion of the built environment is made up of existing infrastructure, overhauling that infrastructure would significantly improve the quality of the performance of the spaces we inhabit. Building retrofits introduce new possibilities, as the benefit of modifying existing resources is a projected median energy savings of up to 16%, corresponding to a $30 billion in cost savings by 2030 [1], [2]. In light of technological improvements in design, coordination and building performance analysis tools, there is a greater potential for communication between team members towards efficient building modifications [3]. Despite the abundance of tools and available data, professional practice is still in search of an integrated approach to improve collaboration between involved parties and produce efficient architectures. The building retrofitting sector can significantly contribute in the upgrade of the built environment from an environmental performance perspective, however there have been limited attempts to make use of the available technologies that promote data integration and management in favour of enriching the information repository and our understanding of existing building artifacts. Moreover, Building Information Modelling (BIM) is an established platform designed to facilitate data integration under one digital environment, however its implementation for existing building retrofitting is more limited than anticipated. This paper investigates opportunities to expand the AEC industry comprehension of the existing built environment. It presents a comprehensive literature review on the use of data in BIM and building performance analytics, followed by the development of a retrofitting design framework based on such data analytics integration.

2. RESEARCH METHOD
The paper is structured around three main arguments concerning ‘real world’ data integration, representation and exchange methods, and how these define user comprehension and predilections in the context of existing, building energy retrofitting. The first segment discusses the relationship between users
and tools and how limitations or general inclination of certain tools influence the ways users interpret buildings artifacts and conduct analyses to retrieve meaningful patterns of information about them. This investigation is focused on how successfully the diverse nature of the built environment is projected on the tools that we have at our disposal. The second segment examines the ontologies of these tools to understand to what extent can the normative ontologies of the most popular tools be extended to represent more diverse, heterogeneous data types that are congruent with the real conditions. Lastly, the narrative concludes with a review of the progressive developments of interoperability methods between different pieces of software. More specifically, the review focuses on technical applications of data exchange, also known as interoperability, between BIM and Building Performance Simulation (BPS) software. Interoperability is a popular research avenue, which is largely invested in by the professional and academic communities due to the inability of BIM software to perform certain tasks, such as performance analytics, within its program environment; therefore, the task execution had to be re-projected in another environment. The paper discusses the nature of the challenges encountered by current applications and the potential of alternative approaches to the representation and exchange of information.

3. UNDERSTANDING DATA AND THEIR ONTOLOGIES

The amount and diversification of data is a distinct characteristic of the built environment [4]. Each participating discipline composes an interpretation of the building, and thus contributes to a project. For instance, an engineer’s interpretation of a building can be via systems and infrastructure, a designer’s interpretation could be via geometry, program and space. As the process of developing a project infers the combination of these diverse interpretations, it is important to establish a common ground for efficient communication and organization of information.

3.1 BIM workflow for energy retrofitting

BIM provided the aspiration of combining all the diverse information under a single model and thus, gradually became more popular in the AEC industry, as people are able to re-use the same information to perform different tasks [4]. There has been a notable increase of BIM applications in building retrofits [3]. The design process for building retrofits is organized in design stages, similar to new building design. In the majority of times teams engage in a conventional design workflow, where individual processes are segregated and have a linear consecutive structure [5]. The design workflow that is commonly used in practice involves rigorous design options exploration during concept stage [5]. Moreover, performance related simulations and energy modelling are carried out after the design has been significantly progressed, thus the design is driven by parameters, which are disassociated from energy performance [5]. Based on the literature review, building performance analytics are not sufficiently integrated in the design process, as they are not introduced and employed from the elementary stages of the design. There are several precedent investigations that explore novel pathways in exploring BIM and its association with building performance [6], as well as BIM applications for energy retrofit of existing buildings. The integration of performance assessment and simulation in BIM applications is a growing trend, however there is inadequate comprehension of the ways to describe all relevant information about a building, including the complete context of its artifacts [7].

3.2 BIM workflow constraints for energy retrofitting

Although BIM did provide a good basis for information convergence and seamless exchange between processes, the collaboration and data exchange in the AEC industry is still relying on document exchange through sequential, distinct processes. This is conflicting with the idea of a BIM workflow that promotes information management, as opposed to drawings and static models [8]. A more recent critique on BIM suggests that it primarily promoted the exchange of geometry information, where other types of semantics where less enhanced by this tool [9]. As a result, processes that have more to do with calculations and building analytics are still not as easy to communicate in the context of BIM. This confines users to the ontologies that are able to be represented within a tool, while there could be numerous other methods of representations along different data vectors. The limitations of tools are reflected in the workflows that have become popular in practice, since users are able to communicate and work with information that is available to them. AEC practice is confronted with various challenges related to the lack of a design platform that can represent other data types, such as thermal, material, deterioration etc. together with geometry, systems and other semantic information, such as cost and time [10]. In order to describe, manage and analyse an existing building successfully, it is necessary to comprehend what types of data are required and what is the best way to organize them [11]. The lack of a common database and a reliable method of accurately representing existing building data is exposing the need for specialists and the breaking down among proprietary software, each specialized in specific datasets [12]. A workflow for energy efficient projects would require the implementation of specialized knowledge at each design phase, so that the output design is evaluated at every stage and the impact of
design decisions on the project’s energy performance are understood by the team [13]. This process under realistic conditions usually involves dilemmas, which can be overcome with sufficient knowledge and information exchange among the professional parties at every design phase. BPS processes can be time consuming, as they often require manual data preparation and manual data exchange between other platforms. This lack of automation causes a lack of consistency in the preparation of the simulation, due to subjective data inputs. Due to the above, the integration of building performance analytics is usually not synchronized with the design process, therefore, does not sufficiently impact decision-making [14]. Moreover, the impact of energy performance criteria can be better understood if the energy simulations are integrated early in the design process, where the possibility of reducing poor performance outcomes increases, while the cost of implementing these processes remains low [15]. In this way, performance analytics tools shift from operation as a monitoring device to an actual design tool.

4. REAL WORLD DATA INTEGRATION

Building retrofitting practices require front loaded data integration processes to take place before any design operation is performed. This mainly refers to the documentation of the project and the combination of disparate datasets under a common repository. Although there has been significant development on the data collection methods in terms of ensuring accuracy and granularity of information, this information comprises of large data sets, diverse semantics and heterogeneous characteristics of the building artifacts.

4.1 Methodologies for data integration

The first data types that were successfully incorporated into BIM platforms are geometric information and material properties, within the existing ontology of the software. This process involves geometry translation and recognition of each object based on the captured data. Each building component is translated and categorized as a BIM compatible object and it contains all the semantic information the program is able to represent [16]. A concept that describes the wealth and liability of information of a BIM model is the Level of Detail (LoD), which defines the level of geometric and non-geometric information [17]. Before the collected data is processed and organized, the LoD is defined according to the specifications and prerequisites of the project [18]. There has been significant research on the translation of building data from Non-Destructive Testing (NDT) methods for existing buildings, with popular practices involving 3D scanning and photogrammetry. [19]. The collected data from these methods are usually in a 3D point cloud form; therefore they need to be converted to geometric forms and eventually BIM elements [20]. The first step is the registration and alignment of the point cloud across a common coordinate system [21]. Subsequently, the data is cleaned of irrelevant information, based on the pre-defined LoD of the project according to Oliver and Huber, the processed data can be differentiated into the following categories [22]: 1) Feature, 2) Shape, 3) Material-based and 4) Statistical matching methods. Advanced research approaches as to how to categorize and structure building data, in order to improve the LoD and minimize uncertainty, relate to object identification methods, which are enabled by computer vision techniques [18]. According to Volk et al., computer vision tends to be more successful for components with geometry, with accuracy levels as compared to manual surveying of the geometry rise up to 93% [18].

4.2 Major limitations in data integration

Moving on to identifying the major hindrances on the technical aspects of energy retrofitting in a BIM environment, we will list out the challenges in the data organization and exchange in relation to BIM platforms. Although there are existing methods in place, they are proven to be time and cost inefficient and they rely on simplification of data sets due to inability of representing certain data types and formats [20]. The major challenges are found in areas of data classification and structuring, which affect the ability of a user to search and re-use these data. A key difference between new building design and building retrofitting is associated with the data types and the level of information granularity required for a retrofit project, combined with the fact that this could differ significantly among different retrofit projects. For instance, for a project, the aim might be to gather data about the material of a wall, and in another, one could go deeper in the dataset and might require the exact chemical composition of that wall. This deviation in the amount and types of information cannot be integrated in pre-defined data dictionaries. Therefore, the data requirements cannot be fully specified from the beginning of the project and the same database structure might not be suitable for all projects and thus, must be recreated for every project respectively. Another difficulty is found within the data itself, as ‘real world’ data collected for retrofit projects are unstructured, usually involve large datasets and can contain a lot of ‘noise’. Furthermore, they could be incomplete or contain overlapping information. This situation is worsened by the heterogeneity of the data resulting from aging building systems, as building deterioration occurs locally, and it is difficult to be described in current software ontologies. For instance,
a brick wall is represented by a surface of a specific material, but another reading could be done based on the deterioration state of each of its individual elements. Combining all datasets under a common semantic network that represents the elements and the relations among them, is one of the most important challenges [23]. The lack of linked data methods creates barriers and uncertainty in the overall procedure, which results in necessary simplifications, in order for the process to move forward. The loss of information due to the representation limitation is probably more consequential in comparison to distorted or overlapped datasets. Other secondary issues occur in geometry translation, where there are several inconsistencies in the process of transferring geometry information into BIM. They are related to room outlines, thermal zoning and errors in the translation of non-planar elements (duplication or removal of elements) [24]. Regarding material properties, although the collected data contain rich information on material properties of the building, these data cannot be translated in their entirety [25]. Less prevalent challenges are the inconsistent quality assessments of BIM models, poorly defined LoD, lack of compatibility between older versions of BIM models and missing element characteristics. Finally, there is a lack of legal and financial analysis regarding the benefits of BIM in retrofitting projects [20], as most regulatory frameworks for BIM differ across nations and are limited to new rather than existing buildings.

5. INTEROPERABILITY

Before getting into the specific artifacts of tools and processes regarding data exchange methods and their effectiveness, it is useful to identify fundamental characteristics of approaches that facilitate user interaction with pieces of software. According to Negendahl, there are three types of models for data integration; central, combined and distributed [26]. The central approach requires a data schema that operates in between software and the information is exchanged via that schema. The combined approach suggests that all processes are performed within a common software environment (i.e. design and analytics). The distributed approach suggests that middleware software connects all necessary tools, which require interpretation of the data that are being exchanged [27]. BIM tools mainly belong in the first category, as some of the analytics processes, such building performance simulations do not take place within the same platform, with the exception of the proprietary software Insight 360, which is an example of the combined approach. Autodesk Insight 360 is an energy, daylight simulation software launched in 2015 as a progression of Green Building Studio [28]. Insight 360 converts BIM models to Building Energy Models (BEM) within the BIM environment, however some parameters are rather simplified and more suitable for early design stages, as the constraints that existed for Green Building Studio are still present. Insight 360 is insufficient for code compliance or LEED certification and it depends on the BIM model quality. The improvement that Insight 360 provided is found in the user experience, as operations occur in the same environment instead of data manual export and import between different environments.

Interoperability is the process of information exchange between one computer system to another. For this to be successful the data to be exchanged need to be able to be represented in the same way by the two pieces of software. For instance, the software would have to be able to represent the same data ontology within its system with another software. The main objective for developing data schemas that can be communicated between various software was the integration of building performance analytics, such as energy consumption, material properties, daylight, occupancy etc. The increase in popularity of BIM implementation contributed to a rigorous development of data schemas in the last twenty years, with the objective of enhancing interdisciplinary coordination [29]. There have been several attempts to associate BIM tools with building performance simulation software. The most commonly used BPS tools that are compatible with BIM data exchange formats are eQUEST, DesignBuilder, OpenStudio, IES-VE and Energy Plus [30], [31]. The motivation for connecting BPS processes with BIM is the fact that a BIM model already contains a significant amount of data that can be used as inputs, which could prevent manual re-creation of the input information for BPS [5]. The review on interoperability methods aims to outline data exchange processes between BPS and BIM by describing methodologies from the early 2000s until present. These methodologies are mainly instances of the central approach described above.

5.1 Central approach data schemas and methods

The most popular, widely used methods for data exchange between BIM and BPS tools are the Industry Foundation Class (IFC) Schema, Green Building XML (gbXML) and Green Building Studio. In this section we will briefly describe the main characteristics of each.

The International Association for Interoperability (IAI) introduced the IFC, which is a semi-automated energy performance simulation schema [5]. According to [32], the IFC file contains a considerable number of information (653 entities) stored in the BIM model, however it requires manual export of data. gbXML was introduced by Autodesk Green Building Studio and is an addition to the Extensible Mark-up Language (XML) format. The gbXML format allows for the exchange of text data via the Green Building Studio web service.
It only accepts rectangular geometry as an input, which limits the options for buildings with irregular geometry [25]. gbXML requires manual export and import of information among the project disciplines [32]. Green Building Studio is an energy analysis cloud-based platform developed by Autodesk, for energy simulation during conceptual stages of the design. Autodesk has developed user interfaces (Sefaira) that connect BIM (Revit) to Green Building Studio. The data are exchanged via the gbXML schema described above and the process forms a single-zone BPS model that contains the extracted information [32]. This method cannot incorporate fine grain information, therefore it is simplified and most times inaccurate [34]. The above schemas and methods have similar limitations, such as constraints in data types, geometry types and manual data preparation. This means that the process of exchanging data is not fully synchronized with the design process; therefore, the quality of coordination depends on the due diligence of the various teams.

5.2 Semantic web

An alternative method deriving from Information Technology (IT) sector, is the use of semantic web technologies that could capture the multifaceted assemblage of information about an existing building. Semantic web technologies operate in the form of graphs, rather than conventional relational databases (table structure) (Fig. 1). Graphs have significant benefits for data that contain many relationships. In a conventional database representing relationships between large data sets would require the joining of large tables and quantities of information, which would be computationally heavy. Graphs are useful structures for modelling objects and their interactions [35]. By implementing an approach based on Resource Description Framework (RDF) graphs, one could represent all building information and link it together. This would increase the flexibility required to assess the building’s environmental performance. The method proposed by Pauwels et. al. is structuring building data as RDF graphs and linking them into a semantic BIM model [11]. This would significantly improve accessing information based on multiple vectors and produce multiple ‘readings’ of the building. It would also enhance the conduct of the overall assessment of the project, suggesting a more intuitive information sharing method [36]. Since graphs are not human legible, there is a need for a user interface that operates as a middleware software between tools [37]. Semantic web methods for the AEC industry are still in early development stages and they have mainly been used for documentation of building heritage, but their employment for environmental performance analytics is still limited compared to the research invested in the developing data schemas for interoperability, which was serves as a data exchange method for performance analytics purposes, as discussed above.

5.3 Major interoperability challenges

The function of interoperability became a necessity, as BIM did not embody every process within its system, hence, processes had to be broken down and be distributed amongst different software. Bi-directional approaches would solve interoperability problems, but they are not generic and are user dependent, as information related to building performance has to be extracted from BIM and entered manually in a BPS software. This process is considered very time consuming, costly and labor intensive, because this information exists in digital models, but cannot be exchanged in an efficient way [5]. For example, in one platform a building can be described as an envelope system with interior spaces, or as multiple stories stacked together, or as a volume, or as an assembly of multiple components related with each other in various ways, but another platform might not be able to represent some of these ontologies. BIM and BPS interoperability faces various technical challenges and it is not at the moment fully resolved and, as a result, it affects both the design and decision-making processes in research and practice. According to [5], although users implement complex data schemas (IFC, gbXML), the methodology is not reliable without manual manipulation of the data. The main reason behind the challenges of interoperability lies on the fact that the level of information of both platforms is respectively incongruent. A BIM model contains a lot more information required for a BPS model. Sibenik et al. claim that this translation causes uncertainties regarding the datasets [38], while [39] concluded on the fact that although BIM data extraction is advantageous in terms of time efficiency,
it does not so far provide one-to-one relationship with the data required for BPS. [40] and [41] agree that disparate data and a lack of common standards lead to the above-mentioned challenges in both new and retrofitting building projects. We can categorize the challenges, based on the types of processes they affect, such as workflow and decision-making challenges, technical challenges and interoperability challenges [42]. There are limited real-world examples in which BIM applications are used in a form that can be replicated, as well as lack of in depth knowledge on the ways these applications should be used for building performance applications [5]. The technical challenges concerning data preparation are in relation to time and error occurrence likelihood [43]. The data interoperability schemas that relate to the data exchange process do not represent the data wealth that is obtained after the collection, as they can represent geometry, material ID and simplified thermal zoning, which are not error free (missing objects, duplicated surfaces, mismatched boundaries etc.). Moreover, only simplified geometry can be translated [25]. [44] added that there is also lack of standards in professional practice regarding adequate documentation of successful green BIM projects.

6. FRAMEWORK

The semantic context of a piece of software limits the data it is capable of using and representing. The assumptions that are made in the creation of its operational ontology create real limits on a system. Incompatibilities in system ontologies are what necessitates the need for specialized methods of re-projecting between systems; creating a reduction in content. A significant reduction in content will lead to restrictions in the plane of expression. It is not possible to know a priori what elements are present and what are not, especially in the case of retrofitting where conditions are wholly unknown. It is not possible to create a singular schema that can represent the whole of everything. Each element is in itself incomplete and requires the ability to link its representation, on the plane of data, to the knowledge set necessary to describe it. This is an additive, modular process, layering knowledge on knowledge in an effort to represent it as best as possible, rather than a subtractive one in which data are removed for the convenience of a normative schematic representation.

Taking advantage of the efforts of linked data in the IT sector, it would be possible to fill in the missing data and expand the information model of the building. Thus, we are proposing a framework for integrating existing building envelope data that includes the following processes from data collection to a Linked Building Data model (LBD) and information sharing, which contains the following modules (Fig. 2):

1. Non-integrated Data: All collected data including clustered RGB and IR images showing thermal anomalies, building component types and materials. Other data may include 3D point clouds, necessary for geometry, climate and location.
2. Data Matching: Is the construction of a graph of the building envelope and the mapping of localized thermal anomalies and artifacts to a 3D model of the envelope containing BIM families with properties as per the collected data (i.e. material type etc.)
3. Data Processing and Routing: The processing of data into matrices for analysis and routing them into an LBD Interpreter, an RDF graph-based software that describes all collected data. In parallel, a BIM model is created containing the types of information that can be represented in the current program ontology.
4. Data Integration and Analysis: A semantic BIM representation that operates as the database that contains all information and their relationships in a common repository. The final part of the framework is

Figure 2: Proposed BIM-BEM in Retrofitting Design Framework
an iterative process of data exchange between other software for analysis and feedback of information back to the semantic model. There is a need for a data serializer to convert data to appropriate formats. This process involves decision-making and is complete once the project has achieved all set milestones.

The proposed framework demonstrates an aspiration of structuring building data as RDF graphs and linking them into a semantic BIM model. This would significantly improve accessing information based on multiple vectors and produce multiple ‘readings’ of the building. This will also enhance the conduct of environmental assessment of the project, suggesting a more intuitive information visualization and sharing method.

7. CONCLUSION

Architects, engineers and stakeholders require a more integrated framework to obtain the right level of comprehension from ‘real world’ building data consolidated into a semantic BIM model and thus; enhance their decision-making progress towards more performative and competent results. This would provide a deeper understanding of the relations between elements in the built environment, their condition and performance. Based on the presented narrative, the development of middleware software that serves as a data interpreter would allow users to have at their disposal a wide variety of data to visualize and perform analytics, such as energy performance. In order to overcome the segregation and loss of information observed in current workflows, we need to shift our thinking towards a linked data approach, where the different types of data come together under the same platform. This would aid in the effective data flow and management between ‘real world’s data and building design platforms, as well as, the latter and environmental analysis tools. Promising benefits of efficient resource management strategies will motivate future research to overcome uncertainties of building documentation and data manipulation prevalent in existing buildings [18].

The deployment of a survey to investigate in more detail current user traits and workflows in practice, would reveal useful information that could inspire future research to address user needs in a relevant way. Finally, as there is a lack of well-developed standards for energy retrofitting, a review of the current policies would further inform the research presented above. The concluding argument that emerges is that data integration in building retrofitting is critical, in order to identify efficient resource management methodologies and further the research to overcome challenges in representing and comprehending the complexity of the built environment.

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performance-based building design during early stages. *Advanced Engineering Informatics.*


Window Design and the Design of Air Flow
Simulation Studies Revealing How Windows Form Air Movement

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This study examines window designs and the design of airflow through the movements of sliding and rotational elements of the windows. Nine different window types are parametrically modelled and paired with a computer fluid dynamics simulation of the airflow velocity and airflow patterns. Both of these aspects being important parts in determining and creating thermal sensations in buildings. Each window design is studied at ten different opening percentages and then assessed through a comparative analysis, registering maximum, minimum and averages velocities, and the specific abilities to steer airflow as an instrumental technique in thermal design. The studies find that the Vertical Pivot window performs best considering air velocity generation and air flow steering, thereby enabling designers to utilise air as a thermal design parameter in a higher degree than the other window types included in the study.

KEYWORDS: Window Design, Airflow, Computer Fluid Dynamics, Adaptive Envelopes, Thermal Sensation

1. INTRODUCTION

Windows are a significant part of building envelopes, both in terms of envelope area and envelope expression, and designed with primary focus to allow sunlight into indoor spaces. The ability to open a window, which is the case in most residential buildings and in many institutional buildings, enable furthermore air to travel from outside to inside and vice versa. Recent reports underline that indoor air is more polluting than outdoor air, due to human, inventory and equipment pollution (1,2). Controlling the airflow between indoor and outdoor, through the building envelope is thus an important performance parameter of the envelope design.

This study examines the air flow patterns and spatial phenomena created by the dynamic movement of window partitions, focused on nine specific window types. These types are chosen, as they represent the vast majority of window designs commercially available and thus have the most significant implementation in the designed built environment. The window types include the Single Hung, Double Hung, Awning Transom, Hopper Transom, Single Casement, Double Casement, Gilder, Vertical Pivot and Horizontal Pivot.

Previous studies of window design related to air flow phenomena are focused on single-sided ventilation conditions (3) and simple openings (4–6) for the understanding of flow conditions, air exchange rate and impact on thermal comfort.

This experimental simulation-based study explores a variation of different window types by identifying, catalogue, model, simulate and compare how the nine window designs and their movable partitions can generate, guide and define air flow phenomena as a basis for future environmental design in architecture and how they perform when they are extensively analyzed for their capacities to create environmental sensations. The paper presents the experimental computational studies, the methods used, the behavioural performance of all the tested designs/positions and the air flow results for both utilitarian and sensorial capacities in future building envelopes.

Figure 1. Vertical Pivot window design, which both opens and steers the airflow.
2. METHODS

Airflow in and around buildings, and in complex urban conditions are affected by a complex mix of building geometries, spatial inventory, contextual elements and urban microclimates (7). However, to allow an isolated understanding of various window designs, and how they form air flow in relation to opening positions, Computer Fluid Dynamics (CFD) simulations are conducted in a series of systematic iterations through a parameterized design model, which is directly paired with a CFD analysis, and then compared for their relative performances across window types and opening degrees.

2.1 Simulation Studies

The nine window designs, including the sliding and rotation movements of partitions are modelled at one end of a space measuring 4x8x3 meters, fig.2, and coupled with a high resolution CFD simulation procedure, fig.3, where each window and ten partition positions are simulated with dynamic meshing to accommodate the changing geometric arrangement of window parts as they move. The coupled computational design and simulation model is based on the Rhino/Grasshopper/Ladybug/Butterfly framework, utilising the OpenFoam kernel for CFD processing. Opposite of the window including moving elements, in the simulation space, is an outlet opening inserted, with the same dimensions as the inlet opening where the window is placed. This enables cross ventilation of the space based on the specific window and composition of movable parts. The external airflow, inducing the internal airflow, is maintained with an orthogonal direction to the building façade with 5 m/s velocity. A complete voxel-grid is analysed, and shown with 4 simulations planes, including one horizontal plane and three vertical cross-sectional planes, combined illustrating the resultant flow behaviour, fig. 3 and 13-20.

2.2 Comparative Analysis Studies

Each simulation run maps data that is then analysed for describing numerically the average air velocity, max/min velocities and auto-generate simulation meshes, which in reveal flow regions and spatial air flow zoning/boundaries, that cannot be identified by avg./max/min values. Values are then mapped and graphed, fig. 4-12, to compare the different window performances in generating, and controlling air flow velocities that can be utilized in environmental design strategies.

3. RESULTS

The results from the studies are presented in two series of figures, focusing firstly on the quantitative data of maximum, minimum and average velocities generated by each design across its opening degrees. The second series of figures look at the simulation planes, focused on the flow patterns that are generated by the specific window.
3.1 Flow Velocities

Each window is simulated for resultant internal velocities as a function of opening percentage related to the specific mechanism, sliding or rotational movement, of the window design. This means that a window, dependent of design, can be fully open, with a percentage of 50%. The reason for this somewhat counter logic condition, is that a double hung window slides its elements in a way where 50% movement is equal to 50% open, whereas a single casement window is 100% open after 50% rotational movement. This is clearly visible in figures showing the velocity patterns below.

Figure 4. Air velocity values for a Single Hung design.
Figure 5. Air velocity values for an Awning Transom design.
Figure 6. Air velocity values for a Hopper Transom design.
Figure 7. Air velocity values for a Single Casement design.
Figure 8. Air velocity values for a Double Casement design.
Figure 9. Air velocity values for a Double Hung design.

From the above 5 studies, it is the Hopper Transom design, which presents the highest velocities, and the most stable values across the openings, particularly when focusing on the average velocities of the internal space.
In contrast are both the centre pivoting designs peaking above 3 m/s, with the Vertical Pivot showing a max of 3.5 m/s, well above the Hopper Transom peak at 2.8 m/s. The average values of the Vertical Pivot are equally the highest in this study, with 0.8 m/s from 20-30% open and again from 60-70% opening. This shows that the non-parallel window element, rotated approximately 20% of the wind direction, increases the flow velocity in the internal space, both in terms of max and averages values.

3.2 Flow Patterns

The flow regimes of the window and successive opening percentages are shown below, illustrating the ability for a window to steer air movement and velocities. The objective here is to understand the

![Double Sliding window design and flow patterns.](image)

The vertical movement in plane with the building façade allows little ability to steer the airflow through element geometry guidance. Flow patterns are created by the simple opening, allowing air to flow in through the top, and bottom, creating a stream condition in the centre of the space directly towards the outlet placed in the opposing wall.
The Hopper Transom, fig. 14, and Awning Transom, fig. 15, create airflows, which largely perform in similarity to the Double Sliding design, guiding the streamline directly to the opposing outlet wall. While rotating across the vertical axis, these patterns are also recognised in both the Single Casement, fig. 16, and Double Casement, fig. 17. The two differences should be noted, the airflow is stronger in both the casement designs, because the awning designs only utilise half the window area for opening, and, the Single Casement enables the steering of airflow, particularly at the lower opening degrees, in a higher manner than the Double Casement. The ability to steer the airflow in a higher degree enables an instrumentality for the occupant (and designer) to utilise this as part of creating thermal sensations within the space. This capacity is even more outspoken in both the centre vertical pivot designs, but with the Vertical Pivot window, fig. 19, allowing the highest degree of airflow control as a function of its opening percentage and thereby its plane orientation in relation to the outside airflow.
Figure 18. Gliding window design and flow patterns.

Figure 19. Vertical Pivot window design and flow patterns.

Figure 20. Horizontal Pivot window design and flow patterns.

4. CONCLUSION
The study gives insights into how windows, when modelled with dynamic movable partitions, can generate, form and guide air flow patterns, which has a direct impact on thermal sensations and spatial definitions based on environmental forces. In this way, results can be used directly to design and programme building envelopes to create specific air flow-based phenomena, both in terms of utility (ventilation strategies) and sensory experiences (thermal tactile strategies). Three specific conclusions are here outlined:

1. Windows, across all types, have a high impact on internal air flow velocity, directivity and zoning.
2. Large variations of velocities are detected across windows types, with some windows enabling a five-fold local velocity condition, suggesting that both window design and its partition composition can be strategically used for passive and active environmental strategies in future envelopes.
3. The Vertical Pivot design has the highest performance for both max./avg. velocities and capacity to steer airflow.

REFERENCES
A Building Simplification Method for UBEM
Reduce computation time for simulations on residential buildings in Israel

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ABSTRACT: The growing proportion of the building stock in cities and their total energy consumption in developed countries are increasing the attention on Urban Building Energy Modeling (UBEM) over the last two decades. This is due to the need of predicting the effects of changes in the national structure stock on the electricity sector. To speed up UBEM long time-consuming simulations, previous works investigated simplified building descriptions. However, they lack on generalization or did not have proper reference to compare their performance with. This paper presents a new approach to simplify models of existing residential buildings in Israel in order to reduce computation time of simulated electricity consumption with minimal drawbacks in accuracy. Five types of simplification that can be applied to any residential building were investigated and compared to detailed reference descriptions using a self-developed tool. The emphasis was put on the automation and consistency among the different types. Tests on virtual buildings, varying geometrical characteristics, and on a case study were conducted. A maximum of 4% error in yearly electricity consumption with a speed up factor up to 10 was obtained.

KEYWORDS: UBEM, simplification modelling, residential building

1. INTRODUCTION
Urban Building Energy Modeling (UBEM) has been receiving increasing attention over the last two decades thanks to the growing proportion of buildings (residential, public and commercial buildings) in the total energy consumption in developed countries [1]. Developing an energy simulation model for a very large inventory of buildings, existing or new, requires a balance between accuracy levels and modeling speed, which is essential for predicting the effects of changes in the national structure stock on the electricity sector as a whole [2].

This paper presents a new approach to simplify detailed building models so as to reduce computation time of simulated electricity consumption with minimal drawbacks in accuracy. This approach is firstly implemented on existing residential buildings types in Israel. Hence, the reliability of the simplification techniques was tested using a large range of combinations of characteristics on virtual buildings. Five simplified building descriptions types were investigated (Fig.1).

Such simplifications would enable UBEM to run on standard computers within an acceptable computation time. Assessments on virtual buildings show that simplification type 4 obtains the best compromise between speed and accuracy. Type 6 is three times faster but with errors twice as high, it might be viable for certain studies. However, type 6 shows better performances than type 4 on real cases tested.

2. BACKGROUND
Urban scale energy modelling research range from statistical analysis of consumption data to predict the behaviour of buildings to strongly coupled thermal and airflow simulations [3]. The former requires available data in order to be applied while the later are defined by physical models that need information about the geometry, materials and many other buildings properties.

Modelling the shape of the buildings become an issue in UBEM. For individual studies, detailed models of just a few buildings is feasible, but it is a time-consuming process. However, it is not time effective as there can be a very large quantity of them. Buildings must be generated automatically using data. Footprints of buildings are generally used for
that purpose. If available data has this level of detail, buildings are modelled as extruded polygons. However, lack of information is the most crucial issue faced while doing simulation at urban scale. Data files that contain information about neighborhood to cities exist, such as GIS’s, which enables to generate interactive maps with multiple layers of data. However, in general, those files miss essential information to model the building as it would be needed for BEM purposes. Usually they only contain the footprint, the number of floors and the age of the building. In order to deal with that missing information, typologies of buildings are implemented [4, 5, 6]. Each building is assigned to one of the predefined typologies. All the buildings assigned to the same type will be assumed to have the same set of parameters, such as materials and occupancy schedules. The assignments are based on known information of buildings. For instance, all buildings that were built in a certain period will be gathered under the same category. However, creating many of them trying to match with accuracy the real characteristics of studied buildings needs to be done carefully as it can lead to gross assumptions, while real characteristics remain unknown, nevertheless.

Typologies assign the same characteristics to all their buildings, except for the few information already available such as heights and footprints. To deal with this limitation, some researchers are trying to introduce variability in the characteristics of buildings in the same typology: they implement a stochastic approach of buildings’ parameters. This variability can be introduced in schedules, loads or even construction thermophysical properties [7]. Those stochastic approaches do not model buildings individual closer to the real ones but improve the accuracy of the global simulation if they are done properly, introducing existing variability among buildings. However, most of time they need long calibrations and require a lot of data to introduce variability and stochastic aspects [8].

Researchers have already worked on simplified models used to speed up simulations while preserving accuracy in UBEM [9, 10]. Some use standard or automatic subdivisions of floors which splits floors into thermal zones efficiently [11, 12]. Some work on the impact of the description of building on calculation duration and accuracy [12, 13, 14]. Various simplification techniques are implemented, such as Floor Zones, Mono Zone, building using Auto Zoning and prototypes simplifying the shape of the footprints. Other works also focus on the use of Zone Multiplier [12] and even subdividing buildings into representative volumes, shoeboxes [15]. Those techniques lack proper reference layout [13, 16] or they did not test the simplifications on enough building geometries [13, 14]. As a result of these limited approaches, they lack the required generality to adapt to various building types or reliable reference building layout to validate properly the obtained results.

3. METHODOLOGY

A tool that can generate and simulate the electricity consumption of buildings, applying on them simplified descriptions, was developed. Initial validation was first conducted on virtual buildings in order to calibrate the tool. It enables to simulate various configurations easily, varying characteristics such as the number of floors, the orientation or the size of the buildings. Later on, the tool was tested on actual cases.

The tool (Fig. 2) is programmed in python and embedded in the Ladybug Tools plugin for the Grasshopper environment on Rhino software, as an interface to generate and simulate models using the EnergyPlus engine [17, 18].

The criteria used to test the simplified building descriptions is the relative error, compared to the reference description, on the total yearly electricity consumption. For simulations at the urban scale, a yearly comparison is enough. However, for certain studies, such as on picks of power used, a smaller temporal scale would be required. Those smaller scales are not considered in this paper.

3.1 Simplified building description

The reference layout (Fig. 1 (1)) represents the actual building, where each apartment is modeled by one thermal zone, as defined in the Israeli Standard 5282 [19, 20]. In order to reduce computation time, thermal zones of the reference case were merged in different stages. The first step of simplification (2) merges apartments by pairs. Simplification (3) merges all the apartments together by floor while the cores remains unchanged. Simplification (4) merges all the core in one zone in the center of the building. Simplification (5) merges the apartments and core of each floor to get one zone per floor. Finally, simplification (6) merges all the zones to get one thermal zone for the entire building.
3.2 Consistency among simplifications

Keeping consistency between the simplified models was part of the tool development. The eliminated walls and ceilings are turned into non-geometrical defined thermal mass, compensating, in this way, for the thermal inertia of the thermal zones. The loads are adapted among simplifications so that they are equal for all building descriptions.

Building descriptions (5) and (6), in addition to the eliminated walls and floors, also merge apartments and cores into conditioned thermal zones. Consistency among descriptions of the simplified models keeps between them the same loads, however, it leads to greater volumes to heat and cool. The volumes of the thermal zones could be artificially modified to fit the real conditioned volumes, but it was not done in this study. Fitting the real conditioned volumes artificially would not ensure better behavior anyway as the inertia of the core would not be captured. Having these conditioned volumes differences is considered as part of the simplification process for building description (5) and (6).

3.3 Automation of the Tool

Building geometry can be either modeled from scratch or imported from GIS. It will be coupled with self-defined typology files. Typology files provide further information about buildings such as materials, window ratios, number of floors, loads and schedules. They can also contain the floor layouts that can be applied automatically to the GIS footprints (Fig. 3). 3D models of buildings with embedded properties can then be generated for each simplification. The tool then generates all models and simulates their electricity consumptions automatically and in parallel.

4. TESTS ON VIRTUAL BUILDINGS

4.1 Generate virtual buildings

A reference case was defined as an elongated, "Train", building type with a typical floor layout (Fig. 1 (1)). All pairs of apartments share a core. The viability of the simplifications was checked, varying multiple geometric characteristics of this reference, in order to identify the best compromise between speed and accuracy. This virtual case tested each combination of the varied parameters, for a total of 1152 virtual buildings (Table 1) for each building description. These virtual buildings were simulated for all the building descriptions, for a total of 6912.

Table 1: Parameters simulated for virtual study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
<th>N values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of floors</td>
<td>2, 3, 4, 5, 6, 7</td>
<td>6</td>
</tr>
<tr>
<td>Orientations</td>
<td>East, South, West, North</td>
<td>4</td>
</tr>
<tr>
<td>N° of Apts/floor</td>
<td>2, 4, 6, 8</td>
<td>4</td>
</tr>
<tr>
<td>Bldg. Length [m]</td>
<td>20, 30, 40, 50</td>
<td>4</td>
</tr>
<tr>
<td>Bldg. Width [m]</td>
<td>8, 10, 12</td>
<td>3</td>
</tr>
<tr>
<td>Total combinations</td>
<td>1152</td>
<td></td>
</tr>
<tr>
<td>Combinations kept</td>
<td>695</td>
<td></td>
</tr>
<tr>
<td>Total Simulations (for 6 Building Descriptions)</td>
<td>4170</td>
<td></td>
</tr>
</tbody>
</table>

However, only 695 combinations, for a total of 4170 simulations, will be considered. The 457 combinations that were not considered, for each building description, have either too small or too large apartment area. Considering such cases may bias, by improving or worsening, the overall results. The error of simplifications for descriptions (5) and (6) is proportional to the proportion of core area on the floor, because they do not physically model cores. Thus, the bigger the apartments are, the smaller is the error. Disregarding those configurations enables to better evaluate the viability of the simplifications. Only the configurations having apartment areas in the range shown in Table 2 will be kept for the elongated building type.

Table 2: Min/Max apartments areas in residential buildings considered in the study.

<table>
<thead>
<tr>
<th>N° of Apts/floor</th>
<th>Min area of Apts</th>
<th>Max area of Apts</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>76.5 m²</td>
<td>146.5 m²</td>
</tr>
<tr>
<td>4</td>
<td>36.5 m²</td>
<td>106.5 m²</td>
</tr>
<tr>
<td>6</td>
<td>36.5 m²</td>
<td>86.5 m²</td>
</tr>
<tr>
<td>8</td>
<td>36.5 m²</td>
<td>72.5 m²</td>
</tr>
</tbody>
</table>

Schedules, loads (lighting, equipment, people) and materials used in this study comply with Israeli Standards 5282 and 1045 definitions and requirements [19, 20, 21]. The HVAC system used has a COP of 3 for heating and cooling. No context is considered for this study. Further research is needed to achieve more accurate data, though for this stage of this study it will not affect the findings, as building...
descriptions are compared among each other on the same base.

4.2 Results for virtual buildings

All the combinations of parameters listed in table 1 were simulated. Figure 4 shows the results summary of changing the number of floors of a standard configuration. The computation time is reduced considerably due to the simplifications, while the relative error of the yearly electricity consumption is below 3%. The more thermal zones the reference model has, the greater the simulations speed up factor is for the simplifications.

Figure 4: Relative error on total yearly electricity consumption and simulation time for theoretical elongated shaped buildings, varying the number of floors. North, 6 apts/floor, L=30, W=10.

The overall impact of simplifications, on all simulations, is similar to the shown in Figure 4. The simplifications speed up significantly the simulations. The mean speed up factors, compared to the reference description (1), range from 1.4 to 10.2 times faster depending on the building description (Table 3). The maximum relative error obtained was 2% for descriptions (2), (3) and (4) and 4% for descriptions (5) and (6) in relation to the results obtained from the reference building. These errors are acceptable for simulations at urban scale. Depending on the accuracy required, the building description (4), having a descent mean speed up factor of 2.7 with a low maximum error of 2%, or (6), having a mean 10.2 speed up factor with a maximum error of 4%, will be the preferred options to be used for BEM.

<table>
<thead>
<tr>
<th>Bldg. Description</th>
<th>Mean speed up factor</th>
<th>Max error</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2)</td>
<td>1.4</td>
<td>&lt;2%</td>
</tr>
<tr>
<td>(3)</td>
<td>2.1</td>
<td>&lt;2%</td>
</tr>
<tr>
<td>(4)</td>
<td>2.7</td>
<td>&lt;2%</td>
</tr>
<tr>
<td>(5)</td>
<td>5.3</td>
<td>&lt;4%</td>
</tr>
<tr>
<td>(6)</td>
<td>10.2</td>
<td>&lt;4%</td>
</tr>
</tbody>
</table>

The referred computation times relate only to the energy simulations and do not include the generation of the model. However, it is worth noting that the simplifications also speed up significantly the modelling time.

The tests on virtual buildings prove that the applied design simplifications, together with maintaining their consistency, are viable for the standard elongated, “Train” building type. Results show that the error achieved, compared to the reference building description, is likely to be less than 4%, while the simulation time is more than 3 times faster. The simplifications are also likely to behave similarly for other simple buildings shapes.

5. CASE STUDY

5.1 Project studied

The simplifications were tested on the Junior-Staff dormitories at the Technion University, a cluster of 6 residential buildings built in 1972 (Fig. 5). Three of the buildings have their main façade oriented to the North-East and the other three to the South-West. The dormitories are designated for families. In this sense they are similar to any other residential building in the city. GIS data and electricity consumption were available.

These buildings have four floors, over a first open floor for the North-East oriented, with four apartments per floor. The models for these buildings were automatically generated by the developed tool, using the GIS file of the Technion and a typology file, as explained in section 3.3 (Figs 3 and 5). Surrounding context is considered for this case study.

Figure 5: Junior-Staff Dormitories. Top: Actual buildings; Middle: Original Layout Plan; Bottom: Detailed description (1), building JS 4 within its context.
The schedules, loads and HVAC system used are the same as those used for the virtual buildings. However, materials were defined according to what was used at the time they were built (i.e. uninsulated concrete walls and single glazed windows). For this study, the floor zone simplification (5) was not tested as simplification (6) was more efficient with similar accuracy.

5.2 Simulated electricity consumption

Figure 6 shows that the relative errors on total yearly electricity consumption don’t exceed 0.5% for any of the 6 buildings with simplified building descriptions, while the speed up factors are close to the one observed for the study on virtual buildings. Overall, for the tested case study, the simplified building descriptions seem satisfactory.

The simplification (4) is less efficient, computational time wise, than in the tests on virtual buildings. Having a zone in the middle of the floor (core), with no connection to exterior walls, causes the simulation engine to generate a mesh on the floors and ceilings. This mesh translates in a rather large number of surfaces with longer simulation time. The mesh issue was present also for the virtual study, though, the benefit of merging zones was greater than the harm of the mesh for rectangular footprints. The footprint shape of Junior-Staff buildings is not that complex, but it still makes the simplification (4) slower than simplification (3). At this stage, lacking a way of overcoming this mesh issue in floors and ceilings when there is a zone in the middle of the floor and the footprint is not a clean rectangle, it will not be profitable to use simplification (4).

The Monozone description (6) is more efficient for this case study. The maximum error on total yearly electricity consumption is 0.25% and the speed up factor around 6.5 compared to the fully simulated building (Fig. 6). This overall behavior is satisfactory.

The results obtained for the Junior-Staff buildings are encouraging regarding the studied criteria: the errors compared to the reference description are less than 0.5% and the speed up factors are similar to those obtained with the virtual study. Only simplification (4) slows down too much the simulation time and therefore is not efficient enough due to the meshing issue mentioned previously.

5.3 Comparison with the real electricity data

Though out of the general scope of this paper, it is worth to mention that the study considers the consistency between the simulated electricity consumption results and the real measured one. This is a challenging task since data is not always available or achievable.

The consumptions obtained for the reference building description simulations were compared to the real electricity consumptions of 2018. The gaps observed are in the mean -30% electricity consumption for the simulated buildings. Having such differences between reality and simulation was expected as various items that affect the consumption are not considered in the IS 5282 and hence in the simulations conducted (i.e. heating water, ovens, dryers, laundry and more). Though these items for the Israeli market are estimated to account for around 30% of the overall electricity consumption of the building, adding this number to the calculations obtained, make them close to the real data, enhancing in such a way the value of the simplifications (Table 4).

Buildings 2 and 6 have gaps noticeably different from the 30% overall mean, however. It might be due to the comparison was made with the only available 2018 consumption data. A comparison with average values over few years would be likely to flatten the gaps.

Table 4: Gap between the simulated electricity consumption using the reference description and the real electricity consumption of 2018 for case studies (assuming 30% for missing loads consumption).

<table>
<thead>
<tr>
<th>Building</th>
<th>Gap on yearly elec. cons.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Junior-Staff 1</td>
<td>-1%</td>
</tr>
<tr>
<td>Junior-Staff 2</td>
<td>15%</td>
</tr>
<tr>
<td>Junior-Staff 3</td>
<td>-4%</td>
</tr>
<tr>
<td>Junior-Staff 4</td>
<td>1%</td>
</tr>
<tr>
<td>Junior-Staff 5</td>
<td>-2%</td>
</tr>
<tr>
<td>Junior-Staff 6</td>
<td>-11%</td>
</tr>
</tbody>
</table>

This primary validation is encouraging as the error committed by the simulation is likely to be less than 10% after the missing equipment are added. Further investigations to model accurately the contribution of the missing equipment will have to be done. Tests with other buildings, comparing average consumption over few years, will have to be done for the next step of validation.

Figure 6: Junior-Staff Dormitories. Relative error on total yearly electricity consumption and simulation time for case studies.
6. CONCLUSION

The use of the proposed simplifications would enable the forecast of the electricity consumption of existing and future neighborhoods at a relatively fast simulation time with reliable results on standard computers. The mean speed factor can be expected to be up to 10 and with an error lower than 4% compared to the original reference modelling. Building description (6) is the most promising simplification as it has the best compromise between speed and accuracy. Building description (4) can also be efficient for more precise studies if a solution is found to solve the meshing issue described in section 5.2.

The proposed simplification process has been proved to be efficient when the emphasis is put on rigor and consistency among models. For now, it is not possible to demonstrate that the technique works on any building type. However, testing the building descriptions on virtual buildings enables to test many realistic combinations of buildings’ parameters. As 100% of the 695 combinations simulated have a relative error on the total yearly electricity consumption compared to the reference description lower than 4%, similar buildings to the one tested are likely to have close, and thus acceptable errors. The tests on real cases lead to satisfactory results as well.

Extended tests on virtual buildings and case studies can be conducted to improve the reliability and extend the viability of the simplified building descriptions. Future works can include simulating more parameters, or calibrate better the implemented ones, such as loads and constructions, and wider ranges of values for the virtual study. Tests on other building types, varying the floor layout should be conducted. Other case studies should be done, calibrating them with real electricity consumption measured data over few years.

REFERENCES

Using Real-time Feedback Daylighting Analysis Method to Estimate Indoor Visual Discomfort

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ABSTRACT: Based on the complexity of interior space and the uncertainty of glare generation in large scale public buildings, this paper proposes an immersive simulation method for glare in the interior of buildings based on real-time feedback. The research aims at using AcceleradRT ray tracing engine based on physical information modelling technology, indoor glare simulation tool, virtual reality technology and mobile eye movement tracking technology to predict users' sensitivity to indoor glare in different directions, thus effectively predicting indoor glare in the early stage of architectural design. This paper takes Changchun university of technology's library as the research object and carries out the design practice of daylighting performance simulation optimization. The research shows that the mobile eye tracking technology can effectively predict the user's sensitivity to the luminance of different daylight sources. The real-time feedback based indoor glare immersion simulation method can dynamically feedback the indoor daylight environment of large space buildings in real time, improve the efficiency and optimization accuracy of daylighting simulation, and provide decision support for the optimal design of indoor daylight environment of buildings.

KEYWORDS: Local climate data, Real-time feedback, Indoor glare, Immersive virtual reality

1. INTRODUCTION
With the rapid development of digital technology and the widespread acceptance of complex architectural space, large-scale public buildings tend to be more complex in form and interior space. In order to meet the requirements of indoor daylighting, reduce the overall energy consumption of buildings, and achieve sustainable development of the ecological environment [1], architects often improve the efficiency of indoor daylighting by adjusting the type and size of skylights [2-3] and optimizing the ratio of windows and walls [4]. However, it is difficult for designers to ensure the indoor daylight while avoiding the occurrence of glare, and the renovation of the indoor daylighting environment requires a lot of human resources and material resources. Therefore, it is necessary to predict the indoor visual discomfort in large-scale public buildings during the architectural design stage.

In recent years, domestic and foreign scholars' prediction methods of indoor glare are mainly divided into three methods: mathematical or analytical modelling analysis, scale model for field measurement, and computer software simulation [1]. Although the mathematical or analytical modelling analysis can use the simplified model to quickly calculate daylighting indicators such as Daylight Factor (DF) and Daylight Autonomy (DA), the accuracy of the results needs to be verified by comparison with the actual measurement results. The scale model for field measurement can simulate the real indoor daylight environment and reflect the actual sky environment, however, it takes a long time to make and it is not easy to make secondary modifications [5]. The computer simulation software method can not only analyse the indoor glare situation of complex building models throughout the year [6], but also obtain three-dimensional rendering maps, so that designers can intuitively feel the distribution of indoor glare [5]. Therefore, in the stage of architectural design, architects usually use computer software simulation methods to predict indoor visual discomfort.

The indoor daylighting analysis method is mainly based on Radiance simulation results [7]. However, due to Radiance has time-consuming and using static-lighting-analysis method's drawback, it is difficult to analyse the daylighting of complex indoor spaces with multiple daylight sources. AcceleradRT is an image rendering engine that can perform highly parallel calculations on computer graphics processing units (GPU) [8]. It uses progressive tracking algorithms to achieve parallel accelerated calculations, which can effectively reduce image rendering calculation time [9]. Therefore, the combination of AcceleradRT engine and dynamic daylighting design strategy can improve the efficiency of daylighting optimization. The purpose of this paper is to propose a real-time feedback simulation method for indoor visual discomfort based on virtual reality technology, and to optimize the process of using the AcceleradRT software for daylighting analysis.
2. METHODOLOGY

The daylighting analysis method based on real-time feedback workflow consists of four steps shown in Fig. 1. We conducted a case study to prove the applicability of the proposed method.

![Diagram showing the workflow of the proposed method](image)

Figure 1: General workflow of the proposed method.

2.1 Visual discomfort indices

The prediction of visual discomfort in architecture depends on the accuracy of the image rendered by the engine and the evaluation index of visual discomfort. AcceleradRT image rendering engine is based on progressive ray tracing technology, which can quickly generate accurate daylighting simulation analysis images, and can obtain real-time visual discomfort evaluation indices’ dynamic changes during the daylighting simulation [9-10]. Since Discomfort Glare Probability (DGP) is widely considered as the most reliable quantitative glare index [11], this study used vertical eye illuminance (Ev) and DGP as visual discomfort evaluation indices.

Discomfort Glare Probability (DGP) evaluates the observer-perceived illuminance level through the vertical eye illuminance (Ev), thus showing a stronger correlation with the user’s response to glare perception. Equation (1) is applicable to the case where the DGP is in the range of 0.2 to 0.8, and Ev is above 380 lx [11].

\[
DGP = 5.87 \times 10^{-2} \times \frac{E_v}{L_s} + 0.0018 \times \frac{1}{\ln(1 + \frac{1}{E_v \times P})} + 0.16
\]

(1)

where DGP - discomfort glare probability;

\(E_v\) - vertical eye illuminance (lux);

\(L_s\) - the luminance of the source, (cd/m²);

\(\omega_s\) - the solid angle of the source seen by an observer;

\(P\) - the Guth position index.

2.2 Tool selection

In the experiment, different plug-in tools based on the Rhino platform were selected according to different experimental precision requirements. Firstly, using Enscape-for-Rhino can real-time rendering the environment which can acquire indoor renderings and record the scene video observed during the path movement. However, it is impossible to perform accurate indoor daylight environment and obtain quantitative simulation data. Therefore, we need use Diva-for-Rhino plug-in to render the indoor daylight environment of the selected observation node, and take the rendering map of the observation node as the main image material in the test process.

The Tobii X60 eye tracker can be used to record data such as the track of eye movement, gazing time, number of fixations, and the corresponding position of fixation points during the experiment. The sampling frequency of the eye tracker is 50Hz, which can record the position changes of the tester’s eyes when observing the video and image quickly in front of the computer screen, to obtain the accurate eye observation results and provide the theoretical basis for the simulation moving path selection.

AcceleradRT is used to show the indoor false-colour map of the interior of the building in real time to the designer. AcceleradRT is a daylighting analysis software based on Accelerad ray tracing engine. It uses progressive path tracking to feedback the daylighting simulation results in real time. In the process of running the software, the daylighting analysis data such as luminance, DGP, and contrast ratios in the scene can be obtained in real time to complete the construction of the virtual reality simulation scene. Combine AcceleradRT with HTC VIVE virtual reality equipment can realize the immersive simulation of building indoor daylight environment and can improve the simulation efficiency.

2.3 Daylighting simulation process

Firstly, developing the reference modelling in parametric approach. According to the design scheme, carry out the parametric modelling of architectural space form, and establish parametric associations between building forms. Construct the geometric information model of interior infrastructure and foundation components, and establish the spatial information model of quasi-simulation building. Based on the physical properties of the building components, select the model interface material that matches the real situation.

Secondly, importing the local environmental information to establish the simulation software platform (Fig. 2). Retrieve and filter the local meteorological data in the simulated experimental area from the database to establish a local daylight environment meteorological data module. Through data port association, establish the parameterized relation between the local daylighting environment meteorological data module and the building information model. Then, import the integrated data of the module to the simulation software platform. According to the layout of building plan and roof skylight, predict the interior areas that will make people feel visual discomfort. Select the typical
perspective of indoor daylight and shadow changes, compare and filter the indoor rendering images of typical time during the whole year, and then determine the time parameters of simulation scene.

Figure 2: Importing the local environmental information.

Thirdly, using the eye-tracker experiment to determine the immersive simulation moving path (Fig. 3). In the preliminary analysis stage, according to indoor daylight environment in the simulation software determine the typical observation nodes, and then design the initial movement path of eye tracker experiment. In the experiment preparation stage, the indoor rendering scene video is recorded in the simulation software platform, and the daylight environment effect picture of the observation node is obtained at the same time. In the eye tracker experiment, record the data such as annotation time, fixation times, corresponding positions of fixation points and eye movement track when the tester observes typical render images under the specific experimental requirements. Through the superposition processing and analysis of image and data, the area with high glare probability and the motion path of simulation experiment are finally determined.

Figure 3: Moving path determination processing workflow.

Finally, conducting the indoor daylighting real-time feedback simulation by visual reality technology to optimize the design. Import the building information model and local daylight environment data module into the AcceleradRT software to generate a real-time feedback pseudo-color image of indoor daylight environment. The designer can modify and optimize the design scheme in time by observing the simulation experiment results of the daylight environment.

3. CASE STUDY
The study takes the library of Changchun University of Technology (43.88°N, 125.35°E) in Changchun, Jilin Province as an example. The south side of the building is adjacent to the campus square, and the north side is adjacent to the main road of the city, so the terrain is relatively flat and there is no shelter from tall buildings. Based on the design requirements and energy saving considerations, the roof is equipped with skylights to meet the indoor daylighting standards. Figure 4 shows the fifth-floor plan of the building and the arrangement of skylights. Since large-area daylight skylights are concentrated in the plane, it is easy to make people feel visual discomfort.

Figure 4: Fifth floor plan and skylight position

3.1 Develop the parametric model
According to the preliminary design scheme of the building, using parametric modelling method established the indoor three-dimensional shape model for immersive simulation, so that the building facade can be timely corrected and optimized. Based on the design requirements, indoor furniture such as tables, chairs and bookshelves were arranged in the parametric model. Using parameterized programming technology, input the material parameters of the model interface according to the actual situation of the environment (Table 1).

Table 1: Material parameter

<table>
<thead>
<tr>
<th>Type</th>
<th>Parameter value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interior wall</td>
<td>void plastic WhiteInteriorWall_70</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>5 0.7 0.7 0.7 0 0</td>
</tr>
<tr>
<td></td>
<td>void glass Glazing_DoublePane_Clear_80</td>
</tr>
<tr>
<td>Window</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3 0.87 0.87 0.87</td>
</tr>
<tr>
<td></td>
<td>void plastic GenericFloor_20</td>
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<tr>
<td>Floor</td>
<td>0</td>
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<tr>
<td></td>
<td>0</td>
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<tr>
<td></td>
<td>5 0.2 0.2 0.2 0 0</td>
</tr>
<tr>
<td>Table, chair and</td>
<td>void plastic WoodFurniture_33</td>
</tr>
<tr>
<td>bookshelf</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>5 0.5 0.3 0.2 0 0</td>
</tr>
<tr>
<td>Ceiling</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>5 0.7 0.7 0.7 0 0</td>
</tr>
</tbody>
</table>
3.2 Import local environmental information

Retrieve local meteorological data from Changchun area on EnergyPlus website. Filter and process the acquired meteorological data as daylighting simulation experiments’ requirement, and establish the local daylight environment meteorological data module. Import the module data into Enscape-for-Rhino, Diva-for-rhino and AcceleradRT simulation tools, to achieve a high degree of similarity between the simulated environment and the real environment (Fig. 5).

![Figure 5: The workflow of importing local environmental information](image)

3.3 Determine the moving path

According to the layout of building plan and roof skylight, predict the area with high frequency of glare. In the scene, the typical perspective A (the camera is 3.8m high from the fifth floor), which can observe the daylight and shadow changes in most reading areas, is selected as the observation angle of the pre experiment (Fig. 6). Obtain twenty scene renderings of perspective A from 8:00 a.m. to 16:00 p.m. on March 21, June 21, September 23 and December 22. Compared with the four groups of indoor rendering images, it is found that at 12:00 on March 21, the sunshine area on the desk and chair is the largest, so more readers may feel visual discomfort in the reading area at that time. Therefore, choose 12:00 on March 21, 2018 as the final of experiment time.

![Figure 6: Schematic diagram of simulation time determination](image)

Import the final building information model into the Enscape-for-rhino platform and predict the area with high probability of glare in accordance with the distribution of indoor daylight and shadow. In the process of initial path selection, the area with high probability of glare is regarded as the main observation area, while the area with uniform illumination and shadow are concentrated as the camera locations. Design the initial moving path of the experiment, and record the scene of the rendered scene observed in the Enscape-for-Rhino platform along with the human viewpoint (Fig. 7). According to the initial path in the platform, record the video of the rendered scene observed in the process of human movement. Using the Diva-for-Rhino plug-in, obtain the meteorological data of Changchun area, import the building information model, render the indoor daylight environment of the selected 14 observation nodes, and take the effect drawing of the observation nodes as the main image material in the test process. The pictures in Fig. 8 record the rendered images at various observation viewpoints according to the moving path. Since viewpoint 3 and viewpoint 12 are in the middle of the viewing area, so the left and right observation directions are selected for analysis.

Using Tobii X60 eye-tracker, predict the most uncomfortable reading area on the fifth floor. Before starting the experiment, play two pre-recorded path movement videos for the tester, and record the tester’s eye movements in the eye-tracker at the same time. Then, according to the moving order of the initial path, 14 rendered images of the scene are played in sequence. The tester searches for the least suitable areas in the self-study area and the reading area as required. The playback time of each picture is manually controlled by the tester. Finally, the most vulnerable reading area in the plane is selected by fitting and stacking the most uncomfortable reading area found by the tester, to further locate the location of the most vulnerable to glare. According to the glare-prone area obtained from the experiment, the initial movement path of the experiment was adjusted and modified to finally determine the simulation experiment movement path ((Fig. 7).

![Figure 7: Typical observation positions and moving path.](image)
3.4 Indoor daylighting real-time simulation feedback

The realization of immersive simulation of indoor daylight environment can truly reflect the glare of all directions of the indoor space to the designer. Therefore, it is necessary to associate the AcceleradRT software with virtual reality technology, which is an innovation of indoor glare evaluation method. Firstly, according to the path of eye-tracker experiment, the camera moves as the human perspective in AcceleradRT. Secondly, record the video image of the pseudo colour image generated in real-time rendering during the moving process of human visual angle, and perform its post-processing. In the processing stage, we need to delete the progressive rendered process image, keep the result of rendering within the unit moving step, and adjust the final video image to the video format matching the virtual reality (Fig. 9). Finally, import the recorded video image into the portable virtual reality simulation device. In the process of observation, the designer will not be restricted by space and time constraints. They can use portable equipment to observe the simulation results of the pseudo colour image of the indoor daylight environment at any time, and modify and optimize the design scheme in time. In addition, because the experimental equipment is small and easy to operate, it can realize the observation of glare environment by many people at the same time, and improve the accuracy of the simulation results of immersion glare. According to the result of simulation experiment, the designer puts forward the design feedback of indoor daylight comfort.

We can clearly observe the daylighting of library space through the sixteen images rendered by the AcceleradRT (Fig. 10). In the process of simulation and analysis, most of the reading areas have good daylighting performance and meet the requirements of indoor daylighting. However, the luminance of the position of the vertical skylight and the near window are higher, so the probability of glare is higher, so in the process of indoor daylighting optimization design, it is necessary to redesign the seat placement in areas or add sunshade facilities with strong incident daylight. Although there is a large area of roof skylight in the plane atrium, the possibility of glare in the reading area of the area is reduced due to the hollowing treatment of the fifth-floor plan, and the area of third-floor and fourth-floor of natural daylighting is also increased. Therefore, the surrounding area of the atrium is a more comfortable reading area in the plane. We can consider appropriately increasing the number of tables and chairs in this area. The reading area on the left and right sides of the plane has a relatively dense roof skylight, which has a high probability of visual discomfort. Therefore, it can be considered to appropriately reduce the number of tables and chairs, adjust the position of tables and chairs, or optimize the roof skylight design.

A quantitative comparative analysis of indoor light environment was conducted according to the DGP and Ev values calculated by AcceleradRT in real time (Fig. 11). The value of Ev is mainly concentrated between 500lux-1000lux, and the value of DGP is mainly concentrated between 20%-35%, indicating that the risk of glare is low in the observation position, but there is still visual discomfort in some areas. Among these fourteen points, viewpoint 5 has the
highest DGP value, so it is the most visual discomfort area which is match for the Radiance’s rendering result. Although viewpoint 3-1 and viewpoint 3-2 are at the same observation point and have the same Ev value, the DGP values are significantly different due to the different azimuth angles observed by the camera. Viewpoint 3-1 is mainly used to observe the influence of skylights and windows on the visual comfort of the left reading area, while viewpoint 3-2 only considers the influence of skylights on the right reading area. Therefore, it is found that under the combined effect of window and the skylight, the probability of visual discomfort is greater. Although the fifth-story library is a symmetrical plane layout, due to the influence of skylight position, solar incidence angle and other factors, the numerical changes of Ev and DGP do not show symmetry changes.

![Figure 11: Different viewpoints' visual discomfort indices.](image)

**4. CONCLUSION**

In this paper, a real-time feedback daylighting analysis method is proposed, which improves the efficiency of daylighting simulation, and can simulate and analyse the complex space of multiple daylight sources. This method integrates architecture, computer science, environmental science and other multi-disciplinary fields. By combining architectural engineering practice with virtual reality technology, immersion simulation can be realized, which is conducive to improving the real experience of designers in the process of daylighting design.

Taking the actual project as an example, this paper discusses and analyses the proposed daylighting design method. In the process of simulation experiment, the tester can intuitively experience the visual comfort of the interior space of the building, and can obtain real-time quantitative data, which is convenient for subsequent revision of the design. It is found that visual discomfort is more likely to occur in viewpoint 5, while reading activities near viewpoint 2, 7, 8 and 13 are more comfortable. For areas with visual discomfort, it can be solved by reducing or adjusting the position of tables and chairs, or optimizing the roof skylight design.

The parametric modelling method in the real-time feedback daylighting analysis method can optimize and adjust the design in time, and improve the efficiency of daylighting design optimization. In addition, by introducing different environmental information, this method can predict the real-time feedback of indoor daylighting environment in different areas, different times and different building types. Therefore, the method of real-time feedback of indoor visual discomfort has practical application value. In the future, relevant research will further improve the intelligent level of real-time daylighting feedback method, optimize the design process, and provide more data reference and daylighting modification suggestions for designers.

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Comparative Analysis of Machine Learning Models Optimized by Bayesian Algorithm for Indoor Daylight Distribution Prediction

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ABSTRACT: Daylight distribution evaluation is vital for daylight design. However, its application in the early design stage is limited due to the time-consuming simulation process. Many statistical models were proposed to reduce the prediction time, yet application of the machine learning model in daylight prediction was relatively rare and has very limited generalization capability. This paper aims to propose a new workflow for indoor daylight distribution prediction, and compare the performance of XGB, RF, SVR and MLP models with Bayesian optimization. The results showed the MLP based prediction model achieved best generalization performance for indoor daylight prediction, which reduced the simulation time to less than 1 second and maintained satisfactory accuracy.

KEYWORDS: Daylight Distribution Prediction, Artificial Neural Network, Bayesian Optimization, UDI, Machine Learning

1. INTRODUCTION

Annual daylight distribution metrics like UDI and DA, are widely used to evaluate the daylight design quality and indoor visual comfort. However, its application in the early design stage is limited due to long simulation time [1].

Machine Learning (ML) based models can be a viable solution for daylight prediction problem, which can make relatively accurate predictions in short time as it avoids the time-consuming raytracing process. Compared with raytracing-based daylight simulation tools, it’s more suitable for early design stage as the rapid daylight evaluation can support the designers making design decision efficiently.

In the past few years, ML based methods such as Neural Network, Support Vector Machine, Random Forest, have been widely applied for building energy consumption prediction [2-20]. However, application of the such models in daylight prediction was relatively rare, and most of them focused on predicting real-time hourly data for built environment.

Existing annual daylighting performance prediction studies based on machine learning are still limited to the bottleneck of generalization ability. The related works are limited to several specific cases with fixed room size and orientation, without generic parametric space representation. Lorenz, C. L et.al used ANN to predict Daylight Autonomy for 28 rooms, all shared the same size but with different fenestration [2]. In the similar research, DA prediction model for rooms of varied size was developed [3]. The problem of such method is that each scenario was trained with different model. As a result, the prediction model failed to generalize in other cases and needs to be trained with corresponding dataset again with any other building configuration.

To overcome the generalization limitation and improve the prediction accuracy, we developed a parametric workflow to generate proper daylight distribution dataset and compared the performance of Multi-Layer Perceptron (MLP) with other popular machine learning algorithms such as Support Vector Regression (SVR), Random Forest (RF) and Gradient Boosting Tree (XGB) to support the selection of machine learning algorithms for daylight distribution prediction modelling. A daylight distribution prediction model with better generalization capability were proposed through systematic training data generation and model hyperparameter tuning with Bayesian optimization.

2. MACHINE LEARNING MODELS

In this section, we give a brief introduction to the MLP, XGB, RF and SVR machine learning models we used for comparison and the related works, as well as the Bayesian Optimization technique used for parametric study.

2.1. Multi-Layer Perceptron

Multi-Layer Perceptron is a kind of Neural Network that only consists of fully-connected layer. A typical MLP model has one input layer of m neurons, h hidden layers containing k neurons and one output layer with n neuron. Each layer calculates the
weighted sum of all inputs and applies a non-linear activation function. Many methods are available for network training, in this research we used the Broyden-Fletcher-Goldfarb-Shano (BFGS) algorithm to train the model, which works best on a small to medium size dataset. MLP has been intensively used in various building performance prediction task in the past decade. Kazanasmaz et al. applied single hidden layer ANN model to predict the hourly indoor illuminance values for an office building [4]. Biswas et al. used simple BPNN to predict the total energy consumption. The above works proved the reliability and accuracy of BPNN in the building energy prediction [5]. Zhou and Liu combined Principal Component Analysis with ANN and SVM and compared their performance on annual UDI classification problem, and shown ANN with outperformed SVM by large margin [6]. Shanfzadeh et al. used ANN along with SVR and Gaussian Process Regression to forecast wind and solar power and energy demand. The ANN performed well in all tasks and was superior at predicting energy demand [7]. Ahmad et al. compared ANN and RF in predicting hourly HVAC energy consumption of a hotel, and find that ANN performed marginally better than RF [8]. A detailed review about ANN in energy prediction can be referred in [9].

2.2. XGBoost

XGBoost (eXtreme Gradient Boost) algorithm was first proposed by Chen in 2016 as an improved version of gradient boosting tree with faster computing speed and better generalization performance [10]. By using boosting strategy, it is capable of fitting very complex function, but also prone to overfitting problem and hard to fine-tuning. XGB has been applied in many fields and achieved impressive success. Hadri et al. compared XGB and RF as well as mathematical method to explore the efficiency of different models. The result shown XGB not only outperformed other methods in terms of accuracy but also showed higher prediction efficiency [11]. Touzani et al. applied gradient boosting machine to develop building baseline energy consumption model using a dataset of 410 commercial buildings. Compared to linear regression and to random forest algorithm, the gradient boosting machine improved the R-squared and the CV(RMSE) in more than 80 percent [12]. Fan et al. made a comparative study for short-term building cooling load prediction considering XGB, SVR, DNN, ELN and the RF methods. The results shown the performance of RF is not as good as the above-mentioned four nonlinear methods [13].

Random Forest is a tree-based ensemble learning algorithm based on bagging strategy. It consists of many simple decision trees and uses different parts of data to train each individual tree in parallel, the result of these trees is weighted and combined to the final result. The RF algorithm overcomes the instability of each individual tree and thus has better generalization ability. Smarra, F et al. developed a RF based model predictive control system for heating system and found its performance comparable to a physics-based MPC controller [14]. Ahmad et al. compared the performance of ANN with random forest both in hourly energy consumption and daylight illuminance prediction for a classroom. The impact of two hyperparameters, max depth and max feature, were explored for RF. It’s found that ANN performs better on energy consumption prediction but RF yield better result on daylight prediction task [15]. Wang et al. used RF and SVR model to predict hourly electricity consumption of two educational buildings and the results showed that showed better performance compared with SVR in building electricity consumption prediction [16].

2.4 Support Vector Regression

SVR is a classical machine learning algorithm based on Support Vector Machine algorithm. SVR has the flexibility to define error tolerance in prediction model and is more robust to outliers. By using kernel function, SVR can also be used for various nonlinear regression problem. Dong et al. applied SVR to monthly building electricity consumption prediction [17]. Li et al. compared the performance of SVR with BPNN, GRNN and RBFNN in predicting hourly cooling load for an office building and shown SVR and GRNN method had better prediction accuracy and generalization than the the other two prediction model [18]. Massana et al. compared ANN, SVR, and MLR in predicting short-term energy load for non-residential buildings. It showed SVR improved prediction accuracy than the other methods [19]. Fan et al. developed and compared SVM and XGBoost model for predicting global solar radiation and recommended XGBoost over SVM considering with the accuracy, stability and efficiency [20].

2.5 Bayesian Optimization

The selection of the most appropriate learning model and hyperparameters is difficult in ML-based prediction modelling, which depending on the specific problem to be predicted. Such model selection process requires rich experience with the relevant machine learning algorithms and adequate time for parameter fine-tuning. The concept of hyperparameter optimization was developed to alleviate the effort of fine-tuning, making such algorithm more accessible to non-expert user. By
iterating through all possible hyperparameter settings, one can find an optimal hyperparameter setting at the cost of very long training time. Bayesian optimization utilizes more sophisticated algorithm to minimize the trials required to find a near-optimal hyperparameter combination. Basically, it trains a surrogate probability model to predict the optimized model’s performance based on performance of former hyperparameters, and then uses an acquisition function to determine subsequent sample point. It performs best for optimization problems that has less than 20 dimensions with continuous domains [21], and can find better hyperparameters faster than random search and grid search and can even outperformed manually tuning method by expert on certain dataset [22].

3. METHOD

In this section, we demonstrated the modelling method of machine learning based prediction model including training datasets generation and best model selection. Firstly, the parametric simulation model was developed to obtain large size of training samples. Afterwards, 4 algorithms were trained based on the generated training datasets and optimized with Bayesian optimization. Finally, the 4 prediction models were compared using Mean Square Error (MSE), Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE), R^2 metric.

3.1 Data Preparation

First, data acquisition and parametric simulation model was developed in Grasshopper to generate large amounts of data for machine learning model training.

A room with rectangular plan and a single window located in Harbin was selected as the reference building. The parametric simulation model (Figure 1) was developed in Grasshopper, with variables listed in table 1. The model used Daysim as daylight simulation engine. whose simulation setting is detailed in table 2.

The daylight sensor points were placed on the plane 0.8m above the floor. Each point was located at the centre of the 10x10 grid dividing the room equally, regardless of room size (Fig.2) as the number of outputs must remain the same for different samples to be utilized by any prediction model.

![Figure 2: All rooms have same grid layout, regardless of their sizes.](image)

The training data were created by sampling the parametric simulation model using Latin hypercube sampling method [23]. Latin hypercube sampling method was chosen because it can create a more representative sample space with fewer samples compared with the random sampling, which effectively reduce the total time required to acquire a representative training dataset. As the sampling method sampling each parameter independently, we filtered and discarded invalid inputs where WWR-Y+WSR>0.9.

After obtaining the raw simulation data, we modified the data to make it better suited for machine learning task. Firstly, all inputs variables were remapped to [0, 1] with min-max scaling function. For tree-based model such as XGBoost and random forest, the result will not be influenced by the scale of input data, but for ANN and SVR this is mandatory. Secondly, the hourly illuminance value recorded at each test point were used to calculate 4 levels of UDI (Table.3) based on a working schedule from 9 a.m. to 5 p.m. Noting that rather than using averaged UDI, we explored more detailed daylight distribution information, which can capture the true spatial characteristic of daylight more accurately. This result in a large number of predicted targets for model, which is rare in previous literature. The intuition is to treat the room space as a whole, thus the relationship between all points in the space can be automatically learned by machine learning model.

![Table 3: Simulation Results & Targets for prediction model](image)

1/5 of the samples were randomly chosen as testing data, others remained as training data. They

<table>
<thead>
<tr>
<th>Target</th>
<th>Range*</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>UDI100</td>
<td>3-37</td>
<td>UDI not achieved lx&lt;=100</td>
</tr>
<tr>
<td>UDI300</td>
<td>0-85</td>
<td>Supplementary UDI where 100&lt;lx&lt;300</td>
</tr>
<tr>
<td>UDI2k</td>
<td>0-92</td>
<td>UDI autonomous where 300&lt;lx&lt;2000</td>
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<tr>
<td>UDI2k+</td>
<td>0-92</td>
<td>UDI exceeded where lx&gt;=2000</td>
</tr>
</tbody>
</table>

* All UDI are calculated based on workday, 9-17

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were processed individually in following step to avoid data leakage.

3.2 Model Training and Selection

After obtaining the dataset, 4 kinds of ML model were developed independently. As different machine learning model having varying hyperparameters that can drastically impact the training result, it’s difficult to claim whose performance is better when only compared a certain one of these models to each other. With the help of Bayesian optimization, we can first identify the optimal hyperparameter for each model type, then compare the optimal model of each kind against each other to determine the best model.

All of these 4 models are implemented using “scikit-learn” library [24], and the name of each parameter corresponds to the name in library. The implementation of Bayesian optimization relies on the “scikit-optimize” python library.

Hyperparameters for different models and their range are listed in Table 4. These parameters are subset of all hyperparameter which are considered most impactful on performance. The upper and lower bounds of each parameter are chosen through preliminary trials and errors. These selected parameters were optimized sequentially by Bayesian optimization for 30 iterations. For each optimization iteration of each model type, the whole training dataset was divided again into training and validation set using five-fold cross-validation method. The average MSE of five cross-validation models was used to rank the hyperparameter combination.

Table 4: Hyperparameters type and range for each model

<table>
<thead>
<tr>
<th>Model</th>
<th>MLP</th>
<th>SVR</th>
<th>GBT</th>
<th>RF</th>
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<td>N_layers (1-4)</td>
<td>C (1-1000)</td>
<td>Max_depth (2-8)</td>
<td>Max_depth (2-20)</td>
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<tr>
<td>N_neurons (8-512)</td>
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<td>N_estimators (10-1000)</td>
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<tr>
<td>Alpha (1e-2-0.1)</td>
<td>Gamma (0.01-10)</td>
<td>Gamma (0.01-10)</td>
<td>Min_samples_split (2-5)</td>
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<tr>
<td></td>
<td>Learning_rate (0.001-0.05)</td>
<td>Min_samples_leaf (1-5)</td>
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</tr>
</tbody>
</table>

Finally, the optimized models were test on the reserved dataset to select the best model, using the following metric, MSE, MAE, MAPE, $R^2$, as formalised in Equations (1) to (4).

\[
MSE = \frac{1}{N} \sum_{i=1}^{N} (predict_i - true_i)^2 \tag{1}
\]

\[
MAE = \frac{1}{N} \sum_{i=1}^{N} |predict_i - true_i| \tag{2}
\]

\[
MAPE = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{|predict_i - true_i|}{true_i} \right) \times 100 \% \tag{3}
\]

\[
R^2 = 1 - \frac{\sum_{i=1}^{N} (predict_i - true_i)^2}{\sum_{i=1}^{N} (true_i - \bar{true})^2} \tag{4}
\]

4. RESULT AND DISCUSSION

As described in Section 3, we obtained 500 input samples and sent them to the parametric simulation pipeline. Then the simulation results were processed and divided into training set of size 400 and test set of 100, followed by the model development process where 4 ML models were trained and optimized.

MSE, MAE, MAPE and $R^2$ of 4 best models were shown in Figure 3. For training dataset, the performance rank is XGB>MLP>SVR>RF. XGB achieved lowest MSE (0.23) during training phase, marginally beating MLP (0.24 MSE). For test dataset though, MLP outperformed all other models by a large margin. Also, it showed much narrower gap between training and test performance, indicating good generalization capability.

![Figure 3: Performance on training and test data of 4 models](image-url)

The difference of prediction models can be contributed to various reason:

1. Except for ANN and Random Forest, other two algorithms do not natively support the multi-output prediction problems. The multi-output was achieved by concatenating the result of individually trained model. Thus, the relationship between all output variables were not considered in these models, which could explain why they were outperformed by ANN.

2. In our experiment, the input features set are well defined as we already know which variable will impact the result, which is equivalent to manual featuring engineering. Thus, the featuring selection capability of each algorithm was not highly relevant. Also, the samples itself have contain few noises except for the inherent randomness in simulation engine.

3. While we replace the random search method with more advanced Bayesian optimization to reduce time cost for exhaustive search, the initial optimization boundary must be specified beforehand and chosen for this specific problem. Thus, different problem formation, such as using different weather data or parametric model, may require different parameter range, and possibly resulting in different performance. Also, the possible range of hyperparameter and the impact of certain parameter subsets were not discussed.
Although for this particular problem, other algorithms are unlikely to win against the MLP even with fine-tuning included judging from the training performance of each algorithm.

The optimal performance was achieved by a 3-hidden layer MLP with 496 neurons, converged within 10 minutes with $10^{-5}$ learning rate. The MLP model generalizes on test dataset with R squared=0.98, MAE=0.76, MAPE=10.7% and MSE=1.27. In MAE distribution plot (Figure 4. Right), Most of errors (above 99%) are within a range of 5, and the error distribution have a centre very close to zero.

The learning curve (Figure 4. left) was created by testing model trained with different size training data on the test dataset. It indicated that the model has stautred on the dataset of 400 samples, adding more data will not yield significant improvement.

![Figure 4: Learning curve (left) and error distribution (right) of MLP model](image)

To take a closer look at the model performance, we created an error map of each individual value by averaging the mean absolute error of all samples. Figure 5. shown test MAE at each sensor points. Most of them have low error, except for some point near the windows. It may result from that the change of windows width will drastically influence the illuminance value near the window, causing them harder to predict.

![Figure 5. Test Mean Absolute Error for each sensor point](image)

A case study of an office building was used to demonstrate the possible application (figure 6). The office plan consisted of simple rectangular office with one side opening, which can all be represented by the parametric prototype proposed in section 2. Even though the original parametric model is fairly simple, it can be matched and mixed to create various layout.

![Figure 6: UDI2k+ of prediction results (left) and Daysim simulation results (right)](image)

On change of any geometry, the MLP model can respond within 300ms (including data transmission time), while simulation by Daysim take about 10 minutes to recalculate on Intel Xeon CPU with multiprocessing. As trade-offs, the result of the prediction model was not as accurate. The overexposure area is visibly larger which is corresponding to the error map, and the result seems more “averaged” than the actual case, which is caused by (1)the daylight simulation engine has inherent randomness which result in small noise in each sample, and the way statistical model was trained will average them. (2)the model learned to prefer continuous change from light to dark. While this may not suffice for a detailed light design, it accurately captures the distribution characteristic. In early design stage, this can serve as very fast and easy way to test the possible daylight performance.

5. CONCLUSION

In this paper, we proposed a machine learning based daylight prediction workflow, and benchmarked the performance of XGB, RF, SVR and MLP. Data simulated with Daysim from parametric study model were used as train and test dataset. The result shown that MLP achieved best generalization performance for daylight prediction models. The XGB model had very good performance on training dataset. But the generalization performance was way less ideal. We suggested that for similar problem with complex relationship between outputs, the ANN based models are better choice.

The proposed prediction model drastically reduces annually daylight prediction time under a second and maintains satisfactory accuracy, making daylight evaluation at design stage feasible. Compared with former researches, the output is the daylight distribution condition of the entire space instead of certain points, which is more intuitive for designer to understand. The predicted UDI can also be furthered processed to calculate Daylight Autonomy, weighted or averaged UDI to support design decision, or provided as extra input for various automatic indoor layout algorithm.

The main limitation of the research paper lies in that the urban context of studied room was not currently considered. Further researches can focus on
adding context inputs and extending the parametric model to cover more use case, such as room with multiple windows opening. The presented workflow to developed and compare different models can also be applied in other problem, such as yearly energy consumption.

For reference, the data, trained models and code will be available online at author’s GitHub page [25].

ACKNOWLEDGEMENTS
This paper is funded by the National Natural Science Foundation of China (Grant No. 51708149), China Postdoctoral Science Foundation (Grant No. 2017M621276) and Heilongjiang Postdoctoral Science Foundation (Grant No. LBH-Z17076).

REFERENCES
Research on Professional Football Stadium Multi-objective Coupling Optimization Mechanism between Wind Environment and Canopy Form

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\textsuperscript{1,2,3}School of Architecture, Harbin Institute of Technology; Key Laboratory of Human Settlement Environment Science and Technology, Ministry of Industry and Information Technology; Harbin, China

ABSTRACT: With the implementation of ‘the overall plan of Chinese football reform’ and ‘the medium and long-term development plan of Chinese football (2016-2050)’ in 2015, as an important carrier of professional football, football stadium is facing new opportunities of the sports industry economy development. At present, researches on wind environment of stadiums mainly focus on a single research object or single influencing factor, while the space quality of professional football stadium is exactly the comprehensive balance of multi-objective health environment, such as the field and the stands areas. Due to many influencing factors involved, multi-objective research is deficient. Setting football stadium model in Beijing as the research object, this paper selected CFD software for the experiment platform, took the field wind environment quality and the spectators’ comfort as the double evaluation criteria. By adjusting the football stadium canopy design parameters, the coupling relationship between the football stadium canopy form and wind environment in winter and summer was studied, and comprehensive architectural design strategies were proposed to expand and deepen the design theory of professional football stadium.

KEYWORDS: Professional football stadium, Canopy form, Wind environment, Numerical simulation, Multi-objective coupling

1. INTRODUCTION

The Chinese Football Association Super League (CSL) average attendance repeatedly hit new height in the recent ten years, and in 2019, the FIFA and Asian Football Confederation (AFC) confirmed that China has won the right to host the 2021 FIFA club world cup and the 2023 Asian Cup successively. As there are only 6 professional football stadiums in China now, it is a huge demand gap. As the athletes and spectators respond to the wind environment differently, and the different demands of windy weather in winter and summer, the canopy form is the key factor to influence wind environment in stadium. It is very urgent to study the coupling mechanism between professional football stadium canopy form and wind environment.

Previous works have mainly focused on the structural load and the single factor—the grandstand and the field wind environment simulation [1-3], but football stadium wind environment results from multi-factors comprehensive influence, on the basis of different evaluation criteria, the single factor influence result has limitation and one-sidedness, therefore it is very urgent to research on multi-objective coupling optimization mechanism of wind environment and professional football stadium canopy form.

According to the current research on the field and the grandstand wind environment of professional football stadiums [4-5], the main contradiction was in the canopy profile selection. Therefore, this study designed the variables as the canopy section profile—flat type, flat and downward type, flat and upward type, curved and downward type, curved and upward type, the canopy tilt angle is selected as 15° [4].

2. METHODS

In this paper, a large number of basic data of professional football field were investigated and studied, and design factors were summarized, so as to determine basic canopy model dimensions and outdoor wind environment evaluation index. Based on theoretical research and CFD simulation, the wind environment of different canopy forms in professional football stadiums under the same boundary conditions were analysed and discussed.

2.1 Professional football stadium modelling

2.1.1 Capacity of professional football stadium model

Based on a large number of basic stadium data investigation and induction, on the consideration of average attendance per game of CSL and 80% occupancy rate limitation for safety reasons in China (Fig.1), the most suitable capacity for China’s stadium is about 30,000 seats medium-sized professional football stadium, so it was selected as experimental model in this paper (Fig.2).
2.1.2 The plane of professional football stadium model

Based on the investigation of the 80 built professional football stadia (Fig.3, Fig.4), the typical fillet square football stadium was selected in the simulation experiment [6]. Due to the high external integrity and strong maintenance formed by 4-side connected canopy, and the single-sided canopy or double-sided canopy were adopted in the early stage of football stadium construction, the canopy may eventually become all-sided canopy with the continuous reconstruction and expansion, so 4-side connected canopy was set as model prototype.

2.1.3 Permeability of Canopy-stand interface model

The gap distance between the canopy and the stands was another major factor influencing the stadium wind environment. It will generate changing wind fields through the different-size gaps, especially when the canopy is completely surrounded, which is the main wind source at the side interface [7]. Since the main variable studied in this paper is the canopy form, the fully closed connection form was selected for the side interface.

2.2 CFD Numerical Simulation

2.2.1 Model establishment

The models in this experiment were established by the modelling software Rhinoceros. To properly simplify the football stadium model, the simplified parts mainly included stands details and canopy forms (Table 1).

<table>
<thead>
<tr>
<th>Profile form</th>
<th>Profile</th>
<th>Perspective</th>
</tr>
</thead>
<tbody>
<tr>
<td>flat type</td>
<td><img src="image1" alt="" /></td>
<td><img src="image2" alt="" /></td>
</tr>
<tr>
<td>flat and downward type</td>
<td><img src="image3" alt="" /></td>
<td><img src="image4" alt="" /></td>
</tr>
<tr>
<td>flat and upward type</td>
<td><img src="image5" alt="" /></td>
<td><img src="image6" alt="" /></td>
</tr>
<tr>
<td>curved and downward type</td>
<td><img src="image7" alt="" /></td>
<td><img src="image8" alt="" /></td>
</tr>
<tr>
<td>curved and upward type</td>
<td><img src="image9" alt="" /></td>
<td><img src="image10" alt="" /></td>
</tr>
</tbody>
</table>

2.2.2 Parameter setting

The simplified model was imported into the ICEM for mesh division, and the mesh was imported into FLUENT ANSYS for simulation calculation.

(1) Calculation Domain

In this paper, the calculated range was 800 m × 600 m × 150m, the models were placed in the first 1/3 of the flow field (Fig.5), and the block rate in the basin was 2.9%, which meet the requirement of less than 3% [8].

(2) Grid generation

Due to the good adaptability of unstructured grid to the model [9], the main body used unstructured tetrahedral grid to divide the model. The basic grid size was defined to be 5-25m. The regional grid near the football stadium was refined and encrypted, and the regional grid away from the stadium gradually became sparse, so that the number of experimental grids was about 2.2 million.

(3) Turbulence Model

This study was a monomer flow around model, using Realizable k-ε turbulence model. Inlet boundary was velocity inlet, outlet boundary was pressure outlet, top and side were symmetrical plane, and the rest of outer watershed boundary was sliding wall surface.

(4) Inlet flow boundary conditions

As the annual temperature range in cold region is large, hot in summer and cold in winter, where there is strong demand for sound wind environment in the stadium. In this paper, the experiment site set in typical cold region city -Beijing (Table 2).As the Chinese Super League (CSL) is held from March to
November and the climate is not suitable for football match after November in winter, wind environment boundary conditions were set as the maximum wind speed and the average temperature in November and the average wind speed and the average temperature in June, July and August. Considering that multiple variables will weaken the accuracy of a single variable and increase the research complexity, this paper ignored the influence of different wind directions, that is, the external wind flowed from the east in summer and the west in winter which is perpendicular to the model's long axis (Fig.6).

![Figure 5: Calculation Domain](image5.png) ![Figure 6: Blowing Direction Diagram](image6.png)

| Table 2: Monthly Data Set of Ground Climate Data of Beijing |
|---------------------------------|--------|---------|--------|--------|
|                                | Summer | Winter  |
| The average temperature        | 25.1°C | 27.3°C  |
| Wind speed (m/s)               | 2.4    | 2.8     |
| Average wind speed (m/s)       | 2.5    | 4.3     |
| Maximum wind speed (m/s)       | 6.7    | 8.2     |

Note: Sorted according to data of China meteorological data network (http://data.cma.cn/)

2.3 Evaluation Criteria Establishing
2.3.1 Evaluation index factor
(1) Different seasons requirements for professional football stadium wind environment

In the cold regions of China, high temperatures and low wind speed in summer has a seriously adverse impact on the spectators' experience and players' sports. An appropriate amount of ventilation can promote human body heat dissipation by accelerating evaporation, and significantly improve the sultry situation in the football stadium in summer [10]. In the cold winter, the wind further aggravates human thermal sensation. Therefore, the wind environment in professional football stadium should be dominated by increasing ventilation in summer and reducing wind velocity in winter.

(2) Different users Requirements for professional football stadium wind environment

The semi-closed professional football stadium exposes both the field and stand areas in the open air, Which is directly affected by the natural environment [11]. Due to the physical quality, behavioral state and spatial differences between athletes and spectators, the wind environment requirements for the field and stand areas are different. As the spectators' physical quality is relatively weak and static state, the low temperature and wind speed are particularly serious interference to the stand area [12]. The wind in the field mainly affects the players' technical performance, and the wind in stands mainly affects the spectators experience and comfort.

2.3.2 Wind environment evaluation criteria for stand areas
(1) Subjective evaluation of thermal comfort
At the end of October 2018, the authors team carried out the investigation and questionnaire survey on "comfort of outdoor winter wind environment” in Tianjin which is very close to Beijing. Taking squares, parks and stadia as the main test places, the team held Im-8000 anemometer and recorded the real-time wind speed, carried out the subjective and objective investigation on the wind environment of outdoor leisure or leisure activity groups, finally collected 380 valid questionnaires (Table 3, Table 4), with an effective rate of 93.4%. The regression model of "Wind speed and human body wind feeling and comfort" was established by inductive analysis.

| Table 3: DSV Scale (according to the questionnaire) |
|---------------------------------------|------|-------|-------|------|-------|
| The body feeling | A large | Larger | Moderate | A little small | Very small |
| DSV         | 2    | 1     | 0     | -1   | -2    |

| Table 4: TCV Scale (according to the questionnaire) |
|---------------------------------------|------|-------|-------|------|-------|
| The body feeling | Very comfort -able | More confortable | Moder -ate | Very uncomforatable | Intoler-able |
| TCV        | 2    | 1     | 0     | -1   | -2    |

![Figure 7: Relationship between wind speed and wind sensation (DSV)](image7.png) ![Figure 8: Wind sense voting value and wind speed fitting results](image8.png)

![Figure 9: Relationship between wind speed and comfort (TCV)](image9.png) ![Figure 10: Fitting results of comfort voting value and wind speed](image10.png)
According to the conclusion of meteorology: When the wind speed increases by 1 m/s at 24°C, the somatosensory temperature decrease increases by about 0.22°C. When the temperature drops to -20°C, the somatosensory temperature decrease increases by about 0.7°C with the increase of wind speed by 1m/s [13]. However, due to the differences in climatic conditions, people in different regions have different adaptability to the environment. In this study, according to the climate characteristics of cold areas in China, a regression model of wind velocity and somatosensory comfort was established by using multi-factor weight regression method(Fig.7-10), and further research was conducted on the basis of previous studies.

It can be seen from Fig. 7 and Fig. 9, draft sensation votes (DSV) are mainly distributed at 0 (moderate) and 1 (slightly larger). When DSV= 0, the average wind speed is 0.90m /s. Thermal comfort votes (TCV) are also distributed at 0 (moderate) and 1 (comfortable), and the average wind speed is 0.80m/s when TCV=0. According to the regression fitting results in Fig. 8 and Fig. 10, when MDSV=0, the neutral wind speed is 0.54m /s, and the slope of the fitting line is 0.26, which means that MDSV will rise by one level for every 4.3m /s increase in wind speed. When MTCV=0, the neutral wind speed is 2.66m/s, and the slope of the fitting line is 0.15, which means that every 3.73m/s increase of wind speed, MTCV will rise by one level.

(2) Objective evaluation criteria for outdoor wind speed

The Parameters adopted in Lawson criteria, Davenport criteria and Dutch wind environment assessment criteria are not exactly the same in terms of wind speed and pedestrian activity types [14].

The comfortable wind speed range obtained by several evaluation criteria was compared and combined with the provisions in China’s Green Building Evaluation Standard: under the conditions of typical wind speed and wind direction in winter, the wind speed at the height of 1.5m in the pedestrian zone should not exceed 5m/s. During the transition season and summer, there is no vortex or no wind area in the site [15], and the static wind (wind speed <1m/s) area should be avoided under the requirement of summer ventilation stipulated by China’s building code [16], thus, the comfort wind speed range applicable to stand area in this paper is obtained as shown in Table 5.

### Table 5: Outdoor Pedestrian Wind Environment Evaluation Indexes In Cold Regions of China (Self-drawn by the author)

<table>
<thead>
<tr>
<th>season</th>
<th>The optimal wind</th>
<th>Comfort-able wind</th>
<th>Tolerable wind speed</th>
<th>Intoler-able wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>0.14&lt;v&lt;2.22</td>
<td>0&lt;v&lt;0.1</td>
<td>2.22&lt;v&lt;5</td>
<td>&gt;5</td>
</tr>
<tr>
<td>Summer</td>
<td>1&lt;v&lt;3</td>
<td>3&lt;v&lt;6</td>
<td>6&lt;v&lt;9</td>
<td>&gt;9</td>
</tr>
</tbody>
</table>

**Note:** unit(m/s)

#### 2.3.3 Assessment criteria for wind environment in the field

It has been proved that the change of wind and direction will affect the tactical direction of football[17]. Generally, the wind in football matches is Class 3-5. If it is excessive, it will affect the process of the game, leading to the players fitness decline and hypoxia [18]. As FIFA does not specify the upper limit of the appropriate wind speed in football matches until now, the wind environment evaluation criteria are set as follows for research convenience: the wind field distribution uniformity and the wind speed variation stability.

### 3.RESULTS and DISCUSSIONS

#### 3.1 Results

##### 3.1.1 Wind field analysis of Horizontal section

The wind field analysis in the pitch at a height of 1.5m from the ground shows that the wind field has the greatest influence on the trajectory of short pass football, players’ physical consumption speed and the long pass football trajectory. The stands area wind field data processing method used in the study is as follows: the height of the spectators ‘ viewpoint was estimated as 1.2m, and the derived section with the same shape as the sitting surface was established at the height of 1.2m vertical upward terrace, and the data isosurface was used as the data display surface [19]. The results are shown in Table 6.

**Table 6 :Wind Field Cloud Map of Horizontal Section (Drawn by the author)**

<table>
<thead>
<tr>
<th>Winter (8.2m/s, 5.1°)</th>
<th>Summer (2.5m/s, 26.1°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The stands area</td>
<td>The field</td>
</tr>
<tr>
<td>The stands area</td>
<td>The field</td>
</tr>
</tbody>
</table>

---

**Table 5: Outdoor Pedestrian Wind Environment Evaluation Indexes In Cold Regions of China (Self-drawn by the author)**
3.1.2 Wind field analysis of vertical section

In this paper, the center line was selected as the vertical section. The results are shown in Table 7. The results are shown in Table 7. Table 7: Wind Field Cloud Map of vertical Section (Drawn by the author)

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
</tr>
<tr>
<td>II</td>
<td><img src="image3" alt="Image" /></td>
<td><img src="image4" alt="Image" /></td>
</tr>
<tr>
<td>III</td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
</tr>
<tr>
<td>IV</td>
<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
</tr>
<tr>
<td>V</td>
<td><img src="image9" alt="Image" /></td>
<td><img src="image10" alt="Image" /></td>
</tr>
</tbody>
</table>

Table 9: Wind diagram of each measuring point in the field

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="image11" alt="Image" /></td>
<td><img src="image12" alt="Image" /></td>
</tr>
<tr>
<td>5 m</td>
<td><img src="image13" alt="Image" /></td>
<td><img src="image14" alt="Image" /></td>
</tr>
</tbody>
</table>

After a comprehensive analysis of the wind field distribution in the stand area and the field in winter and summer, it is concluded that the curved upward canopy has the best performance in maintaining the wind environment stability in the football stadium, the area of the average wind speed fit the optimal evaluation criteria is the largest and the wind speed distribution is relatively uniform. The wind speed changing rate in the flat canopy model is still within the comfortable range, especially in the stand areas on the north and south sides. While the wind environment in the stands under downward canopy is not optimistic. On the whole, the wind environment performance priority order in different canopy forms is as follows, curved and upward type > flat and upward type > flat type> curved and downward type> flat and downward type.

3.2 Discussions

(1) Canopy form Selection for new professional football stadium

Among the different profile canopies, the one with the best wind performance is the upward canopy, followed by the flat canopy, and the worst is the downward canopy. In the actual situation, canopy form selection needs consider the factors such as rain treatment, sound treatment, equipment suspension and light environment in football stadium. Generally speaking, flat canopy performance in these aspects is not as good as that of upward-sloping canopy, so compared comprehensively, upward-sloping canopy should take precedence over others when making design decisions.

(2) Canopy form Selection for redeveloping professional football stadium

For cold areas, it is recommended to choose upward canopy when redeveloping professional football stadiums. If the canopy profile inclination of football stadiums before reconstruction is small, it can also be transformed into flat canopy.
(3) Coping strategies for different wind environment requirements in winter and summer
As the wind velocity in summer is relatively small compared with that in winter, but the temperature is very high. Under the hot and sultry conditions, it is necessary to strengthen ventilation to prevent lawn pests or rotten grass root necrosis and ensure the wind environment stability in field, and improve ventilation in the stand area, which is contrary to the need to reduce the wind velocity in winter. It can be achieved by adjusting the permeability rate of the external envelope interface and the internal seating interface. According to the demand, the interface can be opened to guide the air flow in summer, and closed in winter prevent the invasion of strong winds.

(4) Lack of the research
As computational capacity is limited, there may be more accurate in the operation of numerical simulation, the simplified model extracted in the study is abstract, and the result deviates from the real state, so this study is an ideal state. The actual building wind field environment needs to be determined according to the comprehensive influence of the surrounding site. Due to the limitation of time and space, in order to observe the change of wind field under different canopy forms, the canopy tilt angle is selected as 15°, and other influencing factors such as canopy tilt angle need to be further discussed.

4. CONCLUSION
This study establishes professional football stadium simulation model, and put forward the suitable wind environment evaluation criteria suitable for cold areas in China combined with investigation analysis and objective literature research. The conclusion is drawn that the upward canopy or flat canopy should be preferred and the downward canopy should be avoided as much as possible. From the perspective of wind environmental comfort, this paper proposes a more suitable professional football stadium canopy form optimization mechanism for the cold area in China through multi-objective coupling.

ACKNOWLEDGEMENTS
Project Supported By National Natural Science Foundation of China (Grant No. 51878200)

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Research on Tennis Court Optimum Design Based on Wind Environment Simulation

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ABSTRACT: With the implementation of the ‘healthy China’ strategy, the sports industry has developed rapidly, and sports building construction is also in full swing. The construction of tennis court in China started relatively late. The tennis court quantity and space quality is insufficient, which restricts the tennis developing in China. Existing professional tennis courts are mostly semi-closed, which are susceptible to adverse wind environment and can not meet the competition requirements. In this paper, based on the established professional tennis court numerical modelling and CFD simulation, the wind environment quality is taken as the evaluation criteria, and the wind velocity and wind pressure are the factors affecting the wind environment in the stands and pitch. By adjusting the tennis court stands and canopy parameters, the influence factors of the adverse wind environment on the tennis court are analyzed, and the ideal building model is propose. Finally, design suggestions are put forward, which provides a theoretical basis for the professional tennis courts wind environment optimization in cold regions of China.

KEYWORDS: Tennis court, Wind environment, simulation

1. INTRODUCTION

With the high-quality development of China’s economy, competitive sports develop rapidly². The construction of tennis courts in China starts relatively late, tennis is more popular than other outdoor sports. In the tennis competition, affected by the wind, the tennis direction and velocity will change, which will affect the players’ performance and the game fairness, and the physical comfort of athletes and spectators will also be reduced. The existing professional tennis courts are mostly semi-closed, which are greatly affected by the wind environment and can not meet the needs of the game.² In recent years, retractable roofs have been added to the finals of major tennis venues. However, the non-final courts are less covered due to financial problems. With high energy consumption, the retractable-roof central tennis court breaks through the traditional tennis game natural atmosphere, which has an impact on the fans experience, and also makes the tennis lose the outdoor sport charm. In the semi-closed tennis court, the spectators are directly exposed to the outside natural environment, which will affect the spectators experience. It is still necessary to control the adverse climatic impact on the courts through optimized tennis courts design.

2. METHODS

In the situation of social and economic development, the fairness and justice of competitive sports has been improved year by year. As an outdoor sports event advocating nature, the influence of natural conditions can not be ignored. The wind velocity in tennis competition will directly affect the return point of tennis. In case of windy weather, referees and players can apply for termination. However, athletes should try their best to adapt to the situation when the competition is suspended. Wind velocity and direction will change players’ tactics and impose higher technical requirements. The French Open is often delayed by the weather. It is not uncommon for players to complain about the weather. It can be concluded that the wind influence on tennis are: (1) Impact on competitions’ fairness: Adverse wind direction and wind velocity will have a great influence on the competition fairness. (2) Impact on players’ physical fitness: Strong wind and high temperature will accelerate the decline of athletes’ physical fitness and cannot meet the needs of long-time competition. (3) Impact on the Spectators’ comfort: Wind velocity in spring, summer and autumn has little effect on human thermal comfort, which can be ignored in general. But it makes great impacts on spectators experience in winter particularly in the cold regions. Although tennis advocates outdoor sports, the spectators’ comfort requirement should be improved. (4) Impact on the game process: There is a theoretical blank in the competition suspension regulation on the wind influence. Therefore, it is urgent to study the tennis court wind influence based on the players and spectators comfort need. Wind velocity has a great influence on human thermal comfort in winter³. The purpose of simulation experiment is to optimize the tennis court wind environment with different stands and canopy

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forms. Therefore, this paper studies the tennis court wind environment by numerical simulation in order to control certain wind velocity to meet the outdoor tennis game needs in cold winter area[4].

2.1 Determine the research object
The stands layout directly affects tennis court configuration, capacity and space experience. There are various stands layouts in tennis court, which are inseparable from the tennis game characteristics. The main stands layout form evolved from square and round[5]. The square court has the advantages of flexible form, favorable orientation, convenient combination for temporary seats, etc. The round stand has the advantages of comfortable viewing angle and strong competition atmosphere, but the building scale is fixed and lacks flexibility. The round court is generally used in large-scale courts that need highlight the grandeur, which can be divided into round, oval, polygon.[6] Therefore, this paper chooses the square and round stands layout to simulate the tennis court wind environment.

To respond to the ‘healthy China’ strategy and promote the national fitness plan, this paper aims to set the experimental object as the non-final large-scale semi-closed tennis court in the second and third tier cities in cold area in China. The grading method of China’s tennis court is basically the same as that of the international tennis court (Table 1). The tennis court model is located in Dalian City, Liaoning Province, with 4000 seats. According to the tennis court construction specifications, the tennis pitch is about 1100m², 0.6m/seat is taken, and the stands is about 2400m², a total of 3500m².[6] With the stands arranged around the square or round field. According to the author’s statistics, in the semi-closed tennis court canopy sections, 17% is upward, 58% is flat, and 25% is downward. By summarizing and analyzing the rules of the semi-closed tennis court canopy, the inclination of the canopy of the experimental model is determined as upward 15°, flat 0° and downward 15°. The experimental model refers to the existing tennis court, but due to the limitation of the computer storage and computation capability, the tennis court model is properly simplified. The square tennis court is 55m wide and 65m long; the round tennis court diameter is 68m. There are 11 rows of stands in square tennis court and 14 rows of stands in round tennis court. Other data refer to table 3. (Table 3).

<table>
<thead>
<tr>
<th>Grade</th>
<th>Asian Games, Confederation Cup, tour, international games</th>
<th>More than 4000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade B</td>
<td>National Games, Multi side (double side) international competition</td>
<td>More than 2000</td>
</tr>
<tr>
<td>Grade C</td>
<td>General regular competition</td>
<td>2000 below</td>
</tr>
</tbody>
</table>

Table 2: Tennis court capacity scale

<table>
<thead>
<tr>
<th>Auditorium arrangement</th>
<th>Roof plan</th>
<th>Profile</th>
<th>Isometric drawing</th>
</tr>
</thead>
<tbody>
<tr>
<td>square</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>flat canopy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>downward canopy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>round</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>flat canopy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>upward canopy</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Tennis court dimensions

<table>
<thead>
<tr>
<th>Category</th>
<th>Grade</th>
<th>Competition grade</th>
<th>Capacity of main spectator stands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gregory</td>
<td>Speci al</td>
<td>Olympics, Davis Cup, Grand</td>
<td>More than 10000</td>
</tr>
</tbody>
</table>
2.2 Determine the evaluation criteria

In this research Fluent 17.0 is selected as the experimental platform, ICEM CFD 17.0 as the pre processor and tecplot360 ex 014 RI as the post processor. The research object belongs to the disturbance of bluff body, and the realizable K - ε model is selected as the turbulence model. The tennis court wind environment is determined by the space enclosed by stands and canopy. There are different evaluation criteria of wind velocity at home and abroad. The parameters used in Lawson criteria, Davenport criteria and Shuzo Murakami criteria are different in the world[7][8]. The outdoor wind velocity criteria in China is only V < 5m/s. Before the professional tennis match, the court will be tested for wind velocity. When the wind velocity is high enough to affect the normal hitting track, the referee will suspend the match. However, there is no clear wind velocity limit in the world.

Based on the existing evaluation criteria in the world, through comparison and integration, the wind velocity range suitable to professional tennis court is obtained (Table 4).

Table 4: Wind velocity range of tennis court[6][2][8]

<table>
<thead>
<tr>
<th>Audience area</th>
<th>Optimal Wind Velocity (m/s)</th>
<th>Comfortable Wind Velocity (m/s)</th>
<th>Tolerable Wind Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6&lt;V&lt;2.5</td>
<td>2.6&lt;V&lt;3.1</td>
<td>3.2&lt;V&lt;5.4</td>
<td></td>
</tr>
<tr>
<td>Competition is possible (m/s)</td>
<td>Ending the game (m/s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V&lt;12(the greater the wind, the greater the impact)</td>
<td>V&gt;12.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: The wind environment in the stands mainly refers to the standard in the “sitting” state; The wind velocity in the competition area refers to the wind velocity when the Rio tennis match is suspended;

2.3 Determine the computational domain

The key step in numerical simulation is to determine the calculation domain, which determines the mesh number and calculation quality[9][10]. Too small calculation domain will directly affect the simulation results, and too large calculation domain will increase unnecessary calculation[11]. Considering the 3% blocking rate and the calculation domain full development, and considering the factors such as the height width ratio of the model windward side, the model plane length width ratio, and the model height, the square tennis court calculation domain is 397 × 305 × 99.6m, the air inlet distance is 83m, the air outlet distance is 249m; the round tennis court calculation domain is 436 × 378 × 110.4m, the air inlet distance is 92m, the air outlet distance is 276m (Table 5).

Table 5: Calculation domain of tennis courts model[7]

<table>
<thead>
<tr>
<th>Square</th>
<th>Circular</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Square Tennis Court" /></td>
<td><img src="image2.png" alt="Circular Tennis Court" /></td>
</tr>
</tbody>
</table>

2.4 Determine the boundary conditions

According to the meteorological data (Table 6) of Dalian City in China's surface annual monthly value data set (1981-2010)[8], in winter, the main wind direction in Dalian is north, the average wind velocity is 4.53m/s. The wind direction is perpendicular to the short axis of the tennis court. In the experimental setup, the pitch, stands and canopy were set as sliding wall. In order to make the flow in the basin fully flow, the inlet boundary is defined as the velocity inlet, the outlet boundary is defined as the pressure outlet, and the top and side are set as the symmetry plane.

Table 6: Winter meteorological data of Dalian[8]

<table>
<thead>
<tr>
<th>Winter monthly order</th>
<th>Annual average monthly wind velocity (M / s)</th>
<th>Maximum wind direction in years (including calm wind)</th>
<th>Annual maximum wind velocity (M / s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>4.6</td>
<td>1 (North wind)</td>
<td>25.0</td>
</tr>
<tr>
<td>1</td>
<td>4.5</td>
<td>1 (North wind)</td>
<td>25.2</td>
</tr>
<tr>
<td>2</td>
<td>4.5</td>
<td>1 (North wind)</td>
<td>31.3</td>
</tr>
</tbody>
</table>

2.5 Computational Area Meshing

In the numerical simulation experiment, the polyhedral mesh is adopted, and the high-velocity mesh is divided by the system itself to optimize the model topology. According to the software calculation capacity and model particularity, the grid size of square tennis court is defined as 15m, and canopy and stands is defined as 0.5m, and the final grid number is 2.76 million; the grid size of circular tennis court is defined as 20m, and canopy and stands is defined as 0.8m, and the final grid number is 1.29 million (Table 7).

Table 7: Grid and wind direction analysis chart

| Grid and wind direction analysis chart | Table 7 |
3. RESULTS AND DISCUSSION

There are two main factors that affect the wind environment in the pitch and stands of the tennis court: (1) The wind flow around the tennis court. (2) The wind field formed by the tennis court stands and canopies. The research on the relationship among the plane shape, canopy shape and air flow characteristics of tennis court is helpful to optimize the tennis court configuration in the design stage, improve the thermal comfort of the pitch and the stands, and embody the people-oriented design principle.

In the experiment, the wind environment map at the elevation of 1m and 5m were selected as the basis for discussion, the wind velocity influences on the stands and tennis ball which at the drop point and the highest point were discussed. This paper only simulates the stands layout and canopy form with certain typical characteristics. Other factors are defined as ideal state.

The numerical simulation results are obtained (Table 8). In this paper, the wind environment assessment and analysis basis is as follows: (1) The average wind velocity in the stands and pitch; (2) The uniformity of wind field distribution; (3) The stability of wind velocity change; (4) Adding “reduce wind velocity” as the auxiliary evaluation standard for the windy area [15].

3.1 Analysis Of Test Results Of Horizontal Section

It can be seen from table 8:

(1) In the square straight upward canopy tennis court, the maximum wind velocity in the stands is 2.2m/s, which appears in the area close to north court part, and the minimum wind velocity is 0.32m/s, which appears in the area close to the court in the north of the east and west stands, and the wind velocity in the whole stands is symmetrical; In the pitch, the maximum wind velocity at the elevation of 1m and 5m is 1.6m/s, the minimum wind velocity at the elevation of 1m is 0.64m/s, and at the elevation of 5m is 0.96m/s.

(2) In the square straight flat canopy tennis court, the maximum wind velocity in the stands is 2.8m/s, which appears in the area close to the court in the east and west stands. In the pitch, the minimum wind velocity is 0 m/s, which appears in the center area of the east and west stands and the south stands, with a symmetrical trend between the east and the west; The maximum wind velocity is 1.9m/s at the elevation of 1m and 1.6m/s at the elevation of 5m in the pitch. The minimum wind velocity at the elevation of 1m and 5m in the pitch is 0.32m/s.

(3) In the square straight downward canopy tennis court, the maximum stands wind velocity is 4.9 m/s, which appears in the area near the court on the south, east and west three sides, and the north part, which is close to the court, with a minimum wind velocity of 0 m/s, which appears in the area far away from the court on the north side; In the pitch, the maximum wind velocity is 4.2m/s and the minimum wind velocity is 0.32m/s at the elevation of 1m and 5m.

- Table 8: Simulation results

<table>
<thead>
<tr>
<th>Spectator Seats(Stand interface)</th>
<th>Competition area at 1m level</th>
<th>Competition area at 5m level</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Upward canopy" /></td>
<td><img src="image2" alt="Upward canopy" /></td>
<td><img src="image3" alt="Upward canopy" /></td>
</tr>
<tr>
<td><img src="image4" alt="Flat canopy" /></td>
<td><img src="image5" alt="Flat canopy" /></td>
<td><img src="image6" alt="Flat canopy" /></td>
</tr>
<tr>
<td><img src="image7" alt="Downward canopy" /></td>
<td><img src="image8" alt="Downward canopy" /></td>
<td><img src="image9" alt="Downward canopy" /></td>
</tr>
</tbody>
</table>

(4) The maximum wind velocity in the stands is 2.5m/s in the round straight upward canopy tennis court, which appears in the area close to court in the...
north and south, and the minimum wind velocity is 0m/s, which appears in the area near the court in the north of the center of the east and west sides; In the pitch, the maximum wind velocity is 3.8m/s and the minimum wind velocity is 0.32m/s at the elevation of 1m. The maximum wind velocity is 1.9m/s and the minimum wind velocity is 0.64m/s at the elevation of 5m.

(5) In the round straight flat canopy tennis court, the maximum wind velocity in the stand is 3.2m/s, which appears in the area near the court in the east and west and far away in the south part. The minimum wind velocity is 0 m/s away from the court, which appears in the central area of the north and south sides; In the pitch, the maximum wind velocity is 3.8m/s at the elevation of 1m, 1.6m/s at the elevation of 5m. The minimum wind velocity at the elevation of 1m and 5m is 0.64m/s.

(6) In the round straight downward canopy tennis court, the maximum wind velocity in the stand is 4.1 m/s, which appears in the area near the court on the south side, and the minimum wind velocity is 0m/s, which appears in the area far away from the court on the north-west side. In the pitch, the maximum wind velocity at the elevation of 1m and 5m is 4.2m/s, the minimum wind velocity at the elevation of 1m is 0.64m/s, the minimum wind velocity at the elevation of 5m is 0.96m/s.

### 3.2 Analysis Of Average Wind Velocity Test Results

**Table 9: Average wind velocity analysis chart**

<table>
<thead>
<tr>
<th>Average wind velocity of different audience</th>
<th>![Average wind speed chart of tennis court with different audience]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average wind velocity of square tennis court</td>
<td>![Average wind speed in different positions of square tennis court]</td>
</tr>
<tr>
<td>Average wind velocity of round tennis court</td>
<td>![Average wind speed in different positions of the round tennis court]</td>
</tr>
</tbody>
</table>

For the stands: the maximum wind velocity in the stands appears in the square downward canopy model, and the minimum wind velocity in each model stands is 0 m / s. The order of the average wind velocity is: square downward canopy > round downward canopy > round flat canopy > square flat canopy > round upward canopy > square upward canopy.

According to table 4, the maximum wind velocity of the stand is within the range of tolerable wind velocity. From the perspective of stands wind environment quality, the configuration preference order is as follows, straight downward canopy > straight flat canopy > straight upward canopy; round > square.

For the pitch: the average wind velocity at the elevation of 1m: round straight downward canopy > square straight downward canopy > round straight flat canopy > round straight upward canopy > square straight flat canopy > square straight upward canopy. The average wind velocity at the elevation of 5m: round straight downward canopy > square straight downward canopy > round straight upward canopy > round straight flat canopy > square straight flat canopy. According to table 4, the smaller wind velocity in the pitch, the more suitable for the competition. Therefore, according to the average wind velocity at different elevation of the pitch. The courts configuration preference is that: straight flat canopy > straight upward canopy > straight downward canopy; square > round.

Due to the different requirements of wind velocity in the pitch and stands, square and round tennis courts have their own advantages. For the canopy profiles priority, straight flat canopy > straight downward canopy > straight upward canopy > straight flat canopy. Straight flat canopy can take into account the wind velocity demand of the stands and the pitch. With the increase of the level of tennis match, the requirement of the match fairness increases gradually, and the advantage of square tennis court will increase gradually.

Based on the ideal state, the research neglect minor issues which make little influence in reality, the tennis court wind environment is not only closely related to surrounding environment, but also related to the factors of itself, such as the building form, building density, the canopy form, the structure material, the connection between the canopy and the stand, the location and the entrance and exit size, etc.

At present, the research on the wind environment in the tennis court is a theoretical blank in China. With the rapid development and deep demand of tennis, additional studies assessing the wind environment of the tennis court would be welcome, which will provides a theoretical basis for the strategy of healthy China.

### 4. CONCLUSION

(1) This paper explores the scientific evidence-based architectural design method through simulation experiment results. Through the application of this method, which can improve architect rational thinking and optimization design.

(2) This paper simulates the wind environment performance of ideal model extracted from semi-
closed tennis court, and gives a series of multi-objective optimization design strategies from the perspective of wind environment. It provides practical and reliable rational design basis for the construction or transformation of semi-closed tennis courts in the future.

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REFERENCES
Machine Learning in Glare Analysis: A New Framework for Glare Prediction in Open-Plan Offices

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Abstract: Accurate glare prediction is a challenging task due to its subjective nature, as occupants’ sensitivity to visual discomfort may differ under the same conditions depending on the individual. Although several glare metrics have been developed, limitations still exist. In this study, a new framework was proposed for developing new discomfort glare prediction models with higher accuracy using machine learning (ML) techniques. Machine learning algorithms act as classifier models which suit the stochastic nature of input data and non-linear problems. They were applied to explore their applicability in predicting glare in open-plan office spaces. Post occupancy evaluation (POE) data collected from 80 occupants in four open-plan offices in Brisbane, Australia were used to train ML models and test their prediction accuracy. Various glare indices and multi-region luminance values were extracted from high dynamic range images and used as input features for the training process. Results showed a high potential of using ML, as an overall accuracy of 83.8% was reached using the RUSBoost tree algorithm. The workflow was compiled into an easy-to-use tool called Open-Plan Glare Evaluator (OGE) for open-plan spaces with low illuminance conditions. The same workflow can be reapplied using more data collected from other locations to develop a global glare prediction model using machine learning.

KEYWORDS: Glare, Visual Discomfort, Machine Learning, High Dynamic Range Images, Open-plan Offices

1. INTRODUCTION

Generally, most daylit open-plan offices fail to eliminate glare problems without compromising the overall availability of daylight [1, 2]. Although glare prediction has been widely addressed [1, 3, 4] through conventional statistical methods, most glare metrics were not developed to tackle glare predictions in open-plan offices where electric lighting is more prevalent than daylight [5, 6]. Many studies have reported the accuracy of glare indices in predicting glare in relation to the glare evaluation collected from post-occupancy evaluation POE or experimental studies [6-17].

Glare is a serious problem that affects the productivity of occupants and their well-being. Consequently, creating an accurate prediction model is a persistent need. Glare metrics use mathematical equations developed on the basis of contrast, saturation, absolute threshold, or empirically-derived equations [5]. Some studies have highlighted the limitations of these glare metrics in predicting visual discomfort [8, 18]. By trying to improve their prediction accuracy for specific conditions, new glare metrics have emerged using new field data with different settings. For example, the Unified Glare Probability (UGP) index was derived from a previous metric (UGR) to be used for open-plan offices [19]. Although it reached an overall accuracy of 69%, the True Positive Rate (TPR) was 0.49, which represents the actual glare situations that were predicted correctly. This signified some bias towards the True Negative Rate (TNR), which represent the actual non-glare situations that were predicted correctly. Other glare metrics showed higher prediction accuracies like DGP, which reached 0.74 TPR and 0.72 TNR [5]. However, the cases observed under study were daylight-dominated cellular offices, which differ from open-plan offices that have low daylighting levels. In the area of glare prediction, statistical methods were mainly used to derive thresholds for a given glare metric based on the overall accuracy, True Positive Rate (TPR), and True Negative Rate (TNR). Machine learning is another approach that can be integrated into the process, but has not yet been explored in glare prediction.
Machine learning (ML) techniques have been widely utilised on various applications to create predictive models by finding the non-linear relationships between the input features and the outcomes/responses [20]. In this paper, we evaluated the prediction accuracy of multiple ML models that use glare indices, luminance maps and occupant responses as features for training the models. We then compared these models in relation to the 22 previously-developed glare, luminance and illuminance indices [21]. The ML model that demonstrated the highest prediction accuracy was compiled as a glare evaluator tool (OGE) for classifying both glare and no-glare situations in open-plan offices.

2. METHODOLOGY

2.1 Data collection

A field study was conducted in an open-plan office in Brisbane, Australia, in which the glare responses of 80 participants were collected in parallel with capturing their luminous field of view. Fifty (50) participants did not experience glare during data collection, and thirty (30) reported visual discomfort from glare. Low Dynamic Range (LDR) images at different exposures were taken with a Samsung S7 smartphone, forming High Dynamic Range (HDR) images that provided the luminance information necessary to support the calculation of glare indices [22]. These images were cropped to follow the field of view (FOV) as shown in Fig. 1.

![Figure 1: An example of one HDR image captured and cropped to the occupants’ FOV.](image)

2.2 Feature selection for training ML models

In order to train a machine learning model, features and responses were acquired and formatted in a matrix \((n \times m + 1)\), where \(n\) was the number of responses from the field study and categorised the responses (Glare/No Glare) of the 80 occupants. In this formula, \(m\) was the number of extracted features. The intelligence of ML algorithms lies in finding a relationship between these features and the corresponding responses. A five k-fold cross-validation scheme [23] was used to estimate the accuracy of the model without overfitting. In this scheme, the data was randomly partitioned into five folds; each was used for testing, while the four other folds were used for training.

Two approaches for selecting features were adopted in this study. Firstly, glare scores of 24 glare metrics were calculated and formatted in an 80 by 25 matrix (i.e. 22 features + response). Each score acted as a predictive feature for the 25 ML classification models. Secondly, the average luminance was extracted from HDR images using the multi-region luminance method, which was introduced by Wagdy et al. [24]. The HDR images were then divided into equal regions at seven different resolutions, so the number of regions ranged from 62 at the lowest resolution to 980 at the highest resolution. These were named MRL regions, as shown in Fig. 2. The seven grid sizes were generated parametrically using the brute-force method, which is widely used in parametric analyses and simulations [25-31]. The average luminance was calculated for each region within the FOV and was then input as features for training the ML models.

![Figure 2: An example of Multi-Region Luminance (MRL) showing the smallest (62) and largest (980) subdivisions.](image)

2.3 Evaluation of machine learning models

Evalglare [21] was used to conduct a detailed glare analysis. However, glare indices have their cut-off values established in experimental scenarios which may not be transferred practically into field settings [13]. Besides, glare metrics may classify glare on a scale of four values. As we used binary evaluation in the POE, new cut-off values were established based on the data collected using ROC analysis [32]. Optimal cut-off values that distinguish highest accurate predicted cases between glare and no glare responses were derived. The 22 glare indices were evaluated against the subjective responses of the 80 subjects in order to measure the prediction accuracy of each metric. The accuracy of the ML models was then evaluated against the 22 glare metrics, with the ad hoc thresholds used to generate an unbiased comparison. The performance of the predictive models was filtered based on their overall accuracy, TPR and TNR with an acceptance threshold of at least 70%, 0.5 and 0.5 respectively, as shown in Fig. 3.
3. RESULTS

The ML models' prediction accuracy showed promising results and high potential to predict glare across the assigned features. For each feature, ML algorithms were purified based on their prediction accuracy. They were filtered so that the ML algorithm of the highest performance can be demonstrated for each feature, as shown in Table 1. Support vector machines (SVM), k-nearest neighbours (KNN), Naive Bayes, and tree-based algorithms are among those that reached the highest accuracies. The RUSBoost tree algorithms, along with the average illuminance features using MRL method of 374 regions, achieved the highest overall accuracy of 83.8%, with TPR of 0.8 and TNR equal to 0.86, as shown in Fig. 4.

It was observed that most glare scores did not exceed the TPR criteria. Only EV_dir reached 0.67; however, the overall accuracy was lower than 70%. This showed a bias towards TNR to increase the overall accuracy.

To evaluate the approach of using ML where glare scores act as features, the performance of glare metrics was evaluated using ROC analysis. The overall accuracy, TPR and TNR were calculated for each feature, as shown in Fig. 5. These values showed that TPR and TNR were mostly exceeding the benchmark of 0.5. However, the overall accuracy was below 70%, except for the luminance background metric, which achieved 87.75%, 0.66 TPR and 0.89 TNR, with an optimised cut-off value of 103. By comparing the performance of glare metrics with the derived cut-off values using ROC analysis against using them as features in ML models, it was found that ML increased the overall accuracy prediction as well as TNR. However, TPR was relatively low, as shown in Fig. 6.

Table 1: Highest achieved prediction accuracy across all of the assigned features sorted according to TPR. All models that could not pass the acceptance criteria were highlighted in blue.

<table>
<thead>
<tr>
<th>Features</th>
<th>Overall Accuracy</th>
<th>TPR</th>
<th>TNR</th>
<th>ML Algorithms</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRL-374</td>
<td>83.8</td>
<td>0.80</td>
<td>0.86</td>
<td>RUSBoostedTrees</td>
</tr>
<tr>
<td>Ev_dir</td>
<td>68.8</td>
<td>0.67</td>
<td>0.70</td>
<td>SubspaceKNN</td>
</tr>
<tr>
<td>MRL-544</td>
<td>73.8</td>
<td>0.63</td>
<td>0.80</td>
<td>RUSBoostedTrees</td>
</tr>
<tr>
<td>MRL-739</td>
<td>78.8</td>
<td>0.63</td>
<td>0.88</td>
<td>BaggedTrees</td>
</tr>
<tr>
<td>MRL-133</td>
<td>76.3</td>
<td>0.57</td>
<td>0.88</td>
<td>GaussianNaiveBayes</td>
</tr>
<tr>
<td>MRL-980</td>
<td>76.3</td>
<td>0.53</td>
<td>0.90</td>
<td>BaggedTrees</td>
</tr>
<tr>
<td>Av_Lum_pos2</td>
<td>68.8</td>
<td>0.57</td>
<td>0.80</td>
<td>GaussianNaiveBayes</td>
</tr>
<tr>
<td>MRL-62</td>
<td>77.5</td>
<td>0.5</td>
<td>0.94</td>
<td>GaussianNaiveBayes</td>
</tr>
<tr>
<td>DGP</td>
<td>68.8</td>
<td>0.47</td>
<td>0.82</td>
<td>MediumGaussianSVM</td>
</tr>
<tr>
<td>DGR</td>
<td>71.3</td>
<td>0.47</td>
<td>0.86</td>
<td>KernelNaiveBayes</td>
</tr>
<tr>
<td>Lveil_CIE</td>
<td>71.3</td>
<td>0.47</td>
<td>0.86</td>
<td>KernelNaiveBayes</td>
</tr>
<tr>
<td>MRL-214</td>
<td>72.5</td>
<td>0.47</td>
<td>0.88</td>
<td>GaussianNaiveBayes</td>
</tr>
<tr>
<td>Lum Background</td>
<td>76.3</td>
<td>0.47</td>
<td>0.94</td>
<td>MediumGaussianSVM</td>
</tr>
<tr>
<td>Med_lum_pos</td>
<td>73.8</td>
<td>0.43</td>
<td>0.92</td>
<td>MediumKNN</td>
</tr>
<tr>
<td>Med_lum</td>
<td>76.3</td>
<td>0.43</td>
<td>0.96</td>
<td>SubspaceDiscriminant</td>
</tr>
<tr>
<td>Med_lum_pos2</td>
<td>77.5</td>
<td>0.43</td>
<td>0.98</td>
<td>SubspaceDiscriminant</td>
</tr>
<tr>
<td>CGI</td>
<td>65</td>
<td>0.4</td>
<td>0.80</td>
<td>MediumKNN</td>
</tr>
<tr>
<td>DGI</td>
<td>70</td>
<td>0.4</td>
<td>0.88</td>
<td>CoarseTree</td>
</tr>
<tr>
<td>DGI_mod</td>
<td>70</td>
<td>0.4</td>
<td>0.88</td>
<td>FineGaussianSVM</td>
</tr>
<tr>
<td>VCP</td>
<td>65</td>
<td>0.37</td>
<td>0.82</td>
<td>GaussianNaiveBayes</td>
</tr>
<tr>
<td>Omega_S</td>
<td>71.3</td>
<td>0.37</td>
<td>0.92</td>
<td>SubspaceDiscriminant</td>
</tr>
<tr>
<td>Av_Lum</td>
<td>75</td>
<td>0.37</td>
<td>0.98</td>
<td>LinearSVM</td>
</tr>
<tr>
<td>Av_Lum_pos</td>
<td>68.8</td>
<td>0.33</td>
<td>0.90</td>
<td>SubspaceDiscriminant</td>
</tr>
<tr>
<td>Ev</td>
<td>70</td>
<td>0.33</td>
<td>0.92</td>
<td>CoarseGaussianSVM</td>
</tr>
<tr>
<td>UGR_exp</td>
<td>65</td>
<td>0.3</td>
<td>0.88</td>
<td>GaussianNaiveBayes</td>
</tr>
<tr>
<td>UGR</td>
<td>67.5</td>
<td>0.27</td>
<td>0.92</td>
<td>FineGaussianSVM</td>
</tr>
<tr>
<td>UGP</td>
<td>63.7</td>
<td>0.23</td>
<td>0.88</td>
<td>FineGaussianSVM</td>
</tr>
<tr>
<td>Lveil</td>
<td>66.3</td>
<td>0.23</td>
<td>0.92</td>
<td>MediumGaussianSVM</td>
</tr>
<tr>
<td>Lum_sources</td>
<td>67.5</td>
<td>0.23</td>
<td>0.94</td>
<td>MediumGaussianSVM</td>
</tr>
</tbody>
</table>

Figure 4: Showing the TPR and TNR for the ML model using Multi-Region Luminance (MRL) with 374 equally-sized regions.
Figure 5: Prediction accuracy of the 22 glare metrics using ROC analysis.

Figure 6: Comparing glare metrics performance with optimal cut-offs in ROC analysis and features in ML models.

Figure 7: The simplified process of predicting glare in open-plan offices. OGE loads the specified folder of HDR images and processes them using the pre-trained machine learning model, then creates a CSV file with the prediction output.
4. DISCUSSION

Glare evaluation in open-plan offices differs from glare evaluation in cellular offices due to their design configuration, which is characterised by low illuminance and contrast-based glare. In general, predicting discomfort glare is challenging due to its subjective dimension. People differ in their sensitivity to light; in open-plan offices, several occupants sitting apart may have different perspectives, thereby complicating the space glare evaluation. Various glare metrics have been developed based on experimental studies that focused on cellular offices. However, very few studies focused on metrics that suit the unique lighting conditions present in open-plan offices.

Based on the field data collected, a machine learning approach was explored and compared with the statistical method of glare evaluation. The 22 glare metrics were input as training features in ML algorithms to find the non-linear relationship between glare responses and glare scores. Additionally, the average luminance of equally-sized regions in the FOV was examined as another method for features extraction to train the ML model. The Multi-Region Luminance (MRL) results showed to have a high potential to be used as features for ML algorithms. The MRL of six grid sizes reached the assigned criteria, whereas only MRL-244 failed to pass the TPR criteria with a small margin of 0.03 difference.

Using glare indices as features failed to pass the three criteria, as the TPR was below the 0.5 threshold. However, using these glare scores in ML as features outperformed the direct use of their cut-off values in ROC analysis in terms of overall accuracy and TNR. Thus, it is suggested in future research that multiple glare features can be compiled together and be used as combined features in ML.

The high potential of using ML models in conjunction with low-cost, low-resolution data acquisition systems for glare prediction was emphasised in this study. They reached an overall accuracy of more than 80% with the pre-trained ML OGE model. Although a bias towards TNR was noticed in several cases, a few models succeeded in passing the three criteria (overall accuracy, TPR and TNR), which used the MRL of different region sizes as training features. These results are confined to the data collected in which the lighting conditions of open-plan offices have illuminance ranged from 200 to 600 lux. This approach of using machine learning showed a promising predictive power, which can be enhanced with more data collection to cover a broader range of light situations and subjective glare sensitivity.

4. CONCLUSION

Machine learning techniques are capable of competing with statistical methods of inaccurate glare prediction. They are advantageous in representing the stochastic nature of glare responses and characterising their non-linear relationships with glare prediction, thus enabling the creation of more visually-comfortable office buildings. The workflow is compiled into a developed Open-plan Glare Evaluator (OGE) tool, which can be used as an indicator for glare analysis in open-plan offices, as shown in Fig. 7. The OGE tool and the MATLAB code are both accessible through GitHub: https://github.com/aymanwagdy/OGE-OpenPlan_Glare_Evaluator.

The same machine learning methodology could be further applied to cellular offices where daylight is typically dominant. Therefore, machine learning can become a new way of analysing and predicting glare and informing lighting design about potential visual discomfort. This paper can garner the interest of lighting designers for other daylighting applications, as well as those concerned with the development of machine learning tools.

ACKNOWLEDGEMENTS

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REFERENCES


New Methodological Approach for Glare Analysis on Tunnel Endpoints

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ABSTRACT: When entering and exiting tunnels, high luminance variations may cause severe crashes due to the occurrence of glare and the blackout effect. In this study, we propose a methodology that will effectively minimise the exaggerated light variations that arise over a short distance at the tunnel endpoints. An underpass which has the same characteristics of a tunnel in Brisbane, Australia was selected as a case study; a 3D model of the tunnel was created using Point Clouds, Digital Elevation Model and Open Street Maps. Grasshopper-for-Rhino was used to merge this information in order to create the tunnel's model. The Radiance lighting simulation engine was used to simulate the High Dynamic Range (HDR) images from the drivers' field of view (FOV) to accurately understand their visual experience. These images were post-processed by Evalglare to conduct advanced daylighting and glare analysis. Luminance maps highlighted the problem of high contrast and glare probability in the tunnel entrance. The beneficial outcome of the proposed methodology is not only evaluating glare problems, but also allowing for the optimisation of pre-tunnel lighting that utilizes daylight to maximize energy savings. Thus, the effectiveness of the solar techniques in reducing the contrast and creating a transitional zone that blends the highly illuminated outside with the dark interior can be evaluated.

KEYWORDS: Glare, Tunnels, Daylighting, Road Safety, High Dynamic Range Images

1. INTRODUCTION

Glare is a light phenomenon that causes vision impairment or subjective sensations of visual discomfort [1]. While driving, this visual problem can be experienced due to high contrast or exposure to direct sunlight, resulting in undesired reflections and a low sun angle facing drivers. This causes excessive blinking or squinting. Near tunnels’ endpoints, the risk of glare amplifies when the sun is positioned just above the tunnel entrance, thus increasing the light differential; this overwhelming visual load on the drivers can increase the possibility of crashes. Furthermore, when approaching a tunnel’s entrance, the eyes become affected. As the driver’s vision has already adapted to high luminance levels under the clear sky, the tunnel’s entrance can appear to be a black hole, and once inside, a blackout effect can be felt as illustrated in Figure 1. Du, Z., et al. [2] examined the changes in eyes’ pupil while driving using eye-tracking technology, and they found that more visual load was experienced by drivers when entering the tunnel. A less critical problem also occurs when exiting the tunnel. In general, eyes cannot adapt to sudden changes in luminance levels which may be experienced when entering or exiting tunnels.

Figure 1: shows the black hole effect and the white hole effect found when approaching and exiting the tunnel in images taken with a fisheye lens.

Poor lighting conditions in tunnels presents a major crash risk factor [3]. The sharp transition in lighting levels at a tunnel’s portal is largely responsible for accidents that occur mainly in the morning [4]. Thus, the quality of lighting conditions in tunnels should be maintained, along with the variations of sun and sky conditions. Strategies should target minimising the differences of luminance levels that exist over short distances. According to LOUIS and Tziotis [5], the highest crash rates take place just
before and after the tunnel by a distance of 10 m, as well as near the entrance area (10-150 m). This was also confirmed by Tziotis, et al. [3], who reported that high contrast and a significant light differential at endpoints and glare were potential causes of accidents investigated in four different tunnels.

2. DAYLIGHTING IN TUNNELS

Lighting design should provide high luminance levels at the endpoints in order to address the outside daylight intensity and to reduce the high contrast between the outside and inside. Increasing the luminance through artificial lights without the consideration of energy consumption is not an efficient solution, as tunnel lighting can consume a large amount of energy, especially at the entrance zone [6]. Designing pre-tunnel screens, louvres and redirecting structures that exploit daylight luminance is a promising approach to minimise visual problems that occur while driving in tunnels. Several factors are guiding the lighting design that differ according to each tunnel’s characteristics, which are detailed in the following sections.

2.1 Tunnel classification and zones

Tunnels are classified into three divisions based on their length and exit visibility to determine the appropriate lighting requirements [7]. The first category of tunnels consists of short tunnels, which are less than 25 m and do not require any daytime lighting. The next category, long tunnels, are either geometrically or optically long. The former refers to tunnels that extend to more than 125 m, which always necessitate the standard threshold zone lighting in the daytime. Meanwhile, optically long tunnels are those in which drivers cannot see the exit from the safe stopping distance (SSD), so they should be illuminated in the same way as long tunnels. The final category consists of intermediate length tunnels, which range from 25 m to 75 m and 75 m to 125 m. Other factors interact with these two ranges to determine the lighting requirements, such as the visibility of the exit, daylight penetration (good or poor), the reflectance of walls (either high, > 0.4 or low, < 0.2), and traffic flow (heavy or light) according to the CIE [7]. In the case of intermediate tunnels, all of these factors should be identified to determine if no daytime light is needed, similarly to short tunnels, or if either 50% or 100% of the standard threshold zone lighting is required, like long tunnels [7].

Safety problems in tunnels are commonly associated with poor lighting design. Usually, tunnel length is divided into zones that are used to standardise the lighting needs, which must suitably allow the eye to adapt to changes in light levels for each zone [8]. According to the Commission Internationale l’Eclairage [7], tunnels have different light zones; this starts at the tunnel entrance with the threshold zone, and is followed by the transition, interior and exit zones, as shown in Fig. 2.

![Figure 2: Lighting zones in tunnels adapted from [7]](image)

The threshold zone starts at the tunnel portal, where the eyes start adapting to a lower luminance interior environment. Then, as the eyes get more adjusted, the transition zone starts, and the lighting level continues decreasing until reaching the lowest necessary level in the interior zone, at which point the eyes should have been completely adapted. At the exit zone, the light levels are elevated because of the high brightness of the outside environment, and the eye adaptation is reversed. This endpoint is considered less critical in comparison to the entrance from a safety point of view, as the eye adapts faster from darkness to brightness than vice versa. Also, any obstacle present near the end of the tunnel will appear clearly against the bright background of the exit [8].

The approaching distance before the tunnel portal is described as the access zone. The length of this zone is determined based on the safe stopping distance (SSD), which is measured from the point outside the tunnel where a driver can decelerate and completely stop at the entrance point. This distance depends on the traffic speed; the lower the speed, the shorter the distance [8]. This distance identifies the minimum length of the threshold zone, where the light required at the start of this zone is referred to as Lth [7].

2.2 Lighting requirements at endpoints

The light intensity at the tunnel portals is recommended to remain constant over half the length of the threshold zone; at this point, it can gradually decrease until it reaches 0.4 Lth at the end of this zone, marking the start of the transition zone [7]. The ratio of the sky that is visible in the field of view (FOV) of the driver when approaching the tunnel affects the luminance levels required for the threshold zone (Lth). The average luminance is calculated in a conical FOV of 20 degrees to identify the perceived surrounding luminance, which is referred to as L20. It is measured at a point that represents the eyes of the driver when approaching the tunnel from the safe stopping distance (SSD) [8]. The recommended ratio of luminance at the threshold zone (Lth) to L20 ranges from 0.05 to 0.1 according to the lighting system and the allowed speed [7]. The L20 concept is used as a simplified method to identify the required luminance in the threshold zone, which has the highest lighting
demand [8]. In the exit zone, the lighting levels are usually kept the same as the interior zone [9, 10]. However, in some cases, these levels must be increased gradually to reach five times the interior lighting level over a distance equal to the SSD. The necessary lighting level for the interior zone is 10cd/m² for high-speed roads with a heavy traffic flow, and is reduced to 3cd/m² in low-speed roads with light traffic, as reported by van Bommel [9].

Adding more artificial lighting at tunnels’ endpoints is not the optimal solution for glare-free tunnels. Artificial lights in tunnels are large consumers of energy, mainly because they operate 24 hours each day. Thus, strategies for energy reduction are oriented to:

1) Using efficient artificial lighting equipment.
2) Optimise tunnels’ designs to make use of sunlight.
3) Apply lighting control systems that correspond with the outside ambient conditions, and
4) Improve the surface properties of walls and roads [11].

Controlling luminaire intensity in the threshold and transition zones can be automatically linked with the sun and sky conditions through real-time monitoring of light levels just outside the tunnel. A backup control system is recommended to manage light levels in case of photometric failure [12].

2.3 Pre-tunnel structures

Pre-tunnel lighting (PTL) is a common approach that makes use of ad hoc structures installed in the portal area in order to enhance lighting and reduce the blackhole effect [13]. These structures can reduce the scattered light falling on the eyes from the luminance of the surroundings [10] and utilise sunlight to partially illuminate the portal, thus reducing the need of artificial lights for energy saving. A study by Gil-Martín, et al. [14] showed that a semi-transparent tension structure in the entrance of the tunnel can shift the threshold zone to start earlier, thus allowing sunlight to contribute in achieving the required illuminance for this zone. Different shapes and materials of the tension structure were compared using a simulation method to quantify savings in energy. The shape of the structure had a greater impact on illuminance than the type of material used [15].

The implementation of pergolas was suggested, as they are easier for maintenance than tension structures [16]. However, these structures caused non-uniform daylight distribution which may result in flickering effect and can obstruct clear road vision. Gil-Martín, et al. [17] approached this problem by suggesting the installation of diffusers in voids between the structural beams.

In other studies, more sophisticated systems that introduce daylight inside the tunnel were examined. In Peña-García, et al. [18], light pipes were integrated with heliostats to act as a coupled system to capture and inject sunlight into the tunnel road in the threshold zone. Through theoretical calculations and measurements taken from a mockup, energy savings ranged from 14% to 21% according to the tunnel orientation. Other factors, like landscape surroundings and reflectance of walls and road surfaces, can contribute to the reduction of energy consumption for artificial lighting [12].

The initial and life cycle costs of the applied systems or strategies should result in economic benefits when compared to using conventional artificial lights counterparts [13]. Thus, reliable calculation methods to quantify their benefits are needed.

2.4 Design evaluation methods

To evaluate the performance of the lighting condition in tunnels and the beneficial outcomes of daylighting strategies, analytical and mathematical methods were proposed. Jurado-Pina, et al. [19] suggested a method to identify the probability of sun glare using projections of the sun paths to examine the time intervals when glare problems may occur and identify when mitigation solutions and design countermeasures are needed. To determine the sun and sky’s luminance contribution to road illumination, a general equation (SLT) was proposed in which the efficiency of PTL can be evaluated [20]. Analytical methods are proposed to define the geometric criteria for PTL, and they were applied on hexagonal-shaped meshes that act as a pre-tunnel structure [13].

4. METHODOLOGY

This study aims to introduce a new methodological approach for glare analysis in tunnels’ endpoints using High Dynamic Range (HDR) images. Point clouds are also utilized for the detailed and accurate 3D modelling of tunnels. The proposed methodology was applied as a demonstration on a real case study of an underpass, which is similar to typical tunnels. The case was selected to examine an accessible tunnel in Brisbane throughout the expected critical times (during daylight hours) when the blackhole (entrance of tunnel) and white light phenomenon at the end of the tunnel is more problematic. This case study is located near Sun Corp Stadium on the M3 road, where multiple underpasses form a tunnel-like shape are highlighted in a red colour over the ELVIS- Elevation and Depth – Foundation Spatial Data map as shown in Fig.3

To model an accurate 3D representation of the tunnel, 3D point cloud extracts are used. The point cloud was published by Geoscience Australia in 2015 and was captured by an airborne LiDAR on five-metre grid. It was also combined with the Digital Elevation
Models (DME) of the area to model the ground terrains, as illustrated in Fig. 4 and Fig. 5. By fusing all this information and combining it with the data gathered from Open Street Map, the final 3D model was generated, as shown in Fig. 6.

Figure 3: Shows the selected area for the study.

Figure 4: The DME data that was used to create the terrains.

Figure 5: The 3D point-cloud used to create 3D environment.

Grasshopper, a parametric modelling tool for Rhino 3D modelling software, was used for modelling the tunnel. Diva for Rhino was the interface used for the Radiance and Evalglare lighting simulation engines to conduct the advanced daylighting and glare analysis [21-23]. Next, High Dynamic Range (HDR) images were simulated from the drivers’ field of view (FOV) in order to perceive their experience at multiple, consistently-spaced points throughout the tunnel. Parametric simulation algorithms were used to estimate the daylighting levels, as well as the luminous contrast and glare severity based on luminance maps generated. Theses techniques were conducted based on the best practises in glare [24-28] and daylighting simulations inside the parametric environment [29], as covered in the literature review. The luminance maps were generated for the 180-degree fisheye HDR images for each hour of daytime throughout the year to predict where and when the glare problems could occur. Thus, using the proposed method for modelling and processing the data can yield reliable data for glare and daylighting analysis.

Figure 6: The 3d model of the underpass area.

4. DISCUSSION

Glare problems exist at the tunnel endpoints due to the high contrast between dark and light areas with a contrast ratio reaching more than 1:140, as shown in Fig. 7. The point cloud model is characterised by including all urban design elements and details that affect the luminance of the surroundings. Thus, the captured HDR images can efficiently represent the perceived luminance from the perspectives of drivers in their dynamic state.

Figure 7: the luminance heatmap extracted from the simulated HDR image at the tunnel entrance.

Unlike mathematical equations or mock-ups, the applied method has a higher potential to explore multiple design solutions and to optimize their parameters for safer roads. Through the proposed method, a transitional zone can be assessed and optimized to ensure a gradual blend between the high illuminated outside and the dark interior of the tunnel. The next step will go towards enhancing the lighting
conditions of this transitional zone in order to match the adaptation rate of the human eye to a greater extent.

Being in a motion state with a certain speed makes it more challenging to evaluate the lighting design. The critical part in addressing glare problems in tunnels is increasing the lighting levels at the entrances using daylight techniques. Although these techniques are widely studied in buildings, it can be beneficial to transfer these techniques and apply them to mitigate the tunnel glare problem. For example, dynamic reflectors and shading devices are usually found to perform well in terms of daylighting performance and the control of direct sunlight [30, 31]. These systems can be adapted to the tunnel’s endpoint and evaluated parametrically to increase the lighting levels at the portals areas. These reflectors can have simple shapes, like slats or external sun breakers that are usually used in buildings, which can be scaled up to cover the tunnel entrance [32, 33]. Another static design option that is worth investigating is the solar screens [34-37], as they have geometrical characteristics that are effective in redirecting the sunlight and minimising sun exposure, which may help in shifting the transition zone. Moreover, these screens can be designed based on specific mathematical rules, such as cellular automata, to have a pleasing appearance while maintaining excellent performance [38].

Nevertheless, most conventional tunnel entrances have a simple shade or arch-like geometry, which are easy to build and maintain. However, we believe that if these simple shapes were optimised based on the actual sun path diagram [39], they would have a better performance. On the urban scale, the heights of the adjacent buildings in new or retrofit areas can be regulated [40] by the local councils to ensure sufficient daylight levels near the tunnel entrance for maintaining the efficiency of the new sun reflectors.

4. CONCLUSIONS

The illumination required at endpoint areas should be carefully estimated in order to overcome the blackhole effect and glare problems in the daytime. Increasing luminaires or their intensity do not align with sustainable considerations from the energy perspective. Thus, making use of daylight and redirecting sunlight systems are gaining more recognition. Adding pre-tunnel structures or redirecting techniques allows for the eye’s gradual adaptation to low luminance conditions. This can positively contribute to mitigating problems of glare that occur when there is a large difference between the outside luminance of sunlight and the inside shaded area of the tunnel. However, to maximise their potential against their initial costs and maintenance requirements, a reliable method is needed to accurately predict their contribution to an increase in illumination.

Daytime luminance conditions at the tunnel’s portals are varied according to the geographical location, orientation and surroundings. As this is also sensitive to the surrounding urban context, the detailed point cloud model showed an advantage for accurate prediction of the perceived luminance. Moreover, the parametric simulations of HDR images account for the dynamic changes that occur over the day and year by taking multiple images at critical times, which represent the frequent and severe conditions. Further research should utilise the proposed method to evaluate and optimise pre-tunnel reflectors in order to contribute to drivers’ visual comfort and energy saving.

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Comparison and validation of two simulation workflows for courtyard microclimates

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ABSTRACT: The simulation of urban microclimates in a way that is flexible enough to be included in the early design stages is still a problem to be solved. Furthermore, the necessity to find a balance between accuracy, provided by the use of CFD software requiring high computational power, operational speed and integration with the modelling tool, is an even more complex challenge. Accordingly, this research investigates the use of the Ladybug Tools, a set of plugins for Grasshopper that links analysis and design, in a hybrid workflow, to simulate the thermodynamic performance of courtyards, a transitional space of buildings that is proven to be a passive design strategy to reduce energy consumption. The results show that the hybrid workflow has a similar accuracy to the integrated CFD tool analyzed, but having the advantage of using the same design interface. It also provides the transparency of an open-source software and the possibility of improving the result in further research.

KEYWORDS: Courtyards, Outdoor Simulation, ENVI-met, Ladybug tools, Validation.

1. INTRODUCTION

The design of outdoor spaces in cities is becoming an important area of research due to the potential of these kind of spaces in reducing the Heat Island Effect, increasing the thermal comfort of citizens. At a smaller scale, outdoor spaces such as courtyards can also create microclimates inside the buildings that help increase thermal comfort and reduce energy consumption [1]. Courtyards are considered a traditional passive strategy that has been widely used in many cultures [2]. The performance of a courtyard depends on many variables such as geometry, orientation, materials, existence of vegetation and water bodies or wind. Our role as designers is to combine them to provide the best possible scheme. Nowadays, apart from traditional best practices, we can also use simulation tools that predict their performance.

However, there is a very limited number of tools that designers can use to analyze the performance of these spaces during early design. The large number of factors that determine their performance makes it necessary to employ very powerful software that uses CFD calculations, which results in more accurate data but excessive computation time. One such tool is ENVI-met [3], a widely validated software that uses CFD to simulate microclimates in urban scenarios. It is able to account for the interaction between buildings, vegetation, air, and soil, at a wide range of scales, from the urban scale to the building scale. It provides a huge amount of data in each simulation for all the mentioned elements, requiring a lot of computational power and time, making it unsuitable for early design.

As a result, this research aims to adapt and test a hybrid simulation workflow using the Ladybug tools for Grasshopper, previously analyzed by other researchers in the analysis of outdoor spaces [4], [5], against an integrated software widely validated, as it is ENVI-met, applying both methods to the smaller scale of courtyards. The objective is to analyze whether the hybrid workflow results are accurate enough to be used instead of the more time-consuming integrated software in order to incorporate its use in early design.

The performance of the simulation is analyzed in terms of air temperature at different levels of the courtyard and the thermal delta that the courtyard is able to provide in comparison with the outdoor temperature. This thermal delta is defined as the difference between the outdoor temperature and the courtyard’s temperature. Since the courtyard generally provides a beneficial cooling effect in the hot-arid climate, a higher daily thermal delta means a better thermodynamic performance of the courtyard, providing higher thermal comfort and lower energy consumption in the building.
2. MATERIALS AND METHODS

2.1 Courtyard description

The selected case study is located in Sevilla, (Spain 37°17’01”N 5°55’20”W, elevation 42 m a.s.l), which is Csa in Köppen classification [6], characterized by hot dry summers and mild winters. The building selected is a school distributed around an 11.0 x 7.0 m courtyard with an 8.9 m height. The walls are 40% glazed and 60% covered with white cement mortar. The most characteristic elements in the courtyard are two palm trees that provide some shadow, modelled as cubic shapes inside the courtyard (see Figure 1).

![Figure 1: Model of the courtyard.](image)

2.2 Monitoring

The courtyard is monitored during a whole week in summer, between the 4th and the 9th of June, when the weather is hot and dry. Air temperature, wind speed, and direction outside the courtyard are recorded by a weather station model PCE-FWS 20 to obtain the input data for the simulations. Air temperature and humidity are measured inside the courtyard at 1.5 m height, using sensor model TESTO 174H, to compare the data with simulation results. Only one representative day (June 8th) is selected for data comparison to simulated results. Table 1 shows the characteristics of the instruments used.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Variable</th>
<th>Accuracy</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
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<td>TESTO 174H</td>
<td>Drybulb Temp.</td>
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<td>0.1°C</td>
</tr>
<tr>
<td></td>
<td>RH</td>
<td>±0.1%</td>
<td>2%</td>
</tr>
<tr>
<td>PCE-FWS 20</td>
<td>Drybulb Temp.</td>
<td>±1°C</td>
<td>0.1°C</td>
</tr>
<tr>
<td></td>
<td>RH</td>
<td>±5%</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>Wind</td>
<td>±1 m/s</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1: Technical data of the measurement instruments.

2.3 Integrated Software Simulation

Measured data are compared to simulated data using two different workflows in order to evaluate their performance. The first workflow consists of the use of ENVI-met, which integrates the simulation of all the interdependent parameters of the air, wind, radiation, surfaces etc. In addition to the aforementioned computational power and time limitations that it needs, studies suggest that the accuracy of the software when it is used to simulate small-scale courtyards is not good [7]. Table 2 shows the main inputs for the ENVI-met simulation. The monitored outdoor temperature and relative humidity, as well as the mean wind speed are used as boundary conditions for the simulation.

Table 2: Input variables for ENVI-met

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature /Relative humidity</td>
<td>Monitored data.</td>
</tr>
<tr>
<td>Wind speed and direction</td>
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</tr>
<tr>
<td>Specific humidity at 2500 m</td>
<td>4.5 g/kg</td>
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<tr>
<td>Roughness length</td>
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<tr>
<td>3D tree</td>
<td>Palm</td>
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<tr>
<td>Walls/Roof Materials</td>
<td>Mortar / Tiled</td>
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<tr>
<td>Save Model State (min)</td>
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</table>

2.4 Hybrid Simulation Workflow

The second workflow is a hybrid approach using the Ladybug tools, a set of environmental plugins for Grasshopper that connects various validated simulation engines such as EnergyPlus, OpenFOAM, Radiance or Daysim into the same graphical interface, allowing designers to change the design according to the environmental performance of the model. This method calculates the different factors that intervene in the microclimate separately. Honeybee will run Energyplus for surface temperatures and Radiance for solar radiation. Butterfly will run OpenFOAM for CFD analysis. The outputs of each model are used as inputs for another. Again, outdoor monitored temperature, humidity and wind speed are inputs in the simulation. This kind of workflow has been tested and validated by other authors in urban areas [4], [5]. This research aims to validate it on the smaller scale of courtyards. The main difference from the method applied in other studies is the use of a solver that includes buoyancy forces and surface temperatures in the CFD study, given their importance in courtyards. Here, the OpenFOAM heat transfer solver, called buoyantBoussinesqSimpleFoam, is used. This is a steady-state solver for buoyant, turbulent flow of incompressible fluids that uses the Boussinesq approximation, which means that the air density is considered constant [8]. The workflow described is represented in Figure 2.
3. RESULTS

3.1 Monitoring results

Figure 3 shows the monitored temperatures inside and outside the courtyard on the selected representative day, the 8th of June. The maximum outdoor air temperature rises to 37.7 °C at 14.00 hours and inside the courtyard, it is 33 °C at 3.5 m high and 31.9 °C at 1.5 m, providing 5.8 °C of thermal delta. Maximum thermal delta during the day is 7.4 °C at noon. In the night, temperatures in the courtyard are slightly higher than in the outdoors: an overheating of 1.4 °C happens at 7.00 hours.

Another interesting monitored effect in the courtyard is the stratification that happens at different heights. During the day, differences of up to 3 °C are observed between the lower level at 1.5 m and the higher at 3.5 m.

3.2 ENVI-met simulation results

ENVI-met simulation results are shown in Figure 4, where it can be seen that although the software is able to predict a reduction in the temperature inside the courtyard, the thermal delta is much smaller than in monitored results (maximum calculated thermal delta of 2.0 °C at 14.00 hours). It is also quite constant throughout the day, in contrast to the monitored data where differences at different hours are noticeable and early-morning overheating in the courtyard is observed.
3.3 Hybrid Workflow simulation results

Final results of courtyard temperature from the integrated workflow are shown in Figure 5. The maximum thermal delta using this tool is 2.4°C at 14.00 hours. It is also much lower than the monitored delta. However, the courtyard temperature curve correlates better with the monitored one, showing different thermal delta at different hours of the day, being able to predict also the overheating that occurs in the courtyard during the night.

Figure 5: Hybrid Workflow simulated temperature on the 8th of June.

4. DISCUSSION

The temperature distribution inside the courtyard at 14.00 h from the two different workflows is shown in Figure 6 and Figure 7. This is the time when the simulation provides the maximum thermal delta. It can be seen that the temperature simulated by the hybrid workflow is lower than in ENVI-met, and it is more homogenous inside the courtyard at the same level. On the other hand, ENVI-met is not able to show the stratification inside the courtyard at different levels, while the simulated workflow is able to simulate a temperature difference of up to 2.5°C between the lower and the higher level of the courtyard. This stratification effect has been proven to occur in courtyards of this size by our previous research [9].

Figure 6: ENVI-met simulated air temperature at 1.5 m above the ground of the courtyard at 14.00 h of June 8th.

Figure 7: Hybrid Workflow simulated air temperature at 1.5 m above the ground of the courtyard at 14.00 h of June 8th.

The numerical results obtained from the two different simulation workflows are compared with the results from the monitored data using the following statistical parameters: coefficient of determination (R²) and the Root Mean Square Error (RMSE) which, in order for a model to be considered reliable, must tend to the following values: R² → 1, RMSE → 0. These values are calculated with the mean temperature at 1.5 m from the floor of the courtyard and the outdoor temperature. Table 3 shows the values for each of the simulations.
ENVI-met shows better results for the outdoor temperature, while the hybrid workflow simulation is better in simulating the courtyard temperature, which is our real objective. The coefficient of determination of 0.97 of the proposed workflow is higher than 0.88 from ENVI-met. The Root Mean Square Error is also 0.5 °C lower. These results validate the use of the hybrid workflow in the design process.

This process also has multiple advantages that are not provided by the use of ENVI-Met.

- The hybrid workflow involves the use of open source software, (although it still needs Rhino, which is not free but is already used by many designers). The open source software means that there is more flexibility and transparency about the process that is being followed, and there are ways to optimize the simulation in the different steps. This is not possible with ENVI-met, that follows its own solvers in an obscure “black box” that cannot be modified.

- The hybrid workflow is much faster and is not restricted to the simulation of one whole day to obtain accurate data. It can be simulated hour by hour. This shorter time needed to have results allows their integration in the early design process, characterized by fast changes in the project.

- Importantly for early design, although the hybrid workflow uses many different simulation tools, the Grasshopper interface links all of them to the same geometry –namely, the designer’s own 3D model.

However, there is one disadvantage of the hybrid workflow. It is not easy to include the effect of evapotranspiration of the vegetation or water features, which may be important elements in some courtyards. This factor is one of the main advantages of ENVI-met. However, the flexibility of the hybrid workflow and the open source characteristic of the software involved, make it possible to include the vegetation in the solver in the future. The improvement of the accuracy of the results is also something that needs to be studied.

5. CONCLUSION

This study aims to investigate the ‘goodness of fit’ of the simulation results to the measured data in courtyards, using a hybrid workflow that uses the modelling interface that a designer might be using for the design, which allows a good connection between the simulation results and the early design to make decisions. It is not limited by a long time of simulation to have results and they have shown that the hybrid workflow is valid and has multiple advantages.

ACKNOWLEDGEMENTS

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Table 3: Quantitative evaluation of the simulations performance

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<tr>
<th></th>
<th>R²</th>
<th>RMSE (°C)</th>
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<td></td>
<td>Courtyard</td>
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Big Data Analyses Show New Ways for the Prediction of Energy Consumption for Sustainability Assessment
Reduction to relevant input data for accurate energy predictions of existing residential buildings

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ABSTRACT: The energy consumption during the use phase of buildings is largely responsible for the overall energy necessary over the lifespan of buildings. However, different boundary conditions like climate and weather as well as different indoor conditions can lead to disparities between the predicted and actual energy consumption. A new approach is the use of Artificial Neural Networks (ANN) in order to increase the accuracy in determining the energy consumption of existing residential buildings. Previous studies have already demonstrated the potential of this method. For this work, measurement data of one- and two-family houses were used which allowed the predicted energy consumption by a newly developed ANN algorithm to be directly compared to actual energy consumption. The combined data set includes approximately 14,000 validated data tuples, leading to first hand data. An additional building component condition factor (BCC-factor) was created from the existing data (second hand data). Even though only a limited amount of data and input parameters could be used for this study, the accuracy of the implemented ANN algorithm produced promising results with a weighted mean absolute percentage error (WMAPE) of 22% and a mean absolute error (MAE) of the energy demand of 41 kWh/(m²a).

KEYWORDS: BigData, Artificial Neural Networks (ANN), residential buildings, energy consumption prediction

1. INTRODUCTION
The energy consumption during the use phase of buildings is largely responsible for the overall energy necessary over the lifespan of buildings. Besides the embodied energy and the efforts necessary for the end phase of the buildings (deconstruction, renovation, retrofitting, etc.), this is one of the main indicators for any sustainability assessments.

However, different boundary conditions such as climate and weather as well as different indoor conditions can lead to disparities between the predicted and actual energy consumption. There are few ways out of this dilemma because, in order to achieve comparability of the results, the calculations are based on certain principles such as:

- similar mean climate conditions for regions or countries,
- similar mean indoor temperatures, domestic hot water and electricity for specific use or
- transient or static calculations of energy balances.

Thereby, the most important estimations are hidden somewhere in the mean values for both outside and inside boundary conditions. Unfortunately, these estimations do not always reflect reality with sufficient accuracy for the vast majority of buildings. Even more difficulties arise when non-residential buildings are analyzed [1] due to specific indoor conditions which are usually separated into different zones. In contrast, the energy consumption of residential buildings is often calculated with one single zone and unified conditions for the entire building (except basement and attic). Nonetheless, even for these simpler cases, various reports show inaccuracies as in [2]. Therefore, the purpose of the presented paper is to demonstrate new ways for the prediction of the energy demand of residential buildings using big data analysis. The results show more precise predictions with considerably less effort for data collection compared to standardized methods and dynamic calculation tools.

2. BACKGROUND AND RELATED WORK
Energy quantification methods for existing buildings can be roughly categorized as:

- calculation-based (steady-state methods and dynamic simulation),
- measurement-based (bill-based methods, monitoring-based methods) and
- hybrid methods (calibrated simulation, dynamic inverse modelling) [3].

In most EU-countries a steady-state method is used as the basis for energy performance certificates [4]. With this approach, however, errors during data
collection can occur. This method also leaves room for interpretation during data entry and inaccuracies in simplified calculation algorithms. Together with user behavior, which also has a considerable influence on energy consumption, using the steady-state approach can lead to disparities between the calculated energy demand and the measured energy consumption that can range from ca. 50 % up to 300 % (see figure 1) [5].

A new approach is the use of Artificial Neural Networks (ANN) in order to increase the accuracy in determining the energy consumption of existing residential buildings.

Previous studies have already demonstrated the potential of ANN in calculating energy demand by using data from demand-based energy certificates [6, 7]. However, for this work, measurement data of one- and two-family houses were used which allowed the predicted energy consumption by the developed ANN algorithm to be directly compared to actual real energy consumption.

In Germany two types of energy certificates are allowed for existing residential buildings, either based on energy demand calculation (steady-state method) or measured energy consumption (bill-based method). In order to create a bill-based energy certificate a mean value given in kWh/(m²a) has to be calculated taking into account the last three years and the corresponding energy consumption of oil, gas, electricity or other energy sources. This method is by far less complex and less costly when compared to an energy demand calculation which requires specific U-values, façade areas, thermal bridge indicators, ventilation losses as well as ventilation and heating system parameters. Yet, individual user behavior of the inhabitants influences the results and analogous data sets are available [5].

3. METHODOLOGY

3.1 Data collection and parameter selection

Germany, in contrast to other European countries like Austria or Italy, does not have an open access database for energy performance certificates. Therefore, suitable data sets have to be acquired from various companies or research institutes to conduct studies. In order to choose suitable data sets, first, it had to be decided which attributes or parameters are essential for any kind of energy consumption prediction. A long list with typical parameters for an energy demand calculation according to the standards DIN V 4108-6 and DIN V 4701-10 [8, 9] was compiled, which was divided into three categories.

It is quite difficult to find data sets that contain all parameters of all categories. More importantly, the main goal of this new approach is the reduction of relevant input data which can be entered by home owners without the help of energy experts. For this reason, essential category 1 parameters that must be included in the data sets were defined:

- Geographic Location
- Year of construction
- Building type
- Net dwelling area
- Total heat consumption
- Information about any refurbishment (yes or no)
- Year of refurbishment

Category 2 parameters are also important input parameters for an energy demand calculation. These however, can be derived from category 1 parameters or can be produced based on logical principles if the data is not available.

For example, in Germany there were stringent standards providing energy related requirements for newly constructed buildings as well as for building refurbishments, which was directed by maximum U-values for walls, windows, roofs and floors (to basement or ground). These standards were tightened approximately every 5 years starting with energy demand regulations in the 1970s [10] (see also figure 2).
Because of the strictness of the requirements and the associated costs, U-values of building components can be estimated depending on the year of construction or refurbishment. Similar estimations can be carried out for HVAC-systems. Therefore, standards for the efficiency of these systems provide sufficient information depending on the year of installation.

Category 3 parameters have only a minor influence on the calculated energy demand. These include, for example, information on specific aspects of the domestic hot water system such as the insulation of pipes. For this study category 3 parameters were neglected.

Only data sets containing at least the listed main (category 1) attributes were considered. In the end, two data sets of one- and two-family houses mainly from refurbishment companies were used as a basis for the study. The combined raw data set consists of approximately 55,000 data tuples.

3.2 Data pre-processing

Before any data can be entered into the neural network as input parameters, the data must be prepared and partially edited. Data pre-processing is a crucial part of big data analytics that also has a great impact on the output. The time for data preparation within this study required approximately 80% of the project with the remaining time being used for all other necessary measures including programming the ANN algorithm [11]. In general, data pre-processing or data preparation can be described in three phases:

- Feature extraction,
- data cleaning (how to handle missing data or incorrect and inconsistent entries) and
- data reduction and transformation [12].

**Feature extraction:** Feature extraction has already been partially described in the previous chapter when identifying mandatory parameters (category 1) for data collection. In addition to the category 1 parameters, the combined data set also includes a number of category 2 parameters such as the age and type of the heating system, the type of building component that was refurbished (roof, external wall, windows, basement) and the type of energy carrier for the heating system. In some cases, the data set contains further detailed information on building refurbishment measures. In addition, all extracted attributes from the combined data set correspond to the data quality evaluation criteria according to Wang and Strong [13].

**Data cleaning:** For data cleaning all incorrect or incomplete data tuples and unexplainable values for input variables, such as year of building construction before the 19th century or energy consumption that did not match the net dwelling area, were removed. Missing data entries for input variables were replaced by plausible default values (category 2 parameters). Input variables from a different data set were set to a uniform form, e.g., by using the same units for identical input variables (scaling). For input variables that could not be described by metric specifications (year, quantity or size), such as the type of heating or the type of window frames, the type of window glazing or the type of roof, units and representations were selected so that the data entries of the respective input variables from both data sets are uniformly represented [10].

**Data reduction and transformation:** Finally, all information about refurbishment that was found in the combined data set had to be reduced and transformed into new attributes. There are two reasons for data reduction and transformation. Firstly, the dimension (columns) of the data set should be as compact as possible in order to apply sophisticated and more computationally intensive algorithms [12]. Secondly, by combining several variables into one variable, it can be ensured that even if not all information is known, all defined final input parameters for the ANN model can still be built and entered. For this purpose, an additional building component condition (BCC) factor for the components roof, external wall, window and basement was created. With this factor possible refurbishment measures of the corresponding buildings in these data sets are taken into account.

For the generation of the BCC factor at least the building’s year of construction was necessary. The more information about refurbishment measures or the condition of the building component in general was known, the better the BCC factor could be estimated. The value of the BCC factor lies between 0 and 100. A high BBC factor represents a high energy standard of the building component. Requirements of the current energy regulations were used as reference.

In the following, parameters of category 1 (mandatory input) and category 2 (optional input) that, respectively, must or can be manually entered by the user and are used directly for the algorithm are referred to as 1st hand data. Parameters, that are automatically generated and cannot be entered...
directly by the user, e.g. BCC factors, are referred to as 2nd hand data.

3.3 Training of the ANN model

After completion of data pre-processing, only 14.000 data tuples remained. Therefore, further possibilities were considered in the course of this study to collect more data tuples in the same format and quality as the data tuples in the existing combined data set. An online survey platform was developed in order to collect additional data directly from home owners. At the same time, this platform was designed to serve as the basis for a future web tool to provide a predicted energy consumption to the user with the help of ANN. Of course, there could never be absolute certainty about the accuracy of the data entered by the user or the building’s owner. Because, as already mentioned, the quality of input parameters has a significant impact on the outcome of ANN models, the online survey was specifically designed in order to reduce the possibility of high error rates to a minimum. For example, only closed-ended and multiple-choice questions were used in the survey. Figure 3 shows the concept of training the algorithm as well as the principle structure of the online questionnaire for further data collection.

The neural network used to calculate energy consumption consisted of three layers of 80, 40 and 20 neurons each. The selection of number of layers and neurons was based on the extensive experience of the research partner Kisters AG. The combined data set was then divided into a training data set with 12.500 data tuples and a test data set for validation of the algorithm with 1.500 data tuples. [11]

3.4 Data set representativeness

The representativeness of the combined data set can be validated using an extensive report on buildings including refurbishment measures by the German Energy Agency, dena. The report provides compiled statistics from various sources and provides a comprehensive overview, but unfortunately does not offer accessible data sets, of the current housing situation [14]. The representativeness of the selected data set for training the ANN model can be demonstrated using two examples:

- Year of construction
- Ratio of refurbishment

Figure 4 shows a comparison of the available data utilized in this study and representative information on the building stock by dena [14] for different years of construction. Obviously, the data for the training of the ANN-algorithm fit quite good, however, there is a lack of data of buildings erected after 2001.

The combined data set used for training of the ANN also includes information on refurbishment of external walls, roofs, basement and windows. Similarly, the dena report also provides numbers for the amount of refurbished building elements in Germany (excluding windows). Figure 5 shows the proportion of refurbishment of the different building elements of the data set as well as the dena report.

The difference in scale can be explained by the amount of refurbished buildings within the data set used for this study, which was mostly provided by a
refurbishment company. On the other hand, the dena report represents the entire German building stock and only includes a smaller percentage of refurbished buildings.

Nonetheless, a comparison of the distribution of refurbished building elements shows that the used data set is largely representative of the German building stock. Furthermore, due to the large amount of refurbished buildings within the data set, the trained ANN-algorithm could also provide more realistic energy consumption predictions in case of retrofitting. This may become more important for further application explicitly when refurbishment measures are planned.

4. RESULTS

The trained ANN model is used to generate energy performance data, which outperforms typical energy demand calculations based on static values (U-values, air exchange rates, heating supply degree of efficiency, etc.) in terms of accuracy.

Compared to other references as documented in [5], here, a far larger data set is utilized revealing typical effects when energy demand calculations are compared with energy consumption. Often high values of energy demand calculations around 350 kWh/(m²a) are connected to significantly lower measured energy consumption. One typical reason might be that inhabitants of detached houses with a lower energy standard will not heat up the whole house during winter because of associated costs (pre-bound effect). Another typical reason for a discrepancy between calculated demand and measured consumption might be that inhabitants of detached houses with a higher energy standard will not necessarily pay so much attention to their heating consumption due to the already relatively low associated costs (re-bound effect).

Figure 6 compares the predicted energy consumption using ANN with the measured (real) energy consumption for the training data set (grey dots) and the test data set (black dots).

An interesting finding after analyzing the results is that the ANN forecast model is particularly suitable for predicting energy consumption for one- and two-family houses with a specific energy consumption between 80 kWh/(m²a) and 280 kWh/(m²a). This can be explained by the fact that approximately 93% of the training data set includes buildings within this range.

Even though only a limited amount of data and input parameters was available for this study, the accuracy of the implemented ANN algorithm showed promising results with a weighted mean absolute percentage error (WMAPE) of 22% and a mean absolute error (MAE) of the energy demand of 41 kWh/(m²a) [11].

Figure 7: Comparison of predicted energy consumption by ANN and measured energy consumption (ad. from [11]).

Figure 6: Comparison of predicted energy consumption using ANN and measured energy consumption (ad. from [11]).

Figure 7 depicts a principal overview of the results with the ANN method compared to standard calculations. The research shows that, few data parameters can be sufficient to train artificial neural networks to predict the energy consumption of one- and two-family houses. The advantages of this method lie in the simplicity of the required input data, making tools accessible to average homeowners and inhabitants. Therefore, time-intensive and costly surveying of buildings can be avoided. In addition, results provided by this approach prove more accurate than conventional demand-oriented energy performance certificates.

However, the model still contains drawback such as its dependency on large amounts of data. Furthermore, the application of the model is currently still restricted to existing one- and two-family houses warranting further investigation with larger data sets. Additionally, expanded data sets, which include e.g. user behavior, could help improve the precision of the ANN model.

5. CONCLUSION AND FUTURE WORK

The presented method offers a realistic assessment of the energy consumption of the building stock in Germany. Especially when refurbishment measures are planned for older one- and two-family houses in terms of a reduction of energy consumption...
and corresponding CO₂-emissions the ANN-method outperforms conventional methods. Energy demand calculations (steady-state method) are costly and, particularly for older buildings, less accurate. While a bill-based method generates the energy consumption quite accurately, no specific building characteristics are taken into account to derive refurbishment measures. In contrast, the developed ANN model presented here considers few easy-to-determine building parameters and still predicts the energy consumption accurately.

Today, it can be used for one and two-family houses erected before 2001. However, more data sets of modern buildings are required to further train the algorithm. In doing so, the ANN-algorithm could be trained with data from other residential buildings such as multi-storey buildings and more user specific data. In the future, this work could be used to generate specific recommendations in terms of costs and return on investment when refurbishment measures are scheduled.

Nevertheless, steady-state energy demand calculations will remain important because they provide comparable results for defined boundary conditions as used in standards. In addition, demand-based energy calculations are the only calculation method for newly constructed buildings, since required data is not available, either for ANN or a bill-based method.

Yet, for policy makers, planners and the end-users a general understanding of the discrepancies between energy demand calculations and the real energy consumption seems to be important. Big data analysis obviously offers a new way of realistic energy prediction by principle.

ACKNOWLEDGMENTS
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Multicriteria Pareto-optimization of the modernization of non-residential buildings with a genetic algorithm

Included multi-zone approach for the demand modelling

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The sector of existing non-residential buildings accounts for a significant share of the final energy consumption of the entire German building stock. Thus improving non-residential buildings can make a significant contribution to the declared emission reduction targets. Therefore, it is essential to identify optimal and future-oriented modernization measures systematically. For this purpose, we present an optimization model with the use of a genetic algorithm that identifies the optimal measures for the building energy system including envelope and the supply system. The Pareto-optimization approach aims on minimizing carbon emissions and equivalent annualized costs. We use a multi-zone building model that comprises different usage zones of a non-residential building. Therefore, hourly profiles of internal loads and user electricity caused by the presence and activity of people are modelled. Results show good performance of the energy demand model. The method is applied to an office and laboratory building and we detect three main combinations of measures and different configurations of the plants being part of these combinations. Future work will contain an expanded validation of the demand model and sensitivity analysis of the optimization.

KEYWORDS: Building energy system, Modernization measures, Non-residential buildings, Multi-objective optimization, Genetic algorithm

1. INTRODUCTION

Against the background of the world’s need for CO₂ savings, the German government has set itself the target of an almost climate-neutral building stock in 2050. This results in extensive changes in the energy supply of buildings. Due to a low rate of new constructions [1], existing buildings play a key role. In Germany the majority of these buildings were built before 1977 [2], complying with low energy requirements and hence offers high saving potentials. As modernization measures have a long-lasting and high impact on the energy efficiency and the economic efficiency of the building operation, it is of enormous importance to identify future-oriented renovation and modernization measures. Non-residential buildings (NRB) account for 37 % of the end energy consumption of Germany’s total building stock [3] and thus can make a significant contribution to the stated goal. Compared to residential buildings, NRB are used in many different ways, have a higher power consumption and, by switching on large electrical loads, a significant impact on the residual load. Due to the heterogeneity of NRB, the existing data basis is poor. This applies to general statistics like the number of NRB in Germany as well as to time series that are needed for dynamic simulation and optimization approaches. Especially when it comes to time-resolved profiles for peoples presence or the use of appliances (e.g. computers in an office building) detailed data is not available.

The aim of this study is to show a novel approach to identify the optimal measures for the building energy system (BES) and its configuration in existing NRB. As criteria for determining the optimum the central aspects of the building energy transition in Germany and Europe are proposed: the emission reduction potential and the economic feasibility of measures in order to scale them on the entire building stock. The challenge of the heterogeneous use and less available data in the NRB sector is counteracted with a categorical multi-zone approach. Here, hourly profiles of the electricity as well as the internal loads caused by people and their use of machines and interior lighting are modelled in different usage zones.

Summarized, this work contributes to the following:

- Multi-zone approach for the calculation of hourly demands in existing non-residential buildings.
- Categorical consideration of building types from the non-residential sector.
- Pareto-optimization with genetic algorithms for the identification of modernization measures in NRB.
In practice, commonly used static normative approaches for the building’s demand calculation lead to high differences between the calculated demand and the real consumption [4]. Dynamic building models may overcome this drawback and in contrast to static approaches, time-resolved approaches are used which is advantageous when configuring the building energy system (e.g. power of plants).

In literature, it can be distinguished between two general approaches that are based on national and international standards as well as further approaches to model physical relations. On the one hand, software applications like EnergyPlus (e.g. [5]) and TRNSYS (e.g. [6]) are used to realize complex and detailed dynamic demand calculations for specific buildings. On the other hand, reduction (e.g. [7]) and simplification methods are used in order to reduce computation and parametrization efforts. The goal of these approaches is generic models that can be applied to many different buildings. One promising simplification approach are so called RC-models where the heat-transfer is modelled with electrical resistances (R) and thermal capacities (C), e.g. of the envelope, are represented by electrical capacities. Lauster et al. [8] developed such a model on district-scale and Schütz [9] for the demand calculation of residential buildings. Both showed that these models are suitable for the dynamic demand calculation with sufficient resolution and low computation effort.

As the modernization of buildings underlies many different influences, mathematical optimization approaches can support building owners and planners during the early design stage by a mathematical representation of these influences where all solutions are considered and evaluated using the same priorities [10]. These methods offer a mathematized, generic and objective alternative for the systematic identification of modernization measures. Optimization issues have objective functions that are maximized or minimized depending on the application. With regard to the optimization of a BES, this could be the minimization of the buildings CO₂ footprint. Meanwhile, economic, economic and technical boundary conditions constrain the solution space of the optimization problem. An example is the heating and cooling demand of a building, which must be covered any time. Concerning multi-criteria Pareto-optimizations, several objective functions are considered simultaneously and multiple optimal value pairs of these objective functions result. In each pareto-efficient point, it is not possible to improve the value of one objective function without at the same time worsening another [11].

Evins [12] summarizes the research in the field of BES optimization and states that 40 % of the published papers focus only on improving the building envelope. Only few papers investigate a combinatorial approach considering additionally the supply system [12]. The most common practices for optimizing BES operation are metaheuristics and linear programming. Pickering et al. [13] state that linear programming shows better performance in finding the global optimum in acceptable solving times if an adequate linearization can be found. Heuristics on the other hand are more powerful in optimizing strongly nonlinear problems [13]. One heuristic that is used for many questions in the building sector [14], especially in the field of renovation and modernization [10] are genetic algorithms (GA). These belong to the group of evolutionary algorithms and are a stochastic search method that is based on the principle of natural biological evolution [15]. They can efficiently handle nonlinear problems with discontinuities and many local minima [16].

Research on the modernization of existing NRB commonly focuses on specific cases due to the complexity and variety of this sector. For instance, Ascione et al. combine EnergyPlus and MATLAB to a two-stage optimization to assess retrofitting of an existing hospital [17]. Another example are the investigations by Shao et al. who include analyses of the building planners directly into their optimization model, assess efficiency measures of an office building and thus directly support the planners in the early design stage [18].

From our work done so far, we identified a lack of identifying modernization measures for different NRB types with genetic algorithms and taking into account the envelope as well as the energy supply system.

2. PROPOSED METHOD
At the Institute for Energy Efficient Buildings and Indoor Climate (EBC) of RWTH Aachen University, we develop a calculation model to determine optimal modernization measures for NRB. This builds on an optimization model for residential buildings, whose application is already proven and was developed by Streblow et al. [19].

Within the further developed model, a multi-criteria Pareto-optimization problem is set up and solved by a genetic algorithm (GA). The model is intended to analyse many different NRB. Hence, for the calculations of the heating and cooling demand a generic multi-zone RC-model is set up. This is based on the above-mentioned one by Schütz [9] for residential buildings that relates to ISO 13790. Therefore, in this paper only the model extensions for NRB are described in detail.

2.1 Multi-zone approach for non-residential buildings
Due to the heterogeneity of NRB, a zone-specific approach is chosen. Hereby, hourly user-electricity load profiles (UEL) are modelled for each zone of a building. These profiles reflect the different usages
(e.g. office, laboratory, canteen). This calculation is based on presence and activity profiles for 42 usage zones that are mentioned in Swiss standard (SIA) 2024 [20]. The UELP contain the usage of appliances (e.g. computers) and interior lighting. Furthermore, they make it easily possible to generate hourly internal heat loads that the RC-model uses to calculate heating and cooling demand profiles.

As also being part of the RC-model, solar gains and heat losses by transmission are determined using weather data and the heat transfer coefficients of the building. Transmission losses are assigned to the building zones using a ground area-weighted allocation of the enveloping surfaces as in literature this has been found to be a promising approach (e.g. [21]). For the consideration of the building’s orientation in the solar gains, the weather data’s hourly sun radiation is separated on the four cardinal directions. This calculation is done in dependency of the geographic location. The whole window area is calculated out of building type-specific values for the proportion in the envelope. Window areas of the individual zones are then assigned ground area-weighted. This approach is also recommended for a good balance between accuracy and parameterization and calculation effort (e.g. [22]). In summertime, we model sun-shielding elements by reducing incident radiation on a small part in times the sun radiation is above a threshold value.

With this multi-zone approach, we consider that heating and cooling demand can occur simultaneously in a NRB, as this is a significant difference to residential buildings. Since we analyse buildings with commonly one central ESS these two demands are added up to obtain the hourly demands of the whole building. The total hourly usage electricity demand equals the sum of the UELP of all zones.

Figure 1 and Figure 2 show an extract of the validation of the described demand model. This is based on the annual heating and cooling energy demand of three different office buildings. The blue bars represent the calculated values of the developed demand model with typical heat transfer coefficients depending on the year of construction. The orange bars show the values calculated with the model and the real coefficients of the existing buildings. Between these two only slight differences occur. In comparison to the measured data (grey bars) we see that the results of the model are in the same order of magnitude. This also applies to peak loads, which have also been investigated. In case of the cooling loads in two of the analysed buildings cooling loads were not measured which leads to the assumption that no cooling supply systems are installed. In contrast, concerning to the model these buildings seem to have a cooling demand.

![Figure 1. Validation of the heating load](image1)

![Figure 2. Validation of the cooling load](image2)

Although more explorations have to be done, in general the demand seems to be modelled in a good manner. However, the heating load modelling shows better performance than that of the cooling load.

The pre-processing of the optimization model contains the demand calculation of four possible renovation states in four parts of the building’s envelope that are shown in Table 1.

![Table 1](table.png)

**Table 1. Thickness of insulation layers and windows’ U-values for the energy efficiency measures of the envelope**

(MW: mineral wool, EPS: Expanded polystyrene, PUR: Polyurethane rigid foam, λ: thermal conductivity in W/(mK)).

Consequently, 256 load profiles serve as input for the optimization model and represent the possible combinations of energy efficiency measures of the envelope.

### 2.2 Pareto-optimization with genetic algorithm

The basis of a GA are the so-called **individuals** that consist of **genes**. In this case, each gene represents one measure and each individual one combination of measures for the BES of the investigated existing NRB. Four genes represent the above-mentioned measures for the envelope. Implemented genes for the heating
supply system are boilers (gas and pellet), heat pumps (HP; air-water, sole-water, gas adsorption), heatrods, solar thermal collectors (STC) and district heating (DH). The genes for the cooling supply system are compression chillers (CC) and absorption chillers (AC; fed by DH or STC). Furthermore combined heat and power (CHP), combined cooling, heat and power (CCHP) and Photovoltaics (PV) as well as thermal energy storages (TES) and batteries (BAT) are possible. Hereby solar irradiation on PV modules concerning building orientation and geographic location is treated analogously to the solar gains described above.

The optimization process starts with a first population of randomly created individuals. As shown in Figure 3, this population is evaluated with one objective function (also called fitness function) for the equivalent annualized costs (EAC, Equation (1)) and the yearly CO₂ emissions (Equation (2)) of the BES. This calculation is done on the basis of a modelled operation of the above-mentioned plants and deposed technical and economical specifications like efficiencies and power-related cost functions of the plants.

\[
EAC = \sum_p (I_p - R_p) \cdot \frac{r}{1-(1+r)^{-n}} + c_p 
\]

\[
CO_2 = \sum_p f_{gas} \cdot E_{gas,p} + f_{pel} \cdot E_{pel,p} + f_{ele} \cdot E_{ele,p} 
\]

According to German standard VDI 2067 the EAC of the BES consist of the annualized investments \(k_b\) for the installed plants \(p\) and yearly costs \(c_p\) for operation and maintenance of the supply system, proportionate to the investment of a component. Furthermore, costs for obtained gas, pellets, and for electricity sale and purchase are part of it. All investments are discounted with \(r\) representing the interest rate and \(n\) the total years of the observation period. At the end of this period plants may have a residual value \(R_p\) which is deducted inside the calculation of the EAC.

The CO₂ emissions contain those for direct combustion of gas and pellets and indirect emissions of the electricity consumption through the public grid. They are calculated using emission factors \(f\) from [22] and the total amount of energy \(E\) used from the energy sources.

Good evaluated individuals are then selected for a second population. During the steps mutation and crossover, selected individuals are combined to new ones that are also added to the second population. This process is repeated until a set number of iteration steps. The last population defines the Pareto frontier for this multi-criteria optimization problem.

![Figure 3. Optimization process of a genetic algorithm](image)

3. CASE STUDY AND RESULTS

With the proposed method, different NRB types can be examined and recently it is part of a research project on the modernization of a military hospital, which will be converted into an office and laboratory building called FUBIC. General information of this building can be found in Table 2. According to the current planning status, it contains areas for office (35%), traffic space (31%), laboratories (29%), kitchen (3%), meetings (1.5%), and server rooms (0.5%).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Year of construction</td>
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</tr>
<tr>
<td>Space area</td>
<td>16,024 m²</td>
</tr>
<tr>
<td>Envelope area</td>
<td>13,850 m²</td>
</tr>
<tr>
<td>Current supply components</td>
<td>Gas boiler</td>
</tr>
<tr>
<td>Heat transfer coefficients</td>
<td></td>
</tr>
<tr>
<td></td>
<td>windows</td>
</tr>
<tr>
<td></td>
<td>roof</td>
</tr>
</tbody>
</table>

Figure 4 shows a representative working day of the modelled UELP for the usage of appliances inside the different usage zones. Hereby, the working and absence hours of the people become obvious.

![Figure 4: User-electricity profiles for different building zones](image)

In Figure 5 the heating and cooling demand of the examined building is shown. Typically we see heating in winter and cooling in summer. Furthermore, in
many time steps simultaneous heating and cooling demand can be analysed. This is due to a cooling base load of the server rooms and high internal loads of the laboratory zone. Photovoltaics are built in every solution to support the BES with self-produced electricity. A BAT is also always part of the solutions to compensate the difference between the regenerative production and consumption of electricity. Due to heat-controlled CHP, the capacity of BAT rises with the power of those. Concerning the envelope, the roof is insulated in nearly every solution, as its heat transfer coefficient is low. Windows and outer walls are improved in more ecological solutions and the floor is only changed partly. As the highest state of insulation leads to high cooling loads it is only realized in solutions with absorption chillers when cooling is supported by low-emissions DH.

4. CONCLUSION AND FUTURE WORK
The identification of optimal modernization measures in non-residential buildings is investigated in this work. For the hourly heating and cooling demand calculation a multi-zone approach is developed. It is built on a validated RC-model for residential buildings and includes presence and activity profiles for different zones of NRB. For the identification of the measures of the supply system and the envelope an optimization approach by the use of a genetic algorithm is developed. The general usability of the proposed method is investigated by means of a validation of the demand model and a case study for the optimization approach.

We see advantages in the identification of measures by a GA as this leads to the possibility of an hourly consideration over the whole year and simultaneously low computation efforts.

The Pareto frontiers show a high emission reduction potential in comparison to the existing building energy system. Pellet boilers offer advantages in supplying heat with low emissions but it is important to keep in mind that the sustainable availability for pellets is limited. Furthermore, low-emission cooling supply is possible with absorption chillers fed by district heating. Photovoltaics is installed in economic and ecologic solutions whereby the cost-efficiency rises with the possible area on the roof. The size of battery und thermal storages is mainly dependent on the size of CHP and PV. Concerning the envelope’s insulation strong influences of the ratio of heating to cooling load and the proportion of the window area could be detected.

Additionally in the future an expanded validation of the demand model is planned. As may more technologies, (e.g. fuel cells) will bear potential to be noticed in existing buildings, they could be added to the presented model. Concerning the boundary conditions (e.g. energy prices), an extended sensitivity analysis could show detailed influences on the measures.

Figure 5. Modeled heating and cooling load of FUBIC

Figure 6: Pareto-set of a building energy system

Concerning the BES options in the Pareto frontier mainly three combinations result. Inside these, different configurations of plants occur. More economic solutions contain of CHP for the coverage of the heating demand and compression chillers for the cooling demand. TES in these solutions are relatively large as this increases the full load hours of the CHP. The compromise solutions between the two options are determined by pellet boilers in combination with compression chillers. This is due to the cost-efficient emission reduction in wood-based heat supply. In the more ecological solutions we see pellet boilers combined with absorption chillers that are fed by DH which is because of the low emission factor of DH and the resulting low-emission cooling supply.
ACKNOWLEDGEMENTS

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Planning Post Carbon Cities

A methodology For Modelling Microclimates:
A Ladybug-tools and ENVI-met verification study

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ABSTRACT: Over the last decade, outdoor thermal comfort has become of considerable significance to urban designers and planners. In that concern, parametric design models were acknowledged for supporting the design process with iterative performance-based solutions and for being relatively less time and resource consuming. However, validation studies for such parametric models on the outdoor urban scale are lacking. Meanwhile, studies concerned with geometry optimisation are computationally expensive due to the time required per each simulation. This paper consequently investigates the accuracy and time efficiency of using the workflow comprising the environmental analysis Ladybug-tools, the plugins of Grasshopper3D for modelling the outdoor microclimate. The study verifies the model’s results against the microclimate CFD simulation tool, ENVI-met. The two models are compared in terms of two environmental metrics, the mean radiant temperature and the universal thermal climate index. In this paper, three hypothetical layouts representing basic urban geometry patterns, namely linear, dotted, and courtyard, are simulated in both models. Results show an acceptable range of consistency between Ladybug-tools and ENVI-met, particularly during the hours 8 am to 5 pm. Timewise, Ladybug-tools show their capabilities of not only modelling the microclimate but also their suitability for optimisation studies characterised by a vast number of design solutions.

KEYWORDS: Ladybug-Tools, ENVI-met, Thermal Comfort, MRT, UTCI

1. INTRODUCTION
Over the past few years, outdoor thermal comfort has gained increased attention between urban climatologists and developers who have sought to precisely imitate the built environment. In this sense, researchers have been trying to either distinguish the most accurate models or develop an ad-hoc methodology. Some have coupled different models for a concerted performance, while others have validated the computational models to field observations or verified against already validated engines. A case in point is the study of Naboni, et al. [1] who compared five models, namely ENVI-met, RayMan, CitySim Pro, Ladybug-Tools and Autodesk CFD. Their study, however, showed a significant incongruity between the models, particularly during the summer. This incongruity could be ascribed to the materiality of building constructions and the meteorological inputs for each model.

Furthermore, Jänicke, et al. [2] compared ENVI-met, RayMan and SOLWEIG to field measurements of a green façade for the estimation of heat stress. Their results for calculating the Mean Radiant Temperature (MRT) have shown a mean deviation up to 7 K from the observations. Perini, et al. [3] interpolated the output wind speeds, and plants vapour flux from ENVI-met into TRNSYS in a coupled methodology for estimating the Universal Thermal Climate Index (UTCI). Finally, Elwy, et al. [4] validated the Ladybug workflow against ENVI-met and field measurements. Results have shown an acceptable range of agreement in terms of Physiological Equivalent Temperature (PET) comparisons, however without a clear elaboration for the temperatures’ variations. Meanwhile, the study of the effect of urban morphology on the microclimate entails a huge computational power and extensive simulation time, particularly when using CFD simulations, and hence most of the studies concerned with geometry optimisation are limited to a few number of canyon configurations [5, 6]. Consequently, this paper aims at presenting the Ladybug-tools as accurate and time-efficient for modelling the microclimate as compared to the CFD simulation model, ENVI-met v.4.4.3.

2. METHODOLOGY
Before the version 4.4.0, ENVI-met did not allow for forcing the solar radiation inputs and instead used its embedded terrestrial coordinates to obtain solar radiation values all across the globe [7]. From version 4.4.0 onwards, ENVI-met has enabled the users to full force the meteorological parameters, allowing users to make direct comparisons with other simulation engines. It is worth noting that ENVI-met accounts for the vegetation interaction with the microclimate elaborately, as opposed to Ladybug-Tools which gives an estimation of the evapotranspiration based on the green coverage ratio along with the plant’s albedo and uses the UWG for doing so. Accordingly, in order to avoid these ambiguities, the three hypothetical simple layouts representing the commonly used urban geometry arrangements in Cairo, viz. linear, dotted, and courtyard (Figure 1), are modelled solely in the form of buildings and a ground surface.
2.1 Methods

Mackey, et al. [8] introduced the hybrid workflow for estimating the $MRT$, and mapping the microclimate in a graphical representation. The workflow is based on utilising the plugins of Grasshopper, presumed to simulate each of the thermal comfort determinants individually, and further combine them collectively for comfort calculation. Geometries are firstly created on the Grasshopper canvas to serve as a feeder for different plugins. An elevation model along with average building heights, ground and green coverage ratios, façade to wall ratio as well as thermal properties of constructions are fed into the -UWG-Dragonfly components to morph the .epw file to reflect the urban conditions. $MRT$ is estimated by the three fundamental components; direct solar radiation; atmospheric long-wave radiation; and surface long-wave radiation. The latter is estimated through the EnergyPlus simulation, which is part and parcel of the Ladybug-Tools. The output of this step is outdoor surface temperatures which are further weighted by their view factors using the ray-tracing engine in Rhino. Butterfly could potentially integrate OpenFOAM simulations within the workflow for modelling the urban wind patterns. The sky long-wave radiation and the direct short-wave radiation are accounted for by following the equations specified within the MENEX model and the SolarCal model, respectively. Eventually, by virtue of a generic component, the model provides a full range of thermal comfort indices, e.g. $PMV$, $PET$, and $UTCI$ with a graphical representation.

On the other hand, among the models developed within the field of urban climatology, the 3D numerical model ENVI-met is one of the most convenient models for assessing thermal comfort. The model accounts for all the heat exchange processes between the urban surfaces, vegetation and the airflow field in high temporal and spatial resolutions, as well as calculating all the meteorological parameters governing outdoor thermal comfort, e.g. $MRT$ [9]. ENVI-met has been validated against field measurements [7] and has already been widely used in UHI studies [10]. Drawbacks of the model, nonetheless, include overestimation of global radiation [2], unless measured data is forced to the simulation inputs. Also, ENVI-met requires increased time for modelling geometries from raster-based images, unless linked with Grasshopper which allows for exporting geometries to ENVI-met, albeit, with slight differences due to grid cells variations. The main disadvantage of the model is its excessive simulation time required which approximates real-time; in other words, 24 hours to simulate a day of the year.

2.2 Modelling and parameterisation

Layouts were modelled so far as is reasonably practicable and time-efficient within each model. Geometries are modelled in ENVI-met on a raster basis while for Ladybug-Tools are modelled parametrically in Grasshopper. Figure 1 and Figure 2 show the geometry configurations and a 3D presentation for each layout, where these configurations were estimated from real case studies in Cairo. The coloured circles denote to the points of interest, which shall be further analysed and discussed. Since the study is concerned with the assessment of outdoor conditions, buildings were modelled with no fenestrations.

**ENVI-met.** Buildings were modelled on a 2m grid horizontally and $h_{max} \times 4m$ grid vertically with ten nesting grids from all directions, assuming a flat terrain and the absence of anthropogenic sources. Default building construction materials were used from the ENVI-met database. Building indoor temperature is set to 20 °C, where ground temperatures are set to 25 and 22.5 °C at 2m and 4m depths respectively.

Figure 1: Geometry configurations for the three layouts; (L) Linear; (D) Dotted; and (C) Courtyard (dimensions in meters). Coloured circles denote to (Green) Receptor R1, (Red) R2, (Blue) R3, and (Purple) R4.
Simulations were carried out for a total of 15 hours, on June 7th from 5 am to 8 pm recording the highest difference of 32.5 °C due to the solar obstruction. Further, canyon intersections of interest, as well as the average values over each layout. The general trend of the curves at all patterns seem to be congruent except where the beam radiation abruptly changes due to being obstructed by buildings (L-R2, L-R3, D-R2, C-R1, and C-R4). Temperature differences of these cases occurred at 2-4 pm with a maximum difference of 32.5 °C in L-R2, while the other maximum differences are registered at 5 am as not exceeding 13.5 °C. Also, apart from the outliers, minor variations during the shaded hours, yet leap to nearly 14 °C. Receptors (LB-D-R1) keep a pace higher than those of EM, and holds in proximity during the peak hours, and then falls yet with the same higher values during (6-8 pm) by almost 10 °C. Moreover, a thorough analysis of the receptors has shown that those laid in similar canyon positions fluctuated in the same manner. For instance, located outside the canyon, LB-D-R1 and L-R1 keep a pace higher than those of EM by almost 8 °C, except at 4 pm drops by nearly 14 °C. Receptors in N-S canyons (LB-D-R2 and C-R1) maintain minor variations during the shaded hours, yet leap to match the EM peak values during sunlit hours, and register a variation of 17 °C at 3 pm. Additionally, E-W receptors (LB-L-R2, L-R3, C-R2 and D-R3) plummet at 3 pm recording the highest difference of 32.5 °C due to the solar obstruction. Further, canyon intersections (D-R4 and C-R3) and the west side L-R4 possess higher

3. RESULTS

In this section, the Ladybug-tools model is referred to as LB, while ENVI-met as EM, Linear, Dotted and Courtyard as L, D, and C respectively. Figure 3 shows the temporal variations of MRT at each of the points of interest, as well as the average values over each layout. The general trend of the curves at all patterns seem to be congruent except where the beam radiation abruptly changes due to being obstructed by buildings (L-R2, L-R3, D-R2, C-R1, and C-R4). Temperature differences of these cases occurred at 2-4 pm with a maximum difference of 32.5 °C in L-R2, while the other maximum differences are registered at 5 am as not exceeding 13.5 °C. Also, apart from the outliers, LB appeared to have higher MRT values during the early hours (5-8am) by almost 12 °C, then rises in tandem with EM, and holds in proximity during the peak hours, and then falls yet with the same higher values during (6-8 pm) by almost 10 °C. Moreover, a thorough analysis of the receptors has shown that those laid in similar canyon positions fluctuated in the same manner. For instance, located outside the canyon, LB-D-R1 and L-R1 keep a pace higher than those of EM by almost 8 °C, except at 4 pm drops by nearly 14 °C. Receptors in N-S canyons (LB-D-R2 and C-R1) maintain minor variations during the shaded hours, yet leap to match the EM peak values during sunlit hours, and register a variation of 17 °C at 2 pm. Additionally, E-W receptors (LB-L-R2, L-R3, C-R2 and D-R3) plummet at 3 pm recording the highest difference of 32.5 °C due to the solar obstruction. Further, canyon intersections (D-R4 and C-R3) and the west side L-R4 possess higher

Ladybug-Tools. Layouts were modelled in Grasshopper to match those grid points as in ENVI-met. Unless defined within ENVI-met database, materials' properties were either obtained online [11], derived or assumed with reference to the relevant properties (Table 1). Buildings are defined as Honeybee zones with building program set to “not conditioned” Midrise Apartments, where the ground is defined as a virtual EnergyPlus ground, assuming no wind or sun exposure and no internal loads. Following [8], EnergyPlus simulation is set to “Full Exterior with Reflections” at a time step of 15 minutes.

Boundary Conditions. As a representation of the hot arid climate in Cairo, Egypt, a EnergyPlus Weather (.epw) file for both models was available at [12]. As mentioned earlier, ENVI-met allows for the full forcing of meteorological conditions, where the lateral boundary conditions and the cloud cover are disabled and rather being inferred from the .epw file. While EnergyPlus intrinsically extracts the global horizontal, direct normal, and diffused horizontal radiation values necessary for surface temperature calculation from the .epw file, ENVI-met parses the file to get a unique view. It is worth noting here that, CFD simulations via butterfly are not performed in this study since it has notoriously increased the time of simulation and curtailed the continuity of the workflow with no substantial effects to the UTCI values. Thus, this study, instead, calculates the canyon wind speeds based on the power law using a specific Honeybee component.

<table>
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<td>Medium Rough</td>
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</tr>
</tbody>
</table>

Table 1: Construction materials input for both models.
consistency with EM. However, the longer block length in the courtyard design curtails the solar radiation exposure of C-R3 and hence drops at 4 pm by 17.05 °C. Finally, although C-R4 maintains a high congruity during (8 am-1 pm), it plummeted at 2 pm to record a 20 °C difference. More intriguing, the general trend of average \( MRT \) over the three layouts is quasi-similar. Apart from the early (5-8 am) and late (6-8 pm) hours where differences approach 12 °C, LB stays close to EM with variations not exceeding 6 °C. Influenced by the \( MRT \) values, \( UTCI \) values have followed the same trend, however with no drastic variations (Figure 4). Maximum differences are manifest during the early and late hours, not exceeding 6.43 °C. That is, with 5.8 °C maximum variation for the average \( UTCI \) over the three layouts, LB shows a great conformity with EM during the simulation period and hence exhibits a significant potential to speculate the impact of different urban configurations on the microclimate.

Error calculations are presented in Table 2 showing the Root Mean Squared Error (RMSE), Mean Percentage Error (MPE) and Coefficient of Determination \( (R^2) \). In terms of \( UTCI \), LB results have shown a substantial level of agreement with EM (\( R^2 = 0.97 \)). Figure 5 depicts the comfort maps for each layout and shows the resemblance of each pertaining pattern. As aforesaid, differences are evident during the early and late hours. The maps, thus show the Ladybug-Tools model to be capable of presenting the microclimate and hence is practical for mutating multiple design solutions due to the improved time efficiency.

### Table 2: Error calculations for \( MRT \) and \( UTCI \).

<table>
<thead>
<tr>
<th></th>
<th>Linear</th>
<th>Dotted</th>
<th>Courtyard</th>
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</thead>
<tbody>
<tr>
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<tr>
<td>MPE</td>
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<td>( R^2 )</td>
<td>0.94</td>
<td>0.97</td>
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</table>

4. Discussion and Conclusion

As shown in the results, the variations between the two models can be ascribed to different causes. The surface heat balance within both ENVI-met (EM) and EnergyPlus (EP) is calculated based on empirical equations with slight differences for estimating each component. However, the deduced amount of heat emitted and stored are not accounted for in EP. The heat conduction equation in EM is calculated by a simplified three-node method based on the exterior and interior surfaces’ temperatures with reference to the previous single timestep, while in EP is calculated with reference to a series of temperatures and heat fluxes history of the previous timesteps. In terms of the outside surface temperature, EM calculation of the absorbed short-wave radiation is set to be 50% of the incoming solar radiation, while on the other hand EP uses the Clear Sky Solar Model (as the default in this study) which was reported to overestimate the solar radiation available to the building [13]. Moreover, EP intrinsically accounts for the radiative heat flux from the internal lighting (short-wave) and the zone surfaces (long-wave) in addition to the convective heat flux from the zone air. This could potentially affect the inside surface heat balance and result in a reduced conduction heat flux from the outside surface, thus keeping the outside surface’s temperature higher. Although the amount of absorbed long-wave radiation in EM is almost similar to that of Ladybug-tools (LB) using the ray-tracing with almost 10° vector angles, EM takes into account the geometrical characteristics of the hemisphere, i.e. each vector is weighted by a factor of the angle of incidence to the surface (which tends to be more accurate). Furthermore, absorbed long-wave radiation from surrounding walls and the ground in EM are averaged over the model area. Consequently, irradiated surfaces’ temperatures are indirectly lowered by the cooler surfaces in other shaded parts and vice versa. The effect is diminished during the peak hours where the solar radiation is fairly distributed over the model area. The aforementioned provides some explanation for the increased \( MRT \) and \( UTCI \) during the early hours of the day, which is evident in all cases. The scrutiny of the Python source code has revealed that, when the solar beam is blocked, LB confines the global horizontal radiation to the diffused component. The reflected radiation is defined within the SolarCal model as a function of global radiation, which is limited to the diffused radiation in case of obstructing the solar beam. This explains the sudden rise and fall in LB D-R2, L-R1 and C-R4 as well as the plummets of L-R2, L-R3, as opposed to the EM point \( MRT \) which receives an additional amount of reflected short-wave radiation from the ground and the walls, since the reflected radiation in EM is a function of the direct normal radiation times the inverse view factors. With the notion that the solar altitude reaches its maximum at midday, and the reflected short-wave and emitted long-wave radiation from the irradiated walls are minimised, point \( MRT \) receives a relatively less net all-wave radiation. This is clear in the case of EM at noon, while LB appears to show this trend earlier at 11 am and instead registers higher \( MRT \) at 12 pm. The latter might be attributed to the additional \( \Delta MRT \) within the LB model. As aforesaid, the \( MRT \) calculation within the LB model is based on the three components equally, i.e. the MENEX sky temperature, the solar adjusted \( MRT \) and the long-wave radiation from the surfaces. EM, on the other hand, partitions the incoming long-wave radiation into two equal portions, where the long-wave radiation from the ground represents one of them, while the sky and surfaces share the other portion, uncontestably, underestimating the latter two [7]. This is another attribution for the lower \( MRT \) EM possesses during the early and late hours. It is also worth noting that EP uses the TARP and DoE-2 algorithms for estimating the convection heat transfer coefficients for indoor and outdoor surfaces respectively in terms of the surface roughness and the difference between the surface and the immediate air temperatures as opposed to EM which depends in its calculation on merely the wind speed. This might have possibly resulted in slight differences in the outside surface temperatures and thus more \( MRT \) variations.

Furthermore, the \( UTCI \) variations are shown to follow a similar trend for all the receptors as well as the average \( UTCI \), however with attenuated differences.
Figure 3: MRT comparison within the three layouts

Figure 4: Average UTCI comparison within the three layouts
This is clearly due to the combination of the MRT values with the meteorological variables; wind speed; relative humidity; and air temperature. For a better representation for the UTCI maps as in Figure 5, a Grasshopper plugin, Gismo, was used to allow for the extraction of ENVI-met UTCI values and presenting them in the Rhino scene with the same legend. It is worth mentioning, however, that the “microclimate map” component in LB depicts the UTCI values as a time interval, e.g. 6-7am, rather than at a single hour as in EM (at 7 am). Therefore, slight differences exist from those values plotted in Figure 4. Despite the UTCI variations, the times required for the simulations in each model are considerably disparate. For each layout, the elapsed time differed from ~30 hours for EM to ~5 minutes for LB. It should also be noted that EM simulations run on a single-core processor as opposed to the LB simulations which were parallelised. Notwithstanding, a parallel core simulation in EM is anticipated to run in ~8 hours, which is still much longer than LB. In that sense, LB allows for assessing multiple design iterations with high spatial and temporal resolutions in a significantly shorter time. Hence it is suitable for optimisation studies yielding an immense number of design solutions, which would be infeasible using EM.

5. FUTURE WORK

As discussed, the accuracy of the Ladybug-Tools model is mostly a function of the radiation components determined through a set of Python functions describing the MENEX and SolarCal models. While the latter was initially designed for the indoor environments, future work includes intervening with the source code so as for a more accurate representation for the outdoor conditions and less MRT deviations.

6. REFERENCES


Analysis and Visualisation of Decision Paths towards Reaching Environmental Impact Targets at Early-Design Stage

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ABSTRACT: Environmental impact objectives are commonly found in building performance labels and rating schemes. Anticipating a building’s impact from the conceptual design stage and identifying decisions that do not compromise its chances of reaching these targets is therefore crucial. Yet, few methods and tools are able to provide tangible decision support through a context-specific and early-stage-oriented approach. This paper proposes a workflow to do so based on a generative approach and interactive decision trees. Illustrated on a case study, the approach consists in generating building scenarios by varying parameters not yet fixed at the early stage, including geometrical (e.g. building shape and height), architectural (e.g. façade opening ratio) and technical (e.g. heating system) parameters. The series of scenarios are evaluated in terms of their greenhouse gas (GHG) emissions over their life cycle (including construction and operation), as well as from building-induced mobility. The effects of filtering this database according to a given impact target are explored using a classification algorithm that produces a decision tree showing the proportion of target-complying and non-complying scenarios, as well as the (un)favourable decision pathways. Stakeholders of the planning and design process can therefore get insights into the implications of a given string of decisions.

KEYWORDS: Environmental impact target, decision tree, early design, decision support, life cycle assessment

1. INTRODUCTION

Performance targets related to the environmental impact of buildings over their life cycle can increasingly be found in labels and rating schemes, such as DGNB (developed in Germany) \cite{1}, LEED (that originated in the US) \cite{2}, and the Swiss SNBS \cite{3} and 2000-Watt Site \cite{4} certifications, the latter based on the intermediate targets for 2050 from the 2000-Watt Society concept \cite{5, 6}.

Anticipating the impact of a building from the conceptual design stage and identifying decisions that do not compromise the chance of reaching these targets is therefore crucial. The ENV1.1 criterion of DGNB for instance begins with Indicator 1: LCA [life cycle assessment] in planning, consisting in comparing the "most likely / preferred building variants" in terms of their potential environmental impacts over the construction and use phases \cite{7}. This task could greatly be facilitated not only by a workflow that allows comparing building variants, which are automatically generated and assessed, but that also provides information on the implications of each design decision with respect to the environmental impact of the building.

However, assessing the life cycle performance is highly demanding in terms of time and high-resolution details, which are both limited at the early design stage \cite{8}. In practice, few methods and tools are able to provide tangible decision support through a context-specific and early-stage-oriented approach.

A majority of the existing tools, ranging from simple spreadsheets to advanced dynamic simulation software (e.g. \cite{9, 10}), are essentially made to assess one design, as opposed to providing support towards defining this one design. They are therefore more useful at a stage in the design process where at least some of the decisions have been made, e.g. building shape and dimensions and façade details. Although results can be compared to a performance objective value (e.g. related to a given certification scheme), no information is gained on the influential design parameters or on which changes could ensure compliance.

At the European scale, the latest research suggests two promising paths towards increasing the usability of LCA in early design. First, based on parametric LCA \cite{11}, the German Caala software makes it possible to conduct a real-time assessment based on a simplified 3D model \cite{12}. This method attributes pre-defined building components to reach a level of detail compatible with a LCA.

Another approach consists in applying LCA within a generative data-driven method to construct a knowledge database of multiple design alternatives \cite{13}. This approach was implemented into the French Vizcab software \cite{14}, which supports multi-dimensional data exploration during the design process through parallel coordinate plots enabling a multi-dimensional exploration process \cite{15}.
Indeed, to bring insights to decision makers through a data-driven approach, not only is it necessary to generate a set of design alternatives, but this data must also be presented through meaningful and intuitive visuals. In a comparison of different data visualisation techniques applied to building performance simulation data, [16] stated that “The Decision Tree is [...] the most suitable to show the impact of parameters.”

This paper is a first attempt to use this type of visualisation, to represent the results from a workflow for supporting and informing early-stage decisions among various project stakeholders. The workflow is based on a generative approach and interactive decision trees. The objectives are to identify influential parameters and favourable versus constraining architectural and technical choices, towards supporting the elaboration of an environmental strategy from the planning stage, and the formalization of specifications, for example in the context of a master plan or architectural competition.

2. METHODOLOGY

The method consists in: 1) generating, for a case study piece of land (or lot), a series of building scenarios from a set of variable parameters (e.g. window-to-wall ratio), 2) evaluate their environmental impact, i.e. global warming potential (GWP) expressed in terms of greenhouse gas (GHG) emissions, and 3) investigate the implications of applying different GWP targets on the (un)favourable variable parameter options, through a decision tree-type of visualisation. We briefly present these three phases, with a focus on step 3. Further details on steps 1 and 2 can be found in [17], which describes the overarching applied-research project named SETUP (Specific Environmentally-conscious Targets for Urban Planning). The whole process is semi-automated by streamlining the modelling, simulation, and data processing steps using various software that are introduced in the following sections.

2.2 Generation of scenarios

The case study lot is located on an existing industrial site under development, located in Fribourg, Switzerland. At this stage of the project, only the maximum constructible height (of 19 m) and the building program (office) have been defined in the masterplan. To generate building scenarios on the lot, 16 variable parameters are considered in this study, including geometrical (building shape, depth and height), construction (window-to-wall ratio, glazing type, insulation level, etc.) and technical (e.g. heating system, surface of photovoltaic panels on roof) parameters. For each parameter, a set of at least two options are defined (e.g. window-to-wall ratio of 0.4, 0.65 or 0.9).

Saltelli’s extension of the SOBOL sequence [18] is used to sample the space of possible scenarios; a total of 13,177 scenarios are thus generated and evaluated. Fig. 2 illustrates four example scenarios showing variations, among others, in terms of window-to-wall ratio, building dimensions, and height of the surrounding buildings (context height being one variable parameter).

A 3D model of each scenario is automatically drawn through a parametric modelling script developed in the 3D modelling software Rhinoceros (Rhino) [19] and associated graphical algorithm editor Grasshopper (GH) [20].

2.3 Evaluation of environmental impact

Impacts from the building construction and operation phases are accounted for in the calculation of its GWP. We also consider the building-induced mobility, that is, the impact from the traffic that can be attributed to the building’s existence [21].

The embodied GHG emissions from materials used in the construction phase, as well as related to the systems, are estimated using data (i.e. GHG emission factors and building and component lifetime) from [22] and [23]. Emissions factors are multiplied by the corresponding element’s surface, volume, or number of units, considering also replacements during the building lifetime. These simple mathematical operations are done directly in GH.

Emissions related to the energy consumption for space and water heating and for electricity (lighting, ventilation, etc.) during the operation phase are calculated through dynamic hourly simulations, via GH plugins Ladybug+Honeybee [24], which run through OpenStudio [25] and EnergyPlus [26].

Figure 2: 3D model of case study with location of evaluated lot within the industrial site under development, and examples of the generated building design variants.
Occupancy and load profiles corresponding to an office building are mainly defined based on [27]. As mentioned, further information on simulation hypotheses can be found in [17].

Finally, the GHG emissions associated to building-induced mobility are estimated following the calculation method found in [21], directly coded in GH. Although this mobility impact here remains constant across scenarios, it is included so as to allow comparison of the total results to the Swiss SIA 2040 targets [6], which encompass all three domains (construction, operation and building-induced mobility).

The generation and evaluation process lasts in the order of a few hours for the 13,177 scenarios, the most computationally-demanding step being the dynamic hourly simulations.

2.4 Classification for decision tree

To investigate the implications of imposing a given GWP target, e.g. related to a certain building performance label, the results database is processed through a classification algorithm used to produce an interactive decision tree. Fig. 1 illustrates the structure of an example decision tree [28]. Instances (in our case, scenarios) are classified based on their class and their feature values. The class is here equivalent to the scenario's compliance to the GWP target; yes: below target, no: above target. A feature here corresponds to a variable parameter.

In Fig. 1, the features and their values are respectively represented by nodes (Nx) and branches (bx-y), where y is a value for parameter x.

![Decision tree structure with nodes (Nx), branches (bx-y) and resulting class (yes/no). Schema adapted from [28].](image)

The C4.5 algorithm is here employed through the ‘LearningJS’ library [29], with the information gain as a splitting criterion [30]. Information gain is a measure of the level of ‘purity’ (same class) of the data subsets corresponding to a given feature’s values. It is used recursively to determine the hierarchy of parameters that can best discriminate between complying and non-complying scenarios and that lead to the most compact tree. This visualization thus allows seeing, for the most important parameters, which of their option(s) lead to (un)favourable scenarios with respect to a given indicator target.

It is to note that the ordering of the features, i.e. the relative positioning of the variable parameters in the sequence of nodes, is not fixed. Indeed, as mentioned, the classification algorithm determines the hierarchy of the features and it is therefore not possible to impose a certain parameter order. As such, the resulting sequence will not necessarily follow a logical or chronological project decision stream, as will be seen in the next section.

A dedicated web app, developed in the context of the SETUP project [17], generates the decision tree (i.e. runs the classification algorithm) and produces an interactive visualization from an uploaded JSON file. This file is previously automatically built and exported by an Excel-based tool using the VBA-JSON library [31]. The web app enables users to open/close tree branches and view data on the number of (non-)complying scenarios at each node.

3. RESULTS AND DISCUSSION

The first few nodes and example branches of the decision tree generated from the database are shown in Fig. 3, for a GWP target of (a) 20 kgCO$_2$-eq/m$^2$-yr (corresponding to the SIA 2040 target for office buildings [6]), and for a slightly higher value of (b) 22 kgCO$_2$-eq/m$^2$-yr. Each node is represented as a pie chart showing the share of complying (green) and non-complying (red) scenarios. The overall database distribution, found in the first node (root of the tree), indicates that by increasing the target by 2 kgCO$_2$-eq/m$^2$-yr (i.e. by 10%), the percentage of complying scenarios goes from 55% to 85%. This first piece of information provides insights into the feasibility of aiming for a given performance target. We could also imagine progressively reducing the target to see what GWP value could still be reachable and by which string of decisions. Although not illustrated here, feasibility results drop to 24% and 3% when decreasing the target to 18 and 16 kgCO$_2$-eq/m$^2$-yr respectively. At 15 kgCO$_2$-eq/m$^2$-yr, there are no more complying scenarios (0% feasibility). It must be kept in mind that this result depends on the characteristics of the case study, including the options considered for the different variable parameters.

By comparing the two trees, we also observe that the first parameter is different. In Fig. 3(a), the type of construction for horizontal elements (roof, slabs) is at the root, whereas the heating system is found to be the most efficient classifier for tree (b). According to the target, different parameters are thus brought to the attention of the user, who is informed on the strongly influential decisions. These are captured by the tree root and following nodes and their corresponding branches.
Figure 3: Decision tree (root and example branches) showing at each node (option/parameter) the proportion of scenarios that have an impact below (green) and above (red) the GWP target of (a) 20 and (b) 22 kgCO₂-eq/m²-yr.
As mentioned, the order of the parameters is dictated by the classification algorithm and thus leads, for the presented examples, to a sequence that does not follow a standard decision flow. To allow the user to impose a certain parameter order would require a complementary visualization technique. However, this integration of parameters within a single graph provides an overview of the interplay between parameters that are typically rather treated separately and at different design stages.

In the first tree, the user has opened up the branches corresponding to a concrete construction type, where about 3/4 of scenarios are non-compliant, and a timber frame construction, for which a majority of scenarios are compliant. For both options, the second most important parameter is the heating system. However, we can see that by choosing a timber frame construction, the choice of the heating system is less constrained, as the majority of scenarios remain compliant for all options. The next node for almost all HVAC options is the building height, which, when unfolded, leads to a more diverse set of parameters (fourth tree level). The structure of the second tree shows a different amount and order of parameters.

Out of the visible branches, we can start identifying the combinations of decisions that represent favourable pathways toward achieving each target. In Fig. 3(b), we even see some paths that lead to ‘pure’ nodes for which all remaining scenarios are target-compliant. This is the case for instance for all 5-floors building scenarios that have a heat pump as the heating system.

The decision tree visualization integrates diverse parameters that usually refer to different professions; urban design features related to building dimensions, architectural elements such as window-to-wall ratio, and engineering components such as heating or ventilation system. As such, it can be used as a communication support, providing an overview of the linkages between these parameters, and highlighting the importance of making coordinated decisions. This mixing of parameters that are usually addressed at different stages can however also be perceived as a limitation of the method, since the parameter order cannot be imposed.

Although no survey of statistical significance has yet been done to gather the opinion of professionals on the interactive decision tree, we can here report some preliminary qualitative feedback. The practitioners involved in the working group around the SETUP project, which included among others an architect/urban designer and an engineer, have unanimously emphasized their appreciation for the decision tree, that was singled out as particularly didactic among the various graphical outputs of the SETUP prototype tool (some of which can be seen in [17]).

4. CONCLUSION

This paper presents an interactive decision-tree visualization that maps (un)favourable decision pathways with respect to a given environmental impact target. The tree is generated via a classification algorithm applied on a pre-simulated database of building design scenarios, distinct in terms of a set of parameters that are varied across conceivable options, such as building height, type of ventilation system, and glazing type.

Producing such a database enables exploring multiple alternatives without having to go through manual iterations over the design. The only iteration is on the performance target, that can be varied to see how it affects the compliant and non-compliant decision pathways made visible by the tree.

The decision tree exploits the rich information contained in the database by offering a dynamic, intuitive and simple communication instruments that can be used within an interdisciplinary planning and design team.

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REFERENCES


The Advantages of Simulation and In-Situ Measurement in Different Design Stages

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ABSTRACT: Since the outdoor spaces can encourage people to spend more time in the exterior spaces consequently, they play a significant role to reduce the energy consumption in the interior spaces. In this regard, providing thermal comfort in the design of the open spaces have remarkable importance. In this paper, the comfort assessments by computational simulation and the in-situ measurement have been proposed for different design stages. By consideration of the advantages and constraints of each of them, the complementary usage of both methods increases the efficiency in the derived results.

KEYWORDS: Design guideline, Outdoor comfort, thermal comfort simulation, In-situ measurement; comfort evaluation.

1. INTRODUCTION

The development of the Mpumalanga University campus is one part of the larger scheme for development of several universities in South Africa with a specific intention on the importance of energy-saving. One of the major areas of this study is focused on the design of the outdoor spaces to enhance thermal comfort conditions.

This paper tries to illustrate the approach to extract and analyze the derived data from the simulation process and the in-situ measurement method, which have been used in the design of the Mpumalanga University. In this regard, the first part of this paper demonstrates how the extracted data from the simulation techniques have been used to construct a design guideline. Then, the second part explains the use of in-situ measurement method in the latest stages of the execution of the design as a monitoring technique with detailed information to evaluate the real environment. In the last section, three cases have been determined for comprehensive analyses in order to show the benefit of the experimental study of in-situ measuring method. Besides, it demonstrates how comparison of the lesson learnt from the simulation analysis with the derived information from the in-situ measurement can be used for the improvement of the comfort condition in outdoor spaces.

2. SIMULATION

The main intention of employing the simulation method is to determine the efficient design strategies to enhance thermal comfort in the external spaces. The simulation process has been used in different stages of the design process from very early stages to the final proposal in order to create a beneficial platform for a series of design principles.

The Universal Thermal Climate Index (UTCI) criteria have been used as the base for assessment of the comfort level [1,2]. Thus, the assigned value to the air velocity (Va), relative humidity (Rh), air temperature (Ta) and mean radiant temperature (MRT) have been gained from the Typical Meteorological Year (TMY) data provided by the closest weather station and localized [1]. The method that has been used in the simulation of this project is based on the “Analytical method to assess outdoor comfort based on UTCI” paper [3]. Assessment of the comfort level in each point of interest in the site location has been calculated by overlaying all the collected data from the effective environmental parameters. It should be mentioned that the calculation of the Mean Radiant Temperature (MRT) has been employed based on the Numerical Vector (NV) method [4]. The collected data should be stored strategically to provide easy accessibility for analysis. To do so, separate matrices have been assigned to categorize the collected data [3]. The storing of the collected data in the series of matrices provides the possibility to determine the effective parameters in multiple periods and separately. This technique does not summarize the collected data with a conclusive number as the final result. It gives the potential to define the exact causes that a location is out of comfort, and subsequently, to find the most effective parameter to improve the comfort level.

The intrinsic meaning of each concept should be considered. For example, the “average UTCI” is very vague. Its ambiguity is significant when it comes to the meaning of the average of the cold stress and heat stress. In this case, the number of comfort hours to the
total hours of a year, which shows the percentage of comfort on each point, can be a more beneficial data projection.

One useful strategy in analysis of the collected data is to find the points in the site location that are out of comfort range with conditions of “moderate heat” (28-32 °C) or “slight heat” (26-28°C) that have the potential to be changed into the comfort range by proposing effective strategies in design. The importance of these points is to define the extent of time in which there is the possibility to improve their condition and shift it into comfort range. If the scope of the time has very limited range, consequently, providing the design suggestions becomes less feasible.

Figure 1: Annual moderate heat stress from 8 a.m. to 4 p.m. on left and annual comfort percentage on right.

Filtration of the collected data based on a specified time frame plays an important role to employ more effectual design solutions. In this regard, the analytical process can be optimized by consideration of the space usage and limit the time frame with the maximum usage. Thus, the focus is not to analyze one space for the whole times of the year.

Figure 2: Percent of annual comfort on a different day time period.

Figure 2 illustrates the annual simulation of the comfort level percentage for different hours of the day. As it can be seen, it indicates the high range of discomfort in the morning between 9 a.m. and 12 a.m. and in the afternoon between 12 a.m. and 4 p.m. in external spaces. Therefore, the difference between the percentage of the comfort condition in these images determines the suitable functions for each time frame.

Figure 3 represents the effect of a 50% reduction of solar radiation on the annual comfort result. The most affected areas are located in the open fields, and their condition is enhanced 70% by providing shade. The areas between the buildings are improved 20% on average.

The condition of the points in the middle of the courtyard spaces is enhanced by at least 10% which indicates that the effect of solar radiation in the ground surface of the narrow courtyard is much less than the open areas. This analysis suggests the placement of shade in wider areas rather than the narrow ones.

Figure 3: The impact of a 50% reduction of solar radiation on the annual comfort result.

Figure 4 illustrates the annual simulation of comfort level in daily hours (between 8 a.m. and 4 p.m.) in 2 different chosen points in the site location. Point 115 is chosen in a location far from the main building in an almost empty field. The purpose of analysing this point is to provide the basis for the existing potentials of the micro-climate of the site location without impact from any geometry. The outcomes show a high level of T_{art} (between 30-83°C) which is mostly due to the direct solar radiation, absence of shading devices, and in the result of the reflected radiation, especially the long-wave radiation from the ground surface. This point is on the comfort range for a short period in the year.

Point 307, which is located in the middle of the narrow courtyard, has a higher range of comfort level. However, it has heat stress in the first months of the year due to direct and indirect radiations, and it has cold stress in winter due to the lack of sunlight. This analysis shows the design of an enclosed space requires consideration of the appropriate scale, which provide proper depth to control the required amount of solar radiation in summer and winter to reach a high level of comfort condition. For the analysis of the spaces such as
the courtyard spaces, which have the potential to enable different conditions in the different sections, it should be considered that the assessment of the comfort condition is a summation of all the existing potentials. When a courtyard has direct solar radiation in one part, and shade on the other part, thus, the comfort condition should be analysed for the entire part, not only for one point. Because the chosen point might be either in a comfortable spot or uncomfortable spot and therefore, the result becomes misleading. The analysis of the comfort condition in one area cannot be considered with the “zero-one” law. This logic emphasizes on the probability of comfort in one space to be one or zero, however, it cannot be true. Because one area might provide comfort in some section, while it might be uncomfortable on the other section. So, in the design of such spaces, there is the possibility to consider different potentials in the entire space to provide comfort in different situations. For instance, it is possible to enable the sitting potential under shade or sun simultaneously on two different corners of the space, then the user can decide where is more comfortable to sit during different hours of the day or in different seasons.

Figure 5: The application of the different changes in the effectual parameters.

The adjustment of the derived results from the simulation analysis with “what if” scenarios can lead to potential design interventions. The applied technique to store the collected data into the separate matrices gives the opportunity to find the effective parameters on the creation of discomfort. Thus, it is possible to test the findings by applying adjustments into each space and see if the results are the same as the expectation or not. Figure 5 shows how different parameters can be modified to determine the better usage of each space. The intention of this examination is not to dictate the designer what to do, however, it raises the sensitivity of application the different changes in effectual parameters and to show the possibilities to enhance the design.

3. MEASUREMENT

In Mpumalanga University project, the in-situ measurement method has been applied in the final stages of the project construction to evaluate the performance of the external spaces and to suggest the required adjustments. The benefit of applying this image-based measurement method is to compare the gained information from the simulation to check the proposed “rules of thumbs” in the earlier stages of the design phase. This comparison provides the chance to recognize the shortages, to adjust the design, and to use the lessons learnt for the design of the other developments with the same microclimate condition.

The focus of the in-situ measurement is to record and map the radiant environment on each point of interest. Defining the radiant environment intertwines with a precise understanding of the concept of Mean Radiant Temperature (MRT), one of the most effective parameters in outdoor comfort. The imaging of the radiant environment gives the possibility to calculate MRT and map the radiant flux from each surrounding surface. To clarify the MRT calculation, the efficiency of the environmental parameters on thermal comfort should be prioritized. In this respect, MRT is the most complex parameter that has the highest influence on comfort condition in this climate, the air temperature is the less effective and other parameters like wind and the relative humidity have limited efficiency based on the conditions of the area. Therefore, specific attention has been paid to precisely understand the substantial information about MRT to amend the thermally desired external ambience.

For the measurement process, MRT has been determined based on the Radiant Ambience Imaging (RAI) method [4] and other parameters like wind velocity, air temperature and relative humidity have been captured by using the Kestrel 5400 Heat Stress Tracker. Since the mapping of MRT has been based on series of infrared photos to capture the longwave radiations and high-dynamic-range (HDR) photos to take the shortwave radiations, it provides a better understanding of the effect of the used material and the geometries of the surrounding built environment [4]. This mapping technique shows the amount and direction
of the radiation, and consequently, it indicates how each surface contributes to the existing condition. One of the effective parameters of thermal comfort is the surface material that causes a certain amount of reflection or absorption. The other important parameter is the arrangement of the spatial geometries that has an impact on the amount of solar radiation, shadow creation in different hours of a day, and the sky view factor. The common measuring methods, like the Black Globe method, have several problems such as time-consuming setting and inaccuracy regards to add the wind effect in the calculation of MRT. Besides, they only report a conclusive number as the outcome for MRT which does not give the possibility to separately analyze the effective parameters, such as view factor, emissivity, short-wave and long-wave radiation from different sources like Sun, visible sky, and the built surfaces [4].

The proposed in-situ measurement method provides two advantages, the accuracy and the readability of the impact of each surface separately. It evaluates how the reduction of the radiation from one specific surface effects on the total level of comfort in the selected location. This evaluation process can be used in different stages of the design process, construction phases and even for the post-occupancy evaluation to develop the comfort level in different spaces. The purpose of using the in-situ measurement in the early stages of the design process is to collect the micro-climate condition of the site location by monitoring the relative information of some points in the same micro-climatic context. For example, it can be done by measurement of some assigned points in the adjacent buildings to the site location. Similarly, the experimental measurement method can be used at the latest stages of the project execution or after completion of the construction phase for the post-occupancy evaluation. Since sufficient information about the real physical context with all the details is available at this stage, it is easier to record the total effects of the different parameters. All these aspects give the possibility to revise the design with more effective solutions to improve the comfort condition.

Besides, there is an opportunity to compare the prior predictions from the simulation with the gained results from the in-situ measurement calculation. This comparison gives more comprehensive insight about the shortage of the simulation of the virtual context.

The analysis process of the proposed measurement method has been demonstrated in the next section through the examination of three cases to show how to extract information from the imaging process. All three cases are exterior spaces; the first one is under direct sunlight, the second one is underneath the covered overhang, and the last one is under shade.

### 3.1 Case study 1

Both cases, 1 and 2, are situated in the same courtyard in two different conditions to compare the impact of different parameters in the same space. The courtyard is surrounded by three-story buildings and has the rhombus shape with North-South elongation and a little rotation towards West. Two points have been chosen in this courtyard to be examined; one is located under direct solar radiation and the other one is situated under the shadow.

The first point is appointed above the brick pavement of the sidewalk under the direct sunlight. As it can be seen from the provided chart (figure 6), $T_{\text{MRT}}$ is 36°C, the air temperature is between 26-28°C, the wind speed is around zero and UTCI is 33°C that shows strong heat stress. The main effective parameter that has an impact on the amount of the radiation on this point is the direct sunlight and the subsequent one is the Total Radiation Flux from the pavement. Since this point is situated in an open space, the considerable amount of the View Factor is related to the sky, which has less amount of the radiation in this environment. The illustrated diagram in figure 6 has classified the received radiations in 8 parts, which shows the amount of $T_{\text{MRT}}$ in each section. The lowest amount of $T_{\text{MRT}}$ belongs to the West-South side, which is around 25°C. This low rate of $T_{\text{MRT}}$ is because of the long distance between the assigned point and the surrounding surfaces.

In contrast, the high amount of $T_{\text{MRT}}$ belongs to the North section, mainly because of the presence of the sun. Also, from the South-East to the North-East sections that are close to the façade of the adjacent building, the amount of $T_{\text{MRT}}$ has been increased. The reasons for this increase can be mentioned as the closeness of the point to the surrounding radiant surfaces and the little amount of the Sky View Factor. By assuming that the point is
located in the middle of one octagon, the surface temperature in the Northside is 142°C. So, the effective parameters in defining the amount of $T_{MRT}$ at this point are the pavement, adjacent façade and the sky view factor. The result of the amount of $T_{MRT}$ for each of these parameters can be calculated as the percentage of the total amount of radiation.

3.2 Case study 2

The second point is situated in the same courtyard as the first point is located. However, the location of this point is chosen in the shade. The collected information from the in-situ measurement shows that $T_{MRT}$ is 25°C, air temperature is 26-28°C and UTCI is 24°C, which shows no thermal stress in this point. As figure 7 shows, the close surrounding surfaces are in the shade while the further surfaces are affected by direct sunlight. Therefore, the view factor of the different surfaces plays an important role to define the $T_{MRT}$.

Figure 7: (a) The HDR photo from a silver mirror. (b,e) Total radiant flux densities. (c) Remapped fisheye photo. (d) $T_{MRT}$ from different directions.

3.3 Case study 3

The third point is placed in the corner of the main courtyard from the old part of the university campus. The design of the old section of the campus has been formed based on common knowledge without using any simulation techniques. In this regard, the analysis of this case tries to emphasize the potential of using in-situ measurement procedure after the construction phase as an approach to monitor and evaluate the spatial performance. This point is situated under a giant roof overhang to provide a covered space with blockage the direct sunlight. The overhang is constructed with steel structure and painted corrugated roof sheeting. The primary reason to construct this overhang is to create a thermally comfortable space underneath. The gained results from the measurement procedure show that the air temperature is 27°C and wind velocity is 1 m/s. Although the result indicates that $T_{MRT}$ is 34°C, UTCI is 27°C that shows the slight heat stress condition.

Figure 8: (a) The HDR photo from a silver mirror. (b,e) Total radiant flux densities. (c) Remapped fisheye photo. (d) $T_{MRT}$ from different directions.

Figure 8 illustrates the total amount of the Radiant Flux Density of the ambient environment, which has been calculated based on the RAI method [4]. Based on the evaluated information, the role of the roof sheeting when $T_{MRT}$ is 34°C is related to the Radiation Flux of the roof itself, which represents a surface with 45°C. By consideration of the fact that the view factor of the roof area is 0.28, it means that almost 30% of the selected point is affected by the radiant surface. The outcomes clearly state that although the overhang covers the selected point from the direct sunlight radiation, the absorbed heat by its surface generates thermal radiation that emits long-wave radiation to the underneath area. Consequently, the emitted thermal radiation becomes an effectual factor in the creation of discomfort. It can be seen how the element that has been designed to improve thermal comfort, becomes the main factor to increase discomfort by itself.

In this example, using different material with a lower rate of emissivity for both sides of the roof sheeting can
be suggested. Then, both parameters of the heat absorption and the long-wave radiation would be reduced. Also, extra layers into the bottom part of the roof sheeting can be added to prevent the radiation to its underneath. Examination of this case shows how the design of the overhang has been formed based on the common knowledge and belief about the effect of the direct sunlight and how it has been designed in its simplest possible way. However, after application of the measuring process, it is clear that the physical aspects of the radiant built environment have not been considered in the design process to make a more precise decision about choosing an effective material for the roof sheeting.

The measuring process of the university campus site has been executed in one hot summer day. The results from this process indicate that the outdoor spaces benefit from the proposed “rules of thumbs” from the simulation procedure to provide comfort. In order to extend the findings from the in-situ measuring more comprehensively; the whole process should be repeated for different times of the year to examine the functionality of different spaces more broadly.

4. CONCLUSION

To recapitulate, the main purpose of this paper is to indicate the benefit of application both of the simulation method and the in-situ measurement technique by clarification the advantages of each of them in the design process to improve the thermal comfort in the outdoor spaces. Both methods can be beneficial in different stages of design based on their capabilities in the post-processing section. There is a direct correlation between them in which the in-situ measurement procedure can be taken as one stage of testing the simulation results and to be proof for it. It shows the level of accuracy and reliability of the derived results from the simulation process in the real-world context.

In addition, it can be said that the measurement method is a complementary component to be combined with the simulation process. The in-situ measurement approach is a method to record the required data in a real-world context to calculate all the effective parameters and their total impact. This approach provides more accurate information about the actual physical environment rather than using the simplified virtual context used in the simulation method. Even though there are advanced technologies in the simulation techniques and the environmental calculations, there is a remarkable shortage in the presented data from the simulations. The complexities should be avoided in order to reduce the required time for calculation. So, many parameters such as environmental geometry should be simplified. In fact, it can be said that the simulation process is based on lots of assumptions. To accelerate the computational process, lots of parameters are simplified to constant coefficients, consequently, the sequence of the approximate multiplication leads to less accuracy of the result when the number of the parameters increases. In this respect, the accuracy of the simulation is not sufficient to only rely on that and the uncertainty aspects should be considered. Thus, the monitoring process via in-situ measurement technique at the latest stages of the project execution plays a significant role in the improvement of the design.

Furthermore, the simulation analysis can be executed based on the achieved information from the measurement method. The post-processing potentials in this method provide a detailed examination of the existing condition. And storing the collected data allows providing an efficient database to predict and simulate more accurately for future designs with a similar microclimate condition.

Lastly, the post-processing of the measurement approach provides the numerous possibilities in the analysis that leads to extract a countless amount of information. Moreover, when it combines with the collected data from the simulation analysis, there would be an extensive package of information that provides the possibility to exactly define the effective parameters and their level of sensitivity and effectiveness. Existing potential of the post-processing in the derived information from both techniques allows defining the practical design strategies for improvement of the comfort status.

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REFERENCES

The Effect of Increasing Vegetation Cover on Energy Demand for Heating and Cooling Buildings in a Dense Mediterranean City
Methodology and Case Study

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ABSTRACT: The study examines the effects of adding vegetation to a Tel Aviv neighbourhood on the microclimate, and subsequently on electricity consumption for heating and cooling. Computer simulation was employed to generate modified weather files that account for urban effects in different building configurations. These files were then used as inputs for detailed computer simulation of building energy performance. Elevated night-time temperatures in the urban location increase summer cooling relative to the reference rural site, but reduce winter heating, resulting in a net decrease of 2-7% in overall electricity use for heating and cooling (depending on building characteristics). The reduction in the potential for cooling by night ventilation will increase the prevalence of air conditioning use and make buildings more vulnerable to potential loss of electric power during episodes of extreme heat. Implementing a strategy of extensive planting, so that a green surface fraction of 0.5 is obtained, results in a mean annual temperature reduction of about 0.3 °C and an energy saving relative to the current condition of about 2-3%.

KEYWORDS: building energy simulation; climate cooling potential; microclimate modelling; vegetation; urban heat island mitigation

1. INTRODUCTION
Increasing vegetation cover is one of the main strategies for mitigating urban heat islands and reducing energy consumption in buildings [1]. Computer simulation of air temperature, usually on a typical hot day, has been employed to assess the energy saving potential of vegetation on hot summer days [2] using software such as ENVI-met [3], which includes detailed procedures for describing plants. Most studies have been performed for low-rise buildings in low-density neighbourhoods, and results invariably demonstrate a cooling effect. The studies then estimate the reduction in air conditioning loads, rarely carrying out a detailed building energy simulation. With the exception of studies on green roofs, e.g. Moody & Sailor [4], few modelling studies have demonstrated a systematic methodology for assessing the site-specific effect of vegetation in dense urban neighbourhoods on annual energy consumption. Fewer still have attempted to account for the full effects of shading by adjacent structures, lower wind speed and increased humidity – in addition to modification of air temperature.

The present study has the following objectives: To describe a methodology designed to carry out an assessment of the effect of vegetation on annual building energy consumption, which may be applied in any location; and to illustrate it by means of a case study for several (residential) building types in a warm climate. The case study focuses on a dense, medium rise neighbourhood, a typology that is found all around the Mediterranean and is becoming increasingly common in new construction in developing world cities.

2. METHODOLOGY
Urban microclimate was simulated using the Canyon Air Temperature (CAT model) [5]. Using measured data from a rural reference weather station as input, CAT generates modified TMY files for urban street canyons of varying geometry and different vegetation cover, which incorporate urbanized values for dry bulb temperature of the air, relative humidity and wind speed. These data are used to modify .epw files used as inputs for the EnergyPlus building thermal simulation software (US DOE, 2008).

Energy consumption was simulated for 5 scenarios: 1) a stand-alone building at the rural reference weather station; 2) the same building, but shaded by similar adjacent structures, to account for the effects of shading in a typical city street, but with no modification of the weather file; 3) conditions in
2.1 Study area
Tel Aviv comprises the core of Israel's largest metropolitan area and is located on the eastern coast of the Mediterranean Sea. Its climate is classified as Mediterranean (Köppen Csa), with mild, rainy winters and warm, humid summers. It has 530 heating degree-days (to 18.3 °C) and 3,810 cooling-degree-days (to 10 °C). The study area comprises the Ramat Aviv neighbourhood, about 1.5 km inland from the Mediterranean Sea (32°11'N, 34°79'E). Streets are 15-25 m wide and flanked by buildings of varying height, from two or three storeys to as many as 16 storeys.

2.2 Simulating the urban microclimate
The CAT simulation requires descriptions of the sites of both the weather station providing the boundary conditions and of the urban street canyon that is the object of the exercise. The details required for both locations include the geometry of the site, represented by building height, street width and street orientation; thermal properties of the wall materials and the ground surface; and land cover within a radius of 1,000 meters, specifically the proportion of the surface covered by vegetation and bodies of water, for each of 32 sectors arranged in a radial pattern surrounding the site [6]. In addition, data for the reference weather site (only) include aerodynamic parameters describing the surface roughness, required to generate the logarithmic profile of the wind speed above the ground, and annual temperature data used to model the subsurface temperature.

When the CAT model is run for a single urban location, the required inputs may be entered manually into the text files read by the software. However, the derivation of the inputs for an urban area comprising thousands of grid elements at a resolution of 100 x 100 meters requires an automated procedure to process data from several sources. These sources include a spatially explicit GIS database describing building footprints; and satellite images that are analysed to provide estimates of the surface cover fractions [7]. The values for each grid cell were estimated using an automated procedure developed using the R software [8] and ArcGIS 10.6 [9].

CAT is a ‘canyon’ model, in which the entire urban area is described by means of simplified urban elements referred to as street canyons [10], for which a detailed surface energy balance may be calculated. Zhou et al [11] described an automated procedure for identifying such street canyons and assigning a street orientation even if building footprints are irregular and there are no discernible paved roads between adjacent building blocks, based solely on the plan form view of the buildings and the distances among them.

 Anthropogenic heat, which may have a substantial impact on air temperature in dense urban locations, is estimated using a procedure that accounts for heat given off from buildings and automobiles [11]. Heat transfer from buildings includes steady-state conduction through facades, which is calculated using typical thermal properties of walls and windows and the difference in air temperature between the building interior (according to season) and exterior at hourly time steps. Heat loss by convection is estimated assuming a fixed number of air changes per hour between the interior and the exterior, based on the construction quality and airtightness of fenestration. In summer, heat ejected by air conditioners is assumed to be proportional to the difference in air temperature between the interior and exterior. Heat emitted by automobiles is estimated as the product of the heat emitted by a typical car (3,795 J/m [12]) and the number of vehicles travelling down the street, assigned according to street width (broad streets have more traffic) and a diurnal traffic profile.

2.3 Effects of vegetation
The vegetated CAT model uses parameterizations to estimate evapotranspiration and surface temperature, and accounts for changes in soil moisture and the canopy resistance of different types of vegetation as well as the green surface fraction [13]. This fraction was estimated for the current (baseline) conditions using NDVI values obtained from remote sensing images [11].

2.4 Building characteristics
Energy simulations were carried out for three building variants having the same floor plan but representing different standards of construction: a pre-1980 ‘standard’ building complying with Israel standards for thermal insulation (SI 1045); a ‘green’ building with the same floor plan but complying with the energy requirements of the Israel green building standard (SI 581); and a building with a ‘curtain wall’ design similar to some of the new residential construction in Tel Aviv.

The building has an H-shaped floor plan that is very common in Israel. It comprises four apartments per floor, each of about 84 m² in floor area. The window to wall ratios for all facades of the building are 0.11 - 0.12, except for the curtain wall variant, which has a window to wall ratio of 0.3 on the north and south facades.

The building is a concrete frame construction with infill walls of hollow concrete blocks. Thermal insulation values of envelope elements are shown in Table 1:

Table 1:
3. RESULTS

3.1 Model validation

The microclimate model was validated using the ‘Tel Aviv coast’ weather station data as the objective of the simulation and the rural ‘Bet Dagan’ station of the Israel Meteorological Service, about 7 km inland, to force the model. Fig. 1 illustrates model performance for a typical week in summer.

![Figure 1: Model performance in summer.](image)

The measured temperature at the urban station (light blue circles) is generally warmer at night and cooler in daytime than at the rural reference station (dashed green line). This is due to the combined effect of its proximity to the sea and its urban characteristics. The simulated temperature (solid red line) demonstrates the ability of the model to pick up both effects. Statistical analysis shows a root mean square error (RMSE) for the entire year (8760 hours) of 2.02 °C, with a mean absolute error (MAE) of 1.11 °C.

3.2 Urban effect on air temperature

Figure 2 shows the spatial pattern of the simulated UHI of Ramat Aviv for a typical summer night (July 30, 2016). Temperature differences are displayed relative to the reference weather station at Bet Dagan.

The urban heat island has a clear diurnal pattern, simulated for the hot spot indicated in Figure 3: it is small or even slightly negative during daytime throughout the entire year. At night, the UHI intensity reaches a mean maximum of nearly 3 °C, observed shortly before sunrise, but the variance is quite large, as indicated by the values for the 10th percentile and 90th percentile of hours, at under 2 °C and nearly 5 °C, respectively.

![Figure 2. Ramat Aviv UHI simulated by CAT for 04:00 on July 30, 2016](image)

3.3 Effect of vegetation on air temperature

Increasing vegetation cover to 50% of the non-built area in the suburban neighbourhood is expected to reduce air temperature. Fig. 4 shows the simulated magnitude of this effect over the entire year.

As the figure shows, the effect of adding surface cover vegetation on air temperature is in fact quite modest, for two reasons:

- First, the spatial extent of additional plant cover that may be added to an existing urban fabric is limited. The green fraction of Ramat Aviv, measured within a 1,000 meter radius of the site being modelled, is currently 0.29, and the built fraction of the developed area is 0.22 (some of the periphery is still undergoing development). The scenario evaluated, whereby the green fraction is increased to 0.5, is probably the maximum possible practical
intervention, and would entail a substantial reduction in the areas currently devoted to roads and vehicle parking lots.

- Second, because the effect of evaporation on air temperature in a street canyon is related to not only the horizontal area but also to the ‘complete’ three-dimensional urban surface [14], the impact of such an intervention is comparatively lower in medium or high-rise neighborhoods than in neighborhoods where the majority of buildings are only one or two stories high.

Figure 4: Effect of adding vegetation on air temperature in the urban site.

3.3 Building energy consumption

Table 2 shows the annual electricity demand for heating and cooling the standard case study 8-story building for each of the five scenarios.

<table>
<thead>
<tr>
<th>Building energy demand (kWh/a)</th>
<th>Heat</th>
<th>Cool</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 rural unshaded</td>
<td>16,575</td>
<td>40,734</td>
<td>57,309</td>
</tr>
<tr>
<td>2 rural shaded</td>
<td>20,053</td>
<td>34,636</td>
<td>54,689</td>
</tr>
<tr>
<td>3 existing canyon</td>
<td>10,587</td>
<td>40,503</td>
<td>51,090</td>
</tr>
<tr>
<td>4 ‘green’ canyon</td>
<td>11,681</td>
<td>38,048</td>
<td>49,729</td>
</tr>
<tr>
<td>5 ‘no green’ canyon</td>
<td>9,935</td>
<td>41,930</td>
<td>51,865</td>
</tr>
</tbody>
</table>

The net effect of including shading by similar adjacent structures in the simulation (scenario 2, using the same .epw weather file as scenario 1) is to increase heating demand in winter but reduce cooling demand in summer. Scenario 3 demonstrates the urban effect: the city is warmer, so the building requires less heating but more cooling. Scenario 4, by lowering air temperature, reduces cooling demand but also increases heating requirements. Finally, in Scenario 5, removing all current vegetation increases air temperature, thus lowering winter heat demand but increasing summer cooling relative to the existing situation.

4. DISCUSSION

The objective of this study was to assess the outcome of interventions in the urban fabric to mitigate the effect of the urban heat island, and hence on building energy consumption. The methodology demonstrated here accounts, by means of appropriate software tools, for both urban effects and building effects, at high spatial and temporal resolution on an annual basis.

4.1 Assessing the impact

The urban effect on annual energy consumption depends on the balance between demand for summer cooling, which is aggravated due to the nocturnal heat island, and moderated by reduced winter demand for heating. In the case of Tel Aviv, which has a warm humid Mediterranean climate, the net urban effect was - counter-intuitively - a small decrease in annual energy demand. It is worth noting, however, that while the simulated reduction in winter heating (the difference between scenario 2 and scenario 3 in Table 2) is equal to nearly half of the total demand for the season, the increase in summer cooling demand, which was twice as large in the first instance, is only 17%. Simulation for future climate conditions in the Eastern Mediterranean in the period 2041-2070 project a general increase in seasonal mean temperatures of up to ~2.5 °C [15], so this balance could change as winter heating demand in the urban areas is eliminated entirely. Summer heat will be exacerbated, particularly during strong nocturnal heat island episodes.

Increasing the green fraction yielded a mean annual temperature reduction of about 0.25°C relative to the existing condition, and a small reduction in building energy consumption equivalent to about 2.6% of the total annual demand for heating and cooling.

The electricity consumption of a conventional compression cooling system, such as the split air conditioners commonly used in Israel, depends not just on the sensible heat load, due to the dry bulb temperature of the air, but also on the latent load, due to its humidity. Vegetation can maintain a lower temperature than an adjacent paved surface, despite having a similar albedo (0.2-0.25) because of evapotranspiration, which releases moisture to the air and increases humidity. Thus, although near-surface air temperature in the presence of vegetation may be a little lower, the enthalpy of the air, and thus the total thermal load on the air conditioning system, is nearly the same.

4.2 Limitations of the study

The vegetation modelled in this study consisted of surface cover plants, such as grass or small bushes.
Their effect on building energy consumption was expressed through their impact on air temperature and relative humidity, by means of the modified weather file. Other plant types, such as trees, may have different effects: For example, they may induce a greater temperature reduction during the warmest daytime hours, but a smaller reduction at night, when trees may even lead to warmer air temperature because of reduced radiant cooling; and they reduce wind speed and thus the potential for cooling by ventilation. Vegetation also affects building energy consumption through radiant exchange: Because planted surfaces are typically cooler than pavement, the radiant fluxes incident upon building walls in the vicinity of planted surfaces are usually smaller [16]. This may be expected to lower cooling demand in summer, but increase heating demand in winter.

The cooling effect of vegetation depends to some extent on evapotranspiration. The vegetation model incorporated in CAT [13] simulates changes in soil moisture, which increases in response to precipitation, then decreases gradually in the absence of rain as water slowly evaporates. However, if the surface is planted, the model allows soil moisture values to decrease to a minimum value and, if there is still no rain, are then increased to the field capacity for the soil in question, to represent the effect of irrigation. In reality, irrigation may not be provided at the appropriate interval to compensate for the absence of rain, or it might not be supplied at all.

The buildings modelled in this study are medium rise: 8 storeys high. The impact upon them of vegetation at ground level may thus be expected to be lower than in the case of detached low-rise buildings. Additionally, apartments in the upper storeys of tall buildings do not benefit from the shading effects of vegetation.

Modelling tall buildings creates unique challenges, because the environmental conditions, especially wind speed, change with height above the ground. EnergyPlus has built-in procedures for treating tall buildings that account for the temperature gradient and in particular the effect of wind on the transfer coefficient for convection at wall surfaces. However, it does not simulate the effects of the urban environment on local wind patterns and air temperatures directly [17]. CAT accounts for some of the urban effects, in particular a transformation of wind speed from a measured value at the rural reference weather station to a more realistic urban wind. However, although CAT simulates an urban logarithmic profile for wind, based on estimated roughness length and displacement height as well as a lee vortex in the street canyon, the EnergyPlus input uses just one wind speed value that cannot account for local effects at different building facades.

Finally, the modelled energy consumption is an indication of the relative energy performance of buildings, subject to the precise values assigned to represent occupant behaviour, such as set point temperature or occupancy patterns. While this is true for all building energy simulation, it is important to remember that occupant behaviour may have a great impact on real-world energy consumption: Field studies have demonstrated large variations in actual electricity consumption for heating and cooling even among identical apartments in the same building [18].

**CONCLUSIONS**

The study described a methodology designed to carry out an assessment of the effect of vegetation on building energy consumption. Application of this process allows us to propose the following conclusions:

- Studies focused on energy saving should employ detailed building energy simulation software that is capable of performing dynamic calculations at appropriate time intervals for an entire year.
- Urban effects must be accounted for in the weather files used in any simulation of the energy performance of buildings. The magnitude of these effects is often greater than the impact of the mitigation measures proposed.
- It is essential to model the effect of shading by adjacent buildings or any other sizeable object, including trees (despite that this is still not always required for building certification).
- Generating reliable, appropriate, site-specific, urbanized data for building energy simulation remains a challenge: meso-scale simulations such as WRF are not capable of resolving the urban features at the required spatial resolution, while micro-scale tools such ENVI-met are limited to one or two days at most.
- Any estimate of the potential energy savings from implementation of vegetation is necessarily limited to the precise circumstances for which they were assessed, because it is affected by numerous unique factors such as the spatial extent of the application, the type of vegetation, the amount of irrigation, the geometry of the street canyon, the local climate and the detailed thermal design of the building. Although it may be possible to generalize, it should be accepted that the magnitude of the outcome of any intervention may be within the margin of error of the building energy simulation tool, and is certainly smaller than the actual variations among similar apartments exposed to the same conditions.

The methodology demonstrated here requires advanced computer skills, but the computer resources are modest, especially if the analysis is performed on a limited spatial scale. It may thus be applied nearly anywhere: the basic inputs are the measured climate data at a nearby weather station and a GIS database of building footprints and heights. Additional features of
land cover are generated from satellite images that are publicly available.

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REFERENCES

Cross-disciplinary design optimization: parametric façade design for an educational facility in the Middle East
A case study of shading system genetic optimization

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ABSTRACT: The manuscript reports a positive demonstration of how cutting-edge parametric modelling tools could be integrated into the design workflow from the early stages. It describes the engineer’s involvement in the geometric definition of the shading elements for the main glazed façade in a new educational facility in the Middle East. The geometric characterization of these elements has been optimized since the preliminary phase in accordance with architect’s design, visual permeability of the façade, minimum incident solar radiation on the glazed surface, maximization of the lightness of the whole system, guarantee of adequate user comfort, and minimization the thermal loads due to the critical climatic conditions. Outcome of the analysis shows that optimization of the shadings’ geometry allows for reduction of the annual direct solar radiation gains in the exhibition area up to 48% thus keeping good values of daylighting parameters. The described example suggests that few small optimizations could considerably improve the overall project performance. Parametric optimization should be considered an essential part of the integrated design process for each project feature, following a cross-disciplinary collaboration with the design team.

KEYWORDS: Energy, Comfort, Optimization, Daylighting, Fins

1. INTRODUCTION

During the last years, the use of Building Information Management (BIM) models within the AEC industry for design and construction became part of the integrated process carried on by project teams in order to define and control in real time geometries, forms, masses, and materials according to the design concept developed by architects.

Historically, the overall architectural aspects only pertained to architects, nowadays the collaboration between architects and engineers has increased in relevancy especially due to the introduction of several restrictive standards in the field of energy consumption and according to the predominant added value required by topics and activities such as energy efficiency, sustainability certifications (LEED, BREEAM, WELL, GSAS), thermal and lighting comfort.

This strong connection is supported by several digital tools, which provide a unique capability to speculate creatively and simulate physically within a single design framework. Creativity is seen as both an abstract proposition and an actual implementation with a problem-solving value [1].

For this reason, parametric design, computing power, deep learning, and big data should not be just trending words, but powerful tools to be exploited to ensure a total integration of each discipline in the design process.

This paper presents an example of an application of this process to the façade design of an educational facility in the Middle East. Since the preliminary phases, the project has taken into account a deep involvement of the whole design team in order to share a strategy which reflected the architect’s compositional will, the local climatic characteristics, and users’ needs.

The main focus was given to the façade shading elements optimization, in order to minimize incident solar radiation on the façade and reduce the heaviness of shading devices.

For this purpose, a customized parametric analysis script has been developed in the Grasshopper environment [2] for Rhinoceros software, exploiting validated simulation engines via Ladybug + Honeybee tools [3] and looking for the best genome (i.e. the best shading configuration) via Octopus [4], a goal seeking generative algorithm.

Here, we demonstrate how the optimization and analysis process was developed for this case study, from the software choice for the parametric analyses to results and conclusions.

2. RESEARCH METHODOLOGY

The goal of this paper is to describe a case study where energy and daylighting improvements were allowed by a strong collaboration between architects and engineers. To this end, different aspects have
been considered, starting from a modelling software review, as briefly described below.

Several software solutions are available on the market to perform building physics analyses, and each one is characterized by pros, cons, and specific capabilities. The main issue of most of the common software is that users are typically forced to choose between the option to consider multiple parameters, perform more detailed analyses, and achieve more reliable results on one hand and a fancy Graphical User Interface (GUI) or easy data input on the other. Next pictures (Fig.1 and Fig.2) show a brief comparison of several integrated software suites which allow designers to deal with building physics issues.

The software environment chosen for the purpose of this study is the suite composed by Ladybug + Honeybee in Grasshopper for Rhinoceros, which is capable of performing very detailed and reliable parametric analyses in an easy-to-use platform.

Ladybug is an open source environmental plug-in which allows for the importing and analyzing of standard weather data within Grasshopper, the graphical algorithm editor and visual programming platform for Rhinoceros [5].

Honeybee completes Ladybug, connecting Grasshopper to validated and reliable simulation engines such as EnergyPlus [6], Radiance [7] and Daysim for performing a huge series of analyses, such as energy modelling, thermal comfort, daylighting and glare simulations.

These two plug-ins combined allow for the development of totally customizable and parametric scripts directly in Grasshopper. Moreover, Grasshopper offers the possibility to apply evolutionary principles to parametric design and problem solving through the integration of evolutionary solvers such as Galapagos or Octopus. In particular, Octopus uses generative algorithms to seek for many goals at once, collecting the best optimized solutions between the extremes of each goal. Octopus exploits SPEA2 (Strength Pareto Evolutionary Algorithm 2), one of the latest Elitist Evolutionary Multiobject Optimization (EMO) algorithms [8].

With the desired fitness values to achieve defined, Octopus is able look for the best trade-off (i.e. to define the Pareto frontier – Fig. 3) between a series of parameters, producing a set of possible optimum solutions that ideally reach from one extreme trade-off to the other.

The combined use of Ladybug, Honeybee, and Octopus allows to change the typical standard workflow for building physics analyses: what is usually the output of the analyses becomes the input of a parametric simulation whose results fulfil a required design performance.

3. CASE STUDY

The proposed case study is the parametric design of the main façade shading systems of an exhibition area for an educational facility in the Middle East. The
whole building has been designed by the architects in order to create a direct relationship with residents and visitors, allowing for a proactive and vibrant component to the complex. In particular, the exhibition area, designed with a half-moon shaped plan, is characterized by a large open space, fractionable by moving partitions according to the facility needs, an external perimeter completely opaque, and a fully glazed internal front overlooking a courtyard.

Considering local climatic conditions characterized by high values of solar radiation and outdoor air temperature, it became evident since the preliminary phases, that a large glazed surface would be critical for the people’s comfort and cooling energy requirements.

Therefore, the project team decided to include fixed vertical shading elements (fins) to protect the glazed surface. (Fig. 4). These elements, which have a relevant architectural impact due to their dimensions, have been optimized in order to:

- Minimize solar radiation on the façade to reduce thermal loads;
- Minimize fins’ dimensions to reduce their visual and physical heaviness;
- Allow for an optimal perception of the permeability between inside and outside.

A parametric analysis model was developed with the aim of finding the best compromise between the aforementioned goals.

Considering that solar radiation and daylight availability are strictly related, the shading systems performance has been optimized through both cumulative radiation on façade and daylighting parameters.

3.1 Façade shading system

The proposed façade system is based on a “stick system”. Vertical fins are used as Mullions, with an add-on extruded aluminum frame (rounded shaped to accommodate the variable orientation) and with covering cap attached internally (“inside out” arrangement) to retain the double glazed units. Aluminum pressure plates and silicone, applied inside and outside, creates a waterproof cavity.

There are no transoms, with glass-to-glass horizontal joints. Glazing deadload is supported by brackets connected directly to the add-on aluminum frame fixed to the external Mullions (fins). In order to connect the fins each other, stainless steel ties are integrated within the joints and fixed to the glazing load bearing bracket.

In order to accommodate the variable orientation, the back of the fins structure is made of a semicircular hollow section, where the curved aluminum profile supporting the glass is connected (Fig. 5). A Teflon layer is provided between the aluminum and steel to prevent a galvanic contact between the two materials.

3.2 Shading optimization

The façade is characterized by 120 shading fins organized in 24 groups of 5 elements (Fig. 6).

Considering the targets specified above, the project team decided to identify the best trade-off between the minimum annual cumulative incident direct solar radiation on the façade (target related to cooling load reduction) and the minimum fins’ upper depth (target related to shading heaviness and design permeability).

Degrees of freedom were set according to a series of key-points shared with the architect (Fig. 7):

- Each fin’s lower depth is fixed to 0.5 m, while the upper depth is variable from 0.5 m to 1.5 m in steps of 0.25 m;
- The rotation allowed around the perpendicular axis to the glass is ± 40° in steps of 10°.
In addition, to assure an appropriate homogeneity in the overall design of the fins, the following constraints have been imposed:

- Each fin cannot rotate more than 10° with reference to the adjacent one;
- Each fin’s upper depth cannot be higher than 0.25 m with reference to the adjacent one.

A customized analysis tool was created, where the façade geometry was defined in a fully parametric way and all the desired variables were defined to be free to vary within the allowed ranges.

In addition to geometry, material properties, weather data, analyses input and all required additional input (e.g. mesh dimensions and position, analysis accuracy, etc.) were defined via Ladybug and Honeybee.

All the building physics analyses were performed with Ladybug + Honeybee, and their outcomes were linked to Octopus, the goal seeking generative algorithm. A representation of the script is reported in the following picture. (Fig. 8)

The analysis was run, and three compliant options to be compared were selected on the Pareto frontier (Fig. 10).

- Option 01: higher reduction of fins’ depth and lower reduction of solar radiation;
- Option 02: average values for both shading system dimensions and solar radiation reduction;
- Option 03: lower reduction of fins’ depth and higher minimization of incident solar radiation on curtain wall.

3.3 Radiation analysis

The annual direct solar radiation on the glazed surface of the three options selected on the Pareto frontier was compared to the following two “baseline” solutions in order to appreciate the optimization outcome (Fig. 11):

- Baseline 01: No shading fins;
- Baseline 02: Shading fins perpendicularly oriented in each intersection point with the ellipse shaped façade.

Whilst all of them are considered best trade-offs, Option 01 is characterized by a slightly greater solar radiation on envelope (and slightly lower fins’ dimensions), Option 03 by a slightly lower solar radiation on envelope (and slightly greater fins’ dimensions), and Option 02 can be considered an average trade-off.
Figure 11: Comparison baseline vs selected options.

Outcome of the analysis show how the optimization of the fins’ geometry allows to reduce the annual direct solar radiation gains in the exhibition area up to 48% compared with 25% of a typical solution with perpendicular fins (Fig. 12).

Figure 12: Annual average direct solar radiation on façade.

3.4 Daylighting analysis

Due to computational power demand, daylighting analyses have not been included within the optimization loop but have been performed subsequently, by analysing three representative configurations.

The two baselines and option 3 were compared from a daylighting point of view in order to establish how the optimization affected internal comfort and lighting consumptions.

Daylighting analyses were conducted considering specific simulation parameters (Table 1) and the most common colours and materials optical properties (Table 2).

<table>
<thead>
<tr>
<th>Element</th>
<th>( \tau_v (%) )</th>
<th>( \rho_v(%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glazing</td>
<td>65</td>
<td>-</td>
</tr>
<tr>
<td>Ceiling</td>
<td>0</td>
<td>80</td>
</tr>
<tr>
<td>Internal partitions</td>
<td>0</td>
<td>80</td>
</tr>
<tr>
<td>Floor</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>Context</td>
<td>0</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 2: Physical properties of building elements.

Three main parameters have been accounted for, in order to understand the effect of the optimization on daylighting behaviour in the three different options (Fig.13-14-15):

- **Average Illuminance (Em) [Lux]:** Illuminance (E) averaged on several analysis points.
- **Spatial Daylight Autonomy (sDA) [%]:** Percentage of analysed area with an illuminance of at least 300 lux for at least 50% of the time during annual occupancy hours [9].
- **Annual Sunlight Exposure (ASE) [%]:** Occurrence of direct daylight (typically > 1000 Lux) on annual basis. It is defined as the percentage of area that receives direct daylight over the threshold for more than 250 hours per year [9].

Whilst sDA and ASE give a description of the whole year behaviour, illuminance describes a single hour condition, therefore the analysis has been conducted in different times as reported below.

Figure 13: Average illuminance comparison.

Figure 14: Annual Daylight Autonomy (DA) (left) and annual number of hours with more than 1000Lux (right) in optimized solution.
Results show that the optimized configuration, despite a slight reduction of sDA, can assure sDA values greater than 90%. This means a high value of illuminance during the whole year that allows for important savings on lighting consumption and comfort for occupants.

Considering glare risk, ASE value (34.2%) is considerably smaller than no fins baseline (44.5%) and just slightly higher than non-optimized perpendicular fins baseline (31.3%). ASE values, despite a sensible reduction, highlight however a glare risk that should be controlled with other systems (e.g. curtains) that will be anyway activated more rarely considering the contribution of the fins.

From an illuminance point of view (Em), the highest daylight reduction is during the winter period, however, considering the wide glazed surface, values are more than enough to guarantee a proper daylight to the exhibition area.

4. CONCLUSION

This document shows how computer data, parametric analyses and cooperation between design team members can lead to relevant improvements in consumption reduction, energy efficiency, and architectural aspects.

What was once a theoretical concept found in academia, parametric approach is now an applied concept slowly integrating itself into the building process.

This progress is the result of an evolution in typical design team mindset. The strong cooperation required of this approach, does not mean a loss of leadership or decision-making ability; on the contrary, it is an opportunity to lead design activities towards a more efficient, cost effective, and integrated stage.

The authors believe that the present and future of building design is advanced parametric optimization and they will continue to deepen their knowledge in this field. They intend to develop further algorithms in order to be able to support the whole design team in more and more tasks during all the design stages.

Currently, due to computational power demand, it is difficult to include a high number of objectives in one single optimization process. In the coming years however, it will be possible to increase the number of targets in order to improve the holistic approach of the optimization process, reducing time and easing the dialogue between different specialisms.

REFERENCES

Limiting Vertical Solar Irradiation to Improve Both Daylight and Energy Performance in Office Buildings: An approach to design Complex Perforated Screens

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ABSTRACT: Modulation of daylight and solar gains through shading systems is an important step in building design process. However, only a limited number of design methodologies to evaluate both daylight and energy performance of Complex Fenestration Systems (CFS) have been proposed. One method consisted of sharing shading schedules between Radiance and EnergyPlus, but it requires several simulations that are time-consuming whereas the building design is usually time-limited. Due to the midway step in the previous method consisted of irradiance simulations, establishing a limit for an irradiance metric could help to enhance the overall performance of CFS while optimising the design process. At present, there is a lack of measurable criteria based on solar radiation that can be applied for CFS performance evaluation. Nevertheless, solar radiation has been the most cited parameter driving shading control. This paper aims to determine if there is the potential to employ Solar Energy Density (SED) metric to evaluate the overall performance of complex perforated screens. Statistical results from daylight and energy simulations showed that a vertical SED of 351-552 kWh/m² contributed with strong positive loadings with Total Annual Illumination (TAI) metric whereas negative loadings with Total Annual Energy (TAE) use in office buildings facing towards South.

KEYWORDS: Solar Energy Density, Total Annual Illumination, Total Annual Energy, Complex Perforated Screens

1. INTRODUCTION
Modulation of daylight and solar heat gains through shading systems is an important step in building design process. Complex Fenestration Systems (CFS) can influence considerably the energy efficiency in office buildings, by reducing air conditioning and overheating [1] while improving daylight [2].

Currently, only a limited number of design methodologies and tools to ‘simultaneously’ evaluate the daylight and energy performance of CFS have been proposed. This is due to energy simulation programs cannot deal, at present, with complex shading systems [3]. To overcome simulation tools’ limitations, one method to study CFS consisted of sharing shading schedules between daylighting software and energy simulation program: Shading Coefficients (SC) were generated to analyse the dual performance of bi-dimensional and three-dimensional Perforated Screens (PS) that have the capability to both shade and redirect daylight into interior space [2].

Several simulations were required to apply shading schedules. For instance, both irradiation and daylight calculations were carried out with Radiance while thermal calculations were run with EnergyPlus [2]. Nevertheless, these simulations are time-consuming whereas the building design studies are usually time-limited and task-limited. As an approximate indication, one irradiance calculation with CFS can take ~2 h to over 10 h. Similarly, a daylight calculation can last the same number of hours. Then, it is necessary to provide a shorter alternative method to optimize the design process of complex shading devices.

This experiment considers the irradiance simulations as the shared and midway step in the shading schedules method. Hence, establishing a limit for an irradiance metric could help to limit the solar heat gains and to improve the daylight availability into office spaces. At present, there is a lack of measurable or computable criteria based on solar radiation that can be applied to evaluate the dual performance of complex shading devices. Notwithstanding, solar radiation has been the most cited parameter driving shading control [4].

Some works have depicted that shade is required if the intensity of direct normal solar irradiation hitting the occupants is higher than 233 W/m² [5]. Other authors have observed that shadings actuated when transmitted direct solar radiation (through the transparent façade) is higher than 94.5 W/m² [6] or when vertical solar irradiation is higher than 300 W/m² [7]. Another work has observed that shading is required if direct radiation is higher than 50 W/m² (~5000 lux) and solar gains are higher than 450 W/m² [8].
Since solar radiation has been expressed in different ways (e.g. direct or global solar radiation, incident or transmitted solar radiation), it is very difficult to assess the compatibility of the different criteria. This paper aims to determine if there is the potential to employ one solar radiation metric as a proxy to evaluate the overall performance (daylighting and energy efficiency) of PS used in office buildings.

2. METHODOLOGY

2.1 Setting

The case study is an office space measuring 7 m × 7 m and 3 m in height. It has a fully glazed façade oriented towards South. A PS with circular holes was placed in front of the glazing system, as Fig. 1 shows. The PS was selected as an example of CFS, which has been used in other studies that applied the shading schedule method.

To investigate the dual performance of PS and to diminish the influence of other parameters such as room area and internal model surfaces, these properties remained fixed. Reflectances of walls, ceiling, and floor were set to be 50%, 80%, and 20%, respectively. The PS was characterized by 80% reflectance, and the glazing system was 78.1% visible transmittance and 60.4% solar transmittance.

Instead, the PS was modified by changing specific design parameters, so that a variety of different PS configurations can be compared in terms of their solar and lighting transmission. The following design parameters were set as variables:

- Perforation Percentage (PP) represents the ratio of the total surface of the holes to the opaque surface. Six values were studied: 70%, 60%, 50%, 40%, 30% and 20%.
- Matrix (M) represents the array of the holes in the Z and X axes of the PS. Three arrays were evaluated: 12×28, 6×14, and 3×7 (Fig. 2).
- Depth (D) represents the thickness of the lattice, that is to say, the distance in the Y-axis (Fig. 2). Three values were analysed: 10 cm, 7 cm, and 3 cm.
- Space (S) represents the distance between the inside surface of the lattice and the outside surface of the glazing system (Fig. 1). Three distances were studied: 60 cm, 90 cm, and 120 cm.

Figure 1: Perspective view from the West for the case study. Sensor points for the daylight calculations are placed inside the room, over a horizontal plane (they are coloured in blue). Sensor points for the irradiance calculations are vertically placed 5 mm in front of the glazed façade (they are coloured in red). D: Depth; S: Space.

Figure 2: Comparison of three different matrixes with the same PP 70%. The hole area and the distance between holes change according to the matrix.

2.2 Simulation approach

Three main steps were considered to obtain the performance indicators. Daylight and irradiance simulations were run with Radiance through DIVA-for-Grasshopper. Table 1 summarizes the Radiance ambient parameters that were chosen after a convergence test. Then, energy calculations were run with EnergyPlus through Archsim. The weather file used was the EPW for Seville, Spain. The occupancy time considered is from 8 to 18 h.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>15°C</td>
</tr>
<tr>
<td>Humidity</td>
<td>50%</td>
</tr>
<tr>
<td>Solar Radiation</td>
<td>1000 W/m²</td>
</tr>
</tbody>
</table>

The first step included daylight simulations, from which annual illuminance profiles were obtained. The daylight calculations were performed on a horizontal plane positioned 0.80 m above floor, with 576 calculation points placed 0.25 m apart and 0.50 m from walls (Fig. 1). These illuminance profiles were then used to calculate the annual daylighting metric by using spreadsheets and to obtain the lighting schedule use, both for every PS configuration.
The second step included irradiance simulations that allow obtaining the annual irradiance profiles. Irradiance calculations were performed on a vertical plane positioned in front of the glazing system, with 2100 sensor points placed 0.10 m apart (Fig. 1). The irradiance profiles were used to obtain the annual irradiance metric and all 8760 hourly SC values for every PS configuration and for the case study with no PS. Briefly, SC values were mathematically calculated from the ratio of the solar irradiation falling on the vertical plane with solar protection to that without solar protection. These SC hourly values were then integrated into ‘shading schedules’ representing the yearly shading performance of the PS.

Finally, the third step included energy simulations. The effect of thermal transmittance through walls, ceiling, and floor was set to be adiabatic. The fully glazed façade was clear double-glazing of 6 mm, separated by a 13 mm air gap (U-value of 2.785 W/m²-K and SGHC of 0.703). Occupancy and equipment loads were 0.1 people/m² and 12 W/m², respectively. Lighting loads were 10.76 W/m² and set to be manually controlled according to the DIVA output (lighting schedule use). The shading schedules were also used as input in energy calculations to represent the shading performance of PS.

2.3 Performance indicators and statistical analysis

The following indicators were calculated to determine the yearly overall performance of PS:

- **Solar Energy Density (SED):** Total solar energy received by the vertical analysis surface (Fig. 1) over the run period and per square meter (kWh/m²).
- **Shading Coefficient (SC):** Annual mean value obtained from the all 8760 hourly shading coefficients for every PS configuration. The closer the SC is to 0, the more effective the solar protection is [9].
- **Total Annual Illumination (TAI):** Sum of all the illuminance values in a year (klx) falling on a horizontal plane inside the room (Fig. 1). The results are then averaged over the working plane. This metric was selected as it was deemed to be more sensitive to changes in parameters than any of the other current annual daylighting metrics.
- **Total Annual Energy (TAE):** Zone ideal loads (kWh/m²) for the total year. It considers the energy use for lighting, plus cooling and heating.

These indicators were obtained for a representative sample of PS configurations. The sample was selected through an orthogonal array that required only 18 PS configurations to represent the entire population – a fraction of the full factorial combination of all design parameters and their corresponding values (e.g. 6 PP levels × 3 M levels × 3 D levels × 3 S levels = 162 PS configurations). Fig. 3 summarizes the sample of the 18 PS selected. For more detailed information about the orthogonal arrays, please refer to a more extensive documentation by Chi [10].

The results obtained for the 18 PS were then analysed by applying the ‘Principal Components Analysis’, a multivariate statistical technique that summarizes sample variation from many variables with a smaller number of principal factors. It is used to reduce the number of variables and to assess the correlations between all indicators. Thus, data can be summarized into a few dimensions by condensing all variables into a smaller set of latent factors.

![Figure 3: Sample of PS analysed in this study. PP: Perforation Percentage; M: Matrix; D: Depth; S: Space.](image-url)

3. RESULTS

3.1 Performance indicators and statistical analysis

Simulation results are summarized in Fig. 4, where all PS are grouped by PP in a descending order, from 70% to 20%. The graph points out a similar trend among PP, SED and TAI – the two metrics decreases as PP decreases. However, TAE shows an apparent regular performance with no significant increments related to PP.

To understand how every energy use is related to the PS configurations, a comparison is presented in Fig. 5. Hence, it seems that cooling increases as PP increases, whereas lighting decreases as PP increases. Besides, the overall energy consumption is clearly related to cooling energy use.
3.2 Principal Component Analysis

A Principal Component Analysis was run to consider the main indicators: SED, SC, TAE, and TAI. Table 2 depicts the eigenvalues (also called characteristic values or latent roots) that are the variances of the principal components. The first indicator, SED, had a ~3.4 eigenvalue whereas the other three indicators obtained less than 1. Moreover, the first component explained 84.9% of the data variation. Table 3 and Fig. 6 summarize all contributions from the four indicators analysed.

Table 2: Eigenanalysis of the Correlation Matrix.

<table>
<thead>
<tr>
<th>Eigenvalue</th>
<th>Proportion</th>
<th>Cumulative</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3948</td>
<td>0.849</td>
<td>0.849</td>
</tr>
<tr>
<td>0.5991</td>
<td>0.15</td>
<td>0.998</td>
</tr>
<tr>
<td>0.006</td>
<td>0.001</td>
<td>1</td>
</tr>
<tr>
<td>0.0001</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3: Eigenvectors.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Principal Components</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>SED</td>
<td>0.533</td>
</tr>
<tr>
<td>SC</td>
<td>0.532</td>
</tr>
<tr>
<td>TAE</td>
<td>0.380</td>
</tr>
<tr>
<td>TAI</td>
<td>0.537</td>
</tr>
</tbody>
</table>

Another Principal Component Analysis was performed to look for the relations among the daylighting and irradiation performance indicators with all types of energy use (Fig. 7). In brief, SED showed the same eigenvalue that SC while a strong correlation with TAI. Then, SED and TAI had small negative loadings with the second component, whereas TAE and all energy uses had large positive loadings with the second component. Lastly, TAE and lighting showed a high opposite relation across the first component.

Therefore, it is inferred that increasing illuminances or decreasing irradiances does not necessarily contribute to reducing total energy consumption. It was confirmed that daylight contributes to reducing the use of electrical lighting. However, daylight also results in increments of cooling loads, and, as a consequence, in increments of the total energy use. For TAE, cooling played a major role than lighting. Hence, specific thresholds for the indicators should be identified to improve the PS overall performance.

Additionally, the score plots in Fig. 8 show the PS results grouped by design parameter: a) PP, b) M, c) D, and d) S. From Fig. 7 and Fig. 8, it is observed that quadrant II (+ -) brings together those PS configurations that achieve the best overall performance, that is to say, those PS that increase the illuminances whereas decrease the lighting, cooling, and total energy use. Accordingly, Table 4 summarizes the ‘optimal PS’.
In brief, it is better to specify PS with high PP, less number of big-sized holes, more distance separation, and wide thickness. Intermediate PPs allow choosing different matrices and distances, but thicknesses from 7 to 10 cm must be preferred. A low PP goes well when it is used in PS with medium-sized holes, short distance separation from the glazing, and thin thickness. PP lower than 40% must be avoided.

3.3 Limiting Solar Energy Density (SED)

The main of this paper is to determine if there is the potential to employ the SED metric to evaluate the overall performance of PS. As it was observed, SED showed a strong correlation with TAI and an opposite relation with TAE (mainly with lighting). From here, it is inferred that optimizing SED could lead to improving TAI whereas reducing TAE and lighting. Therefore, Table 5 summarizes the results of the indicators obtained for the optimal PS since they are key to understand the overall interrelations.

Table 5: Simulation results of the optimal PS. Numeration of PS is set according to Fig. 3.

<table>
<thead>
<tr>
<th>PS</th>
<th>SED (kWh/m²)</th>
<th>TAI (klx h)</th>
<th>TAE (kWh/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>552</td>
<td>6024</td>
<td>108</td>
</tr>
<tr>
<td>4</td>
<td>491</td>
<td>5617</td>
<td>112</td>
</tr>
<tr>
<td>5</td>
<td>454</td>
<td>5155</td>
<td>105</td>
</tr>
<tr>
<td>7</td>
<td>351</td>
<td>4262</td>
<td>109</td>
</tr>
<tr>
<td>8</td>
<td>363</td>
<td>4374</td>
<td>107</td>
</tr>
<tr>
<td>9</td>
<td>435</td>
<td>4620</td>
<td>104</td>
</tr>
<tr>
<td>11</td>
<td>373</td>
<td>4387</td>
<td>112</td>
</tr>
</tbody>
</table>

Simulation results from the optimal PS showed that a vertical SED from 351 to 552 kWh/m² contributed with good levels of yearly natural illuminances – from 4262 to 6024 klx h. At the same time, that SED range led to annual energy consumption from 104 to 112 kWh/m². Therefore, the cited range for the SED metric could be used as a proxy to evaluate the overall performance (daylighting and energy efficiency) of office buildings facing towards South.

Regarding the TAI results, it should be noted that they represent the annual overall illuminance. Thus, an analysis taking into account specific seasons or days is advisable to comprehend the daylighting performance. Fig. 9 shows the temporal maps of two optimal PS with the peak results: PS3 and PS7. Hence, winter is the critical season with illuminances over...
5000 lux, a threshold reported as a cause for closing blinds [8].

![Temporal maps showing the annual illuminances calculated for two optimal PS: PS3 and PS7.](image)

Figure 9: Temporal maps showing the annual illuminances calculated for two optimal PS: PS3 and PS7.

Furthermore, a critical moment was selected to better understand the daylight distribution: December 22th, at 14 h. Fig. 10 summarizes the illuminances and irradiances quantified for the two selected PS. This approach could help to further investigate about optimization of dynamic and movable shading screens.

![Illuminances on the working plane and irradiances on the vertical plane, for two optimal PS, at Dec 22th, 14 h.](image)

Figure 10: Illuminances on the working plane and irradiances on the vertical plane, for two optimal PS, at Dec 22th, 14 h.

4. CONCLUSION

This paper proposed a SED range from 351 kWh/m² to 552 kWh/m² as a proxy to evaluate the daylighting and energy performance of PS used in South façades at Mediterranean climates. Limiting SED could help to design optimal PS at initial stages, just by running irradiance calculations. Thus, the total number of simulations can be reduced, leading to saving time during the building design process.

Statistical results showed that SED had a strong positive relation with TAI, whereas a negative relation with TAE. Besides, in the overall energy use, cooling played a major role than lighting.

The findings here presented could be integrated into current guidelines, e.g. limiting SED when awarding points for efficient building designs. All the results obtained for the present analysis are obviously linked to the chosen case study. However, it is believed that the method applied could be extended to analyse different building spaces, orientations and locations. A wider study currently ongoing is considering a multiplicity of other indicators (e.g. Dynamic Daylight Metrics and Daylight Glare Probability) to find new correlations and to include other performance assessments. Future research should also include data measured in real spaces against which the simulated values could be compared.

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REFERENCES
Design Process for Pop-Up Architecture: Outdoor comfort and urban revitalization

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ABSTRACT: This paper shows a temporary structure development based on environmental design concepts, informed by analytical procedures of performance assessment. The design purpose was the requalification of open spaces in the city of São Paulo, by providing the minimum structure for their maximum usage, offering pedestrians the possibility of stopping in comfortable and inviting open urban areas. The project was divided into three phases: at first, an empiric survey was carried out at the chosen site, which included interviews with residents and pedestrians, coupled with in situ measurements of environmental variables. The second phase was the design concept development informed by the collected data. In the third phase, the proposal design was simulated with parametric tools in order to guarantee the resultant environmental conditions. The simulations showed that the structure decreased the solar radiation on the area and the illuminance levels drop by half compared to the scenario without intervention. Also, the results showed that the area’s Perceived Equivalent Temperature (PET) is lower in the scenario with the structure than in the scenario without it.

KEYWORDS: Temporary architecture, Urban revitalization, Outdoor comfort, Design process, Empiric survey

1. INTRODUCTION

Architecture is very often related to some sense of permanence, firmness, longevity and durability, always connected to the place and time in which it was designed. However, over the last years, the number of projects for short-time and dynamic places is increasing and becoming a new solution. This type of design is known, among different names, as temporary architecture, ephemeral architecture, and pop-up architecture, and it refers to an intervention, structure, display, enclosure, or interactive space, that can be temporary, flexible, collaborative and adaptable for different people, uses, and times [1]. Temporary urbanism can also contribute to the regeneration of underused urban spaces and help making the transition to future resilient and sustainable cities. Therefore, this approach should be considered in urban planning, as a complementary practice to city-making [2].

In the context of this discussion, this paper shows the development of a temporary structure based on concepts of environmental design, informed by fieldwork and analytical procedures. The purpose of this environmentally informed design project was the requalification of open spaces in the city of São Paulo, by providing the minimum structure for their maximum usage, offering pedestrians the possibility of stopping in comfortable and inviting urban open places. The focus of the contribution was on fieldwork methods and techniques to improve the environmental quality, and therefore to revitalize urban open spaces in a hot, polluted and dense city. This design exercise was part of a collaborative research project between the Faculty of Architecture and Urbanism of the University of São Paulo (FAUUSP) and the College of Natural Resources from the North Carolina State University (NCSU).

2. PROJECT CONTEXT

2.1 Local context

The site for the project development is part of the Centro Universitário Maria Antonia (CEUMA), which belongs to the University of São Paulo (USP). It is strategically located in the city center of São Paulo, in an area of great concentration of cultural and educational institutions. The space offers several exhibitions, short courses, lectures, debates, film festivals, book releases, among other cultural activities. In addition to it, CEUMA also hosts the Gilda de Mello e Souza Library, with a collection dedicated mainly to aesthetics (Fig. 1). Bound by the blind facade of the Rui Barbosa Building and the access facade of the Joaquim Nabuco Building, there is an interstitial area between the buildings with 166.45 m² (shown in orange in Figure 1). The area is constantly used as a place of...
permanence by visitors of CEUMA, and by students from USP and from Mackenzie Educational Complex (school and university located in front of the space), and by users of CEUMA. Thus, the demand and the need for qualifying this space justify its choice.

2.2 Urban context

CEUMA is located at Maria Antonia Street, in the district of Consolação. According to São Paulo Master Plan (2016), it is located in a Mixed Zone (ZM) and, more specifically, it is a Special Cultural Preservation Zone, being characterized as a Representative Real Estate (ZEPEC-BIR), due to its architectural and historical value [3]. In addition, it is within the Macrozone for Urban Structuring and Qualification and nearby an Urban Transformation Structuring Axis (Consolação Avenue), that articulates “urban mobility and development with the objective of reversing the urban structuring model and expanding the population’s right to the city” [3].

This already shows the region dynamism, which is intensified by the existence of the Mackenzie Educational Complex, a cultural center - SESC Consolação - and the countless restaurants and bars in the surroundings.

2.3 Climatic context

São Paulo is located in a region of high-altitude tropical climate, characterized by low temperatures, torrential summer rains and mild rainy winters. Located in the southeast region of Brazil, the city’s latitude is 23°30’S, the longitude is 46°37’O and the altitude is approximately 792 meters above sea level.

According to data from the Climatological Normals of the National Institute of Meteorology [4], São Paulo has an average annual temperature of 19.3°C, an average maximum temperature of 24.9°C and an average minimum temperature of 15.5°C. The city has an average relative humidity of 78% and a total of 1732.7 hours of direct sun during the year.

Figure 2 illustrates the momentary temperature variation for São Paulo, in association with the average, average maximum and average minimum temperatures for each month. February has the highest average temperature, 23.46°C, but January is the month with the highest average maximum temperature, 28.1°C. July is the coldest month, with an average temperature of 17.47°C and an average minimum temperature of 13.27°C.

Regarding the values of solar radiation, Figure 3 shows that the month of February has the highest average global radiation, 550 W/m². January, the month with the highest average maximum temperature, has an average global radiation of 509 W/m², and July, the coldest month, 388 W/m².

From the Wind Rose (Fig. 4), it is possible to notice the predominance of the wind occurrence. Thus, for the city of São Paulo, the prevailing wind directions are south, south-southeast and southeast, with speeds between 3 and 4 m/s.

3. METHODOLOGY

In order to settle the main conception of the project, an investigation has been taken to analyze the CEUMA’s microclimate conditions and its users’ needs. The measurements were made on April 26th 2019, collecting data every 15 minutes between 9:30 am and 12:30 pm. Measurements were expected to be carried out throughout the afternoon, however rains prevented them from continuing. The measurements recorded values of dry bulb air temperature, globe temperature, air movement (direction and velocity), relative humidity, and sound pressure level. In parallel, a study of sun access and shadings in the site has been developed to complement the analysis.
Along with these studies, 135 questionnaires were applied, with respondents’ consent, to indicate the general perceptions of the CEUMA’s users about the environmental conditions of the space, including ergonomic, thermal and acoustic conditions. A response scale from 1 to 5 was created after calculating the average user satisfaction with the answers to these questionnaires.

Based on the data collected by the questionnaires and measurements, the design process of the pop-up architecture was developed using the Grasshopper 1.0 parametric design software, which combines geometric design and simulation tools (like Ladybug 0.0.68 and Honeybee 0.0.65 plugins) with non-geometric data, such as optical and thermal characteristics of the materials [5, 6]. The simulations were included as a part of the design process, because the designers could modify the structure shape and its materials to fit a thermal and lighting performance that meets the CEUMA users’ expectations.

4. EMPIRIC SURVEY

The measurements carried out in the first design phase included thermal, daylighting and acoustic variables along the day of fieldwork. Table 1 presents minimum and maximum measured values for each environmental variable.

<table>
<thead>
<tr>
<th>Environmental variable</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature (°C)</td>
<td>23.9</td>
<td>28.2</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>62.2</td>
<td>78.3</td>
</tr>
<tr>
<td>Radiant temperature (°C)</td>
<td>25.9</td>
<td>37.5</td>
</tr>
<tr>
<td>Air speed (m/s)</td>
<td>0</td>
<td>3.5</td>
</tr>
<tr>
<td>Illuminance in the sun (lux)</td>
<td>16,500</td>
<td>80,000</td>
</tr>
<tr>
<td>Illuminance in the shade (lux)</td>
<td>1,400</td>
<td>7,500</td>
</tr>
<tr>
<td>Sound pressure level (dB)</td>
<td>64.2</td>
<td>71.7</td>
</tr>
</tbody>
</table>

The questionnaires [7] pointed out users’ satisfaction regarding to the general environment perception, risk of assault, risk of trampling, green areas, noise, temperature, sun, wind, obstacles on the sidewalk and sidewalk pavement. Figure 5 illustrates the responses from the interviews with residents and other pedestrians, highlighting that the lowest levels of satisfactions correspond to sidewalks conditions, acoustics and safety.

Figure 6 exhibits the variation of air temperature, globe temperature and relative humidity along the morning, as well as how users’ average satisfaction regarding temperature responded to these variations. The satisfaction level was higher from 9:45 to 10:15 am, when temperatures were between 24.2 and 25.1°C. From that time on, satisfaction declined as air temperature increased.

Users’ satisfaction concerning noise followed the same variation pattern of the equivalent continuous A-weighted sound pressure level ($L_{Aeq}$) measured until 11:45 am, exposed in Figure 7. By noon, although the measured levels increased significantly due to the increment on pedestrians and vehicles flow, users’ average satisfaction had little fluctuation. That might be related to changes in noise type – as there were more people talking – and in users’ general perception of space, since its use as a permanence area was intensified.

The outdoor illuminance shows maximum peaks of 80,000 lux in the sun at noon and 7,500 lux in the shaded area at 9:45 am. The minimum values were 16,500 lux in the sun at 9:30 am, and 1,100 lux in the shade at 10 am (Fig. 8).
The sun path caused by the surroundings, in general, provides a longer sun access for the area close to the sidewalk, both for winter and summer. The other part of the site, however, receives sunlight only in summer due to the proximity of tall buildings.

In addition, users were asked about suggestions and requests for the area. The answers frequently pointed out the improvement of sidewalks and the provision of comfortable places to short and long stops qualified by shading and security. Although the low satisfaction related to the sound pressure level, there were no suggestions or requests to improve acoustic conditions.

5. DESIGN CONCEPT DEVELOPMENT

The development of the design concept was based on empirical analyses of the context in a wider and general understanding of the urban context within the definition of users’ needs and potential activities applied to the temporary structure.

Moreover, to understand the versatility and dynamics of the people who would use this project, it is important to highlight the issues considered for the project’s design concept, encompassed by mobility, flexibility, replicability, dynamics and the possibility of different uses for a public space designed for the permanence and passage of people. In addition, this structure allows to be expanded, assembled, disassembled and applied in other city places, stimulating new kinds of open spaces occupation.

Regarding that, studies were developed to establish a flexible and permeable structure formed by seven hexagonal geometric shapes with four meters long each, supported by triangular modules with 0.85-meter height and 1-meter base.

The roof material was defined according to the incidence of solar radiation, in order to provide shaded seating spaces in the summer solstice. In this context, four hexagons were made of translucent honeycomb polycarbonate and three of them were made of glued laminated timber. The ceiling height was also designed to protect the area of the direct solar irradiance and to provide a more interesting aesthetics for the project. Moreover, the hexagons present 2.58 m, 3.44 m or 4.30 m height from the floor (Fig. 9, 10 and 11).

6. COMPUTATIONAL SIMULATIONS

The project was simulated to evaluate the solar radiation, natural lighting and comfort levels, using two software extensions of the Grasshopper parametric modelling plugin, Honeybee and Ladybug [6]. Two scenarios were simulated, one without the pop-up structure, here called the baseline model, and another with the insertion of the pop-up structure, called the proposed model.

The natural lighting simulation methodology was based on environmental certification procedures, such as LEED (Leadership in Energy and Environmental Design) and HQE (Haute Qualité Environnementale), which evaluates the illuminance in lux on the floor plan at 9:00 am and 3:00 pm on the equinox days (September 21st and March 21st). The
simulation of direct solar radiation recorded an incident impact in the month of February, which is the period that has the most incident damage, according to the climate file analysed [4]. The sky used for the calculations was the cumulative sky [8].

Radiance, the simulation engine used by Honeybee, is a tool that searches a better accuracy for calculating lighting levels using the Ray Tracing method [9]. In addition, Radiance can analyse opaque, transparent and translucent materials using reflectance and light transmission as data inputs. In this way, it was possible to analyse the impact of translucent coverage on the distribution of radiation and space lighting in the proposed model scenario. The material characteristics used in the simulation are described in Table 2. The reflectance of the surroundings was considered as grey. The light transmission of the translucent covering was obtained through technical catalogues of the manufacturer and studies about material properties [10, 11].

<table>
<thead>
<tr>
<th>Material</th>
<th>Reflectance</th>
<th>Emissivity</th>
<th>Light Transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural and roofing wood</td>
<td>0.66</td>
<td>0.82</td>
<td>-</td>
</tr>
<tr>
<td>Surroundings' reflectance</td>
<td>0.40</td>
<td>0.80</td>
<td>-</td>
</tr>
<tr>
<td>Translucent polycarbonate plaque</td>
<td>-</td>
<td>0.90</td>
<td>0.32</td>
</tr>
</tbody>
</table>

The baseline scenario, without the proposed structure, has a variation of illuminance between 20,000 lux in an area facing the street, and 7,200 lux, in an area shaded by the surroundings. In the proposed scenario, the illuminance levels drop to 3,600 lux, under the opaque roofs, located near Maria Antonia St. The translucent cover also decreases the levels of illuminance, varying from 7,200 to 10,800 lux (Fig. 12).

As a comfort index, the Physiological Equivalent Temperatures (PET) [12] were calculated for two cases: one with a seated person, with the metabolism rate equals to 1.0 met (Fig. 14) and another case in which the user is walking through the coverage, an activity that has a metabolism rate of 2.6 met, according to ASHRAE 55 [13]. The clothing isolation in both cases is 0.61 clo, which characterizes a person wearing pants and a long-sleeved shirt, according to the same standard. In both cases, the in situ collected data and the simulation for April 26th were considered. The results show that the coverage increases the individual’s level of comfort in both situations. During the beginning of the day, the
coverage acts better as an element of thermal comfort to the user, while, when arriving at noon, even with the increase in the PET, the scenario with coverage has a lower level of comfort.

7. FINAL CONSIDERATIONS

A temporary structure was developed with conditions to be reassembled in other locations with a lack of spaces for permanence and social living in São Paulo and in other places with different climatic contexts. Meanwhile, it is worth mentioning that the project developed in this work is a prototype, therefore it is still necessary that more tests with other modular changes are carried out in different places and climates.

This research elucidated the remarkable importance of developing an innovative design for temporary structure adapted to an urban context, considering the environmental comfort concepts together with technological design tools.

Just because a temporary architecture is not meant to stay in a place forever, it does not mean that the development process cannot consider environmental variables and specific local needs. Combined to that, the concept design must be thought having in mind that the structure may be used in different places, increasing its period of use.

Moreover, it was reinforced the importance of integration between methods and analysis to achieve the design concept.

ACKNOWLEDGEMENTS

Thanks to everyone involved in this research pro-design project, including tutors from FAUUSP, UNICAMP and North Carolina State University (Eric S. Money, Perver K. Baran, and J. Aaron Hipp), as well as the colleagues from FAUUSP (Cristiane Moraes, Gerson Brancalião, Iuri Talili, Paula Fraceschini and Rafaella Gradwohl) who contributed to this concept design.

REFERENCES

Remote Piloted Aircraft as support for the study of urban parameters

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ABSTRACT: This article presents a survey conducted through a Remote Piloted Aircraft (RPA), to define urban morphology conditions for implementing monitoring weather stations. In the process of observing the constructive characteristics of open spaces for users in cities, this method is still incipient. The mapping allows the acquisition of images of use and occupation, height data of the elements that compose the landscape, among others. With this type of data acquisition, it is possible to fill a gap existing in most public agencies, which concerns Database - basic data for analysis of the territory for planning. The use of this type of survey allows quick updates, if necessary. In this study we obtained, as products, the Digital Surface Model (DSM), the average height of the elements that make up the built space (vegetation + built elements) and the 3D model of the area under study. Based on these products, areas were selected for the implementation of two weather stations for the online acquisition of climate data (air temperature and humidity, and wind speed and direction). These stations will support the participative model for remote acquisition of data from users regarding comfort conditions in open spaces.

KEYWORDS: Remotely Piloted Aircraft, urban parameters, weather stations, urban morphology, Database

1. INTRODUCTION

This article presents a survey conducted through a Remote Piloted Aircraft (RPA), to define urban morphology conditions for implementing monitoring weather stations. The use of drones is growing and diversifying rapidly, with the use in agriculture and construction being important points in terms of application due to the significant savings in the cost of the survey and the measurements made. Applications for surveying risk and disasters areas; as well as use in television, cinema, events and for providing detailed land survey information for architectural, urban and landscape projects; are increasing. Most applications are "eye-in-the-sky", using the drone as a positioning system for optical observation and recording, sometimes combining functions of automatic image recognition, photogrammetry for volumetric information or other automatic post-processing to collect additional information from a given area [1].

In the process of observing the constructive characteristics of open spaces for users in cities, this use is still incipient. The administration Brazilian cities, in most cases, lack the digital information of the use and occupation, height and design of buildings and size of occupied areas (green areas, paved areas, etc [2].

Knowing the relationships between microclimate and user comfort provides tools for large-scale planning and design, enabling a better life for people in urban spaces.

According to Mills [3], if climate studies had been incorporated into city zoning, many environmental problems could have been reduced. Whenever exposed to open urban spaces, users are subjected to large-scale weather conditions and the built environment around them. Studies in the area of environmental comfort and climate in open spaces presuppose the acquisition of data related to environmental conditions, the physical characterization of spaces and the opinions of users, gathered by subjective responses [4].

In this study we obtained, as products, the Digital Surface Model (DSM), the average height of the elements that make up the built space (vegetation + built elements) and the 3D model of the area under study. Based on these products, areas were selected for the implementation of two weather stations for the online acquisition of climate data (air temperature and humidity, and wind speed and direction). These stations will support the participative model - App (Opine) for remote acquisition of data from users regarding comfort conditions in open spaces.
2. THE METHODOLOGY

The methodology to obtain the necessary data for the location of the meteorological stations was carried out by the Remotely Piloted Aircraft Survey (RPA).

2.1 Study Area

The site of the air survey was a segment of the Campus of the Cidade Universitária Armando de Salles Oliveira (CUASO)/São Paulo University (USP), Brazil. CUASO is located in the city of São Paulo, in the West Zone of the city, Butantã district (geographical coordinates S 23°33'44", W 46°43'39" and sea level 765 m). It occupies a total area of approximately 3,650,000 m² and 80,000 to 100,000 people circulate on campus daily. This choice was due to the use of the Opine App, developed to be used in the university campus, where most of its population is undergraduate and graduate students, totaling, on average, 70% of campus occupants.

The use of App Opine will make it possible to verify the perception of open spaces in relation to thermal environmental conditions, acoustics, lighting and ergonomics and allow the quick acquisition of these opinions coming from users. Thus, it will provide quantitative subsidies regarding the number of users of open spaces and their perception of these spaces and will point to a possible calibration that represents the process of climate adaptation [4]. In Fig. 1 it is possible to observe the location of the campus in the city of São Paulo.

2.2 Remotely Piloted Aircraft Survey (RPA)

The surveys were performed using a Remotely Piloted Aircraft (RPA), Phantom 3 Advanced/DJI model, assisted by ground control points raised through Global Navigation Satellite System (GNSS) positioning, for the generation of accurate orthophotomosaics and Digital Terrain Models (MDT) [5, 6, 7].

The following steps were necessary: 1) Mission planning; 2) Mission flight (longitudinal and lateral flight overlap); 3) Calibration of the acquired images; 4) Survey of the ground control points; and, 5) Generation of the Digital Surface Model (DSM), Fig. 2.

The mission planning must be made by observing the target area to be flown over; as well as the national regulations and legislation [7]. The definition of the length, width, and distances flight are important factors to be considered; they are related to the time and calculation of the resolution of the area to be flown over. The regulations and legislation require registration and certification by ANAC - Agência Nacional de Aviação Civil and ANATEL - Agência Nacional de Telecomunicações. The execution of flights are also subject to the current legislation (ICA 100-40) which deals with "Remotely Piloted Aircraft Systems and Access to Brazilian Airspace" ("Sistemas de Aeronaves Remotamente Pilotadas e o Acesso ao Espaço Aéreo Brasileiro") of the Airspace Control Department (Departamento de Controle do Espaço Aéreo) [8].

The mission flight covered the area of interest. In general, the flight occurred at a maximum height of 120 meters and covered an area of ~63 ha, with the acquisition of 640 images in approximately 30 minutes. The final resolution of the generated images (cm/px), orthophotomosaic and Digital Surface Model, was ~5 cm and 30 cm respectively. For the selected area, images with RPA were acquired through automatic flights with longitudinal overlap (~80% of the area of two consecutive photos of the terrain) and lateral (~60% of the photos of the adjacent flight ranges), generated with small format camera.

The image calibration process was performed with the Agisoft Metashape Professional software (v. 1.5.2 from Agisoft, LLC), by inserting the interior and exterior orientation parameters of the sensors. These parameters are necessary to correctly calculate the angles and position of the sensors, as well as the distortions of the systems. For this purpose, the
software requires the following information: (i) image resolution; (ii) focal distance; and (iii) centre coordinate of the image. The alignment of the images was performed by computing similarities between properly oriented overlapping images. To ensure greater accuracy of this process, the positioning of the images should be corrected with the aid of ground control points [6, 9].

The **survey of GCPs - Ground Control Points**, was made through the GNSS - Global Navigation Satellite System - positioning of the reference stations and the GCPs defined for the mapping of the study area. For this purpose, reference stations (Base Station) were implemented within the survey areas, providing short baselines (less than 3 km) for the markings distributed throughout the area [10]. The GCPs and checkpoints were collected for about 2 hours and 5 points were collected in streets parallel and transversal to the Praça do Relógio - 4 points at the ends of the square and 1 point in the middle of the overflight survey area.

The **DSM - Digital Surface Model** - was generated with the Agisoft PhotScan Pro software by means of a TIN - Triangular Irregular Network - by Delaunay triangulation, which uses the criterion of maximization of the minimum angles of each triangle [10]. The DSM was created from a cloud of points with three-dimensional coordinates representative of the objects of the study surface (vegetation, buildings, etc.), resulting from the process of image alignment [12,11]. The quality control of the DSM was performed from a set of checkpoints of the study area, which were not used in the generation of the models, through the measurement of accuracy by the Mean Squared Error (MSE) [13; 10].

### 3. RESULTS AND DISCUSSION

The following items were the results obtained with the acquisition of the images by RPA.

#### 3.1 Orthophotomosaic, Digital Surface Model (DSM), and Topographic profiles

Fig. 3 shows the image generated by the RPA with the geographic distribution of the buildings, vegetation and the main avenues of the study area (CUASO).

![Figure 3 – Orthophotomosaic.](image)

In Fig. 4a it can be seen that the altitudes vary between 720 – 780 m, with the height of the buildings varying between 10 and 25 m. The topographic profiles of the DSM (A-A’ and B-B’ respectively) show that both stations are in relatively lower areas with tree-tops varying between 5 – 20 m. The avenues where they are installed are 40 m (station 1) and 20 m (station 2) wide (Fig. 4b).

![Figure 4 – a. Digital Surface Model (DSM) and b. Topographic profiles of weather stations.](image)

It was decided to detail this area due to the displacement of the students in the university campus and for being “more open”, morphologically. This campus area is composed of a service area (bank branches), the Praça do Relógio (a place for student meetings and various activities) with the Torre do Relógio as orientation landmark; as well as access to food courts and student housing buildings.

#### 3.2 Average height of the elements and 3D Model of the area under study

With the acquisition of the images via RPA it was possible to identify the average height of the elements that make up the built space - vegetation + built elements; as well as create a 3D model of the area (Fig. 5a.), the DTM - Digital Terrain Model (Fig. 5b.) and the heights of the elements - built and natural that make up the study area (Fig. 5c.).

The Digital Terrain Model (DTM) was generated to support the 3D visualization of the elements. It also shows the area’s topography, an important element in geoprocessing applications, for example.
The subtraction of the Digital Surface Model (DSM) from the Digital Terrain Model (DTM) images was important in generating the height model of the surface objects. Information about the geometric parameters of the city such as flat area index, frontal area index and average height of buildings are the basis for several urban studies such as roughness ($z_0$) and ventilation [14, 15, 16, 17, 18].

The mapping allows the acquisition of images of use and occupation, data on the heights of the elements that make up the landscape, among others. With this type of data acquisition it is possible to fill a gap existing in most public agencies, which concerns Database - basic data for analysis of the territory for planning.

As in most Brazilian cities there are no three-dimensional models, the use of this acquisition methodology becomes an important tool for collecting information to be used for visualization and mapping of areas in cities. Adding this type of mapping to future surveys associated with a participative model, for example, aggregates information on land use and occupation and an additional perspective on the recognition of open spaces.

3.3 Campus Weather Stations Locations

The location of the weather stations was defined by the composition of the volumetry around the pre-established points and proved by the images acquired by the survey with RPA. Open areas of the campus were sought so that there would be no influence of the natural and constructive elements in the acquisition of the climatic data; as well as for being places of passage of the campus users. Fig. 6 shows the geographical position of the stations.

According to the morphological characteristics identified, these locations meet the characteristics necessary for the acquisition of data from users of open spaces [4].

Installed in mid-August 2018, the stations (WXT520 Weather Transmitters/ VAISALA brand) had a trial period for acquisition, storage and verification of data collected and viewed on the server. The continuous measurement sensors are installed at 5 m height. The sensors collect data on the following climate variables: temperature (air temperature) and air humidity...
(relative humidity), direction (wind direction, gust direction and lull direction) and wind speed (average speed, maximum speed and minimum speed).

Data is acquired every 15 minutes and this information is transmitted to the server and stored for subsequent correlation with user responses and evaluation of the sensation of environmental thermal comfort. Each station has its own battery and solar panel to recharge the battery - if necessary. The station can operate autonomously for a long time. The monitoring of the battery capacity can be made in the Database, as there is a data entry column in the table.

The data presented here are from 01 February 2019 to 29 February 2020. After March 15, 2020 - beginning of the Social Isolation - Covid-19 - the data is stored in the USP server (Fig. 7 and Fig. 8).

In Fig. 7 it is possible to identify that for both stations the data of relative humidity and average air temperature have similar profiles. The data of relative humidity, maximum and minimum, are on order of 77% (station 1) and 76% (station 2) for the month of February/2020 and of 55% and 54% for the month of April 2019. For the air temperature data the maximum and minimum values were: 23.1°C (station 1) and 23.5°C (station 2), registered in February/2019 and December/2019. The small difference between the stations will be better analyzed in the future. As for the minimum temperatures, these were: 15.7°C (station 1) and 15.4°C (station 2), both for April/2019.

In Fig. 8 it is possible to identify the wind lull velocities, averages and gusts recorded by the two stations; as well as the predominant direction of each speed. In general it is possible to identify that there is a predominant direction of the south/southeast quadrant for both stations. The maximum speeds / gust recorded were 3.4 m/s (station 1) and 3.89 m/s (station 2). In terms of average speeds the values were: 1.30 m/s at station 1 and 1.77 m/s at station 2. With respect to the wind, station 2 seems to be more influenced by speeds, but not by direction.

The measurements made have the objective of helping to better characterize the climatic conditions of the environments analyzed at the campus of USP/Cidade Universitária and also to contribute to the analysis of the results obtained at the measurement sites with the data sent concomitantly by the users. The stations are currently fully operational; that is, sending data through the mobile phone transmission system to the server and these are visualized in the database. Information is then cross-analyzed in the system developed for this purpose.

A 300 m radius was defined around the devices where the application should be “seen” and answered by the users - this next step should have started operating in the first quarter of 2020 but did not, due to Covid 19 (Fig.9).

4. CONCLUSION

The survey by RPA proved to be more interesting than the high-cost alternatives (e.g. photogrammetric or with LiDAR and stereo satellite images), and more efficient (high accuracy and immediate updating) and applicable in any urban context. There are several products - morphological
parameters - that can be obtained from an acquisition by RPA. These are flexible in operation and time resolution, providing more possibilities of use in various areas of knowledge such as climate, construction, acoustics, vegetation, etc.

ACKNOWLEDGEMENTS
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REFERENCES
Evaluation of Dynamic Daylight Metrics
Based on Weather, Location, Orientation and Daylight Availability

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ABSTRACT: This paper demonstrates that it is possible to achieve 3 daylight credits of Leadership in Environmental and Energy Design version 4 (LEED v4) in all latitudes and orientations. This study uses a space with sidelight windows and shading devices representing a section of a typical office in a multistory building. To comply with LEED v4, the space has been simulated under different weather, location, orientation, and daylight availability conditions. Simulations were done using the DIVA-for-Rhino and Grasshopper plugins. Twelve selected locations with their vertical facades facing the cardinal directions were simulated. The design variables were window size, geometry, and optical properties of the shading devices. Findings show that to comply with the Spatial Daylight Autonomy (SDA) and Annual Sunlight Exposure (ASE) metrics of LEED v4 daylight credits, the south-facing facades require minimum shading devices in low latitude locations (0°–25°), extended shading in intermediate latitudes (25°–50°), and shading that exclusively blocks the window glass in high latitudes (> 50°). In general, north-facing facades do not require shading except at equatorial locations. East- and west-facing facades at all latitudes require extensive shading devices similar to south-facing facades in high latitudes.

KEYWORDS: Daylighting, Metrics, Parametric Design, LEED v4, High-low Latitudes

1. INTRODUCTION

On average, most people spend more than 90% of their time indoors and, in consequence, are often exposed to poor lighting, both in terms of quality and quantity. Many studies have shown the benefits of good daylighting in buildings, including as social benefits (well-being and health) and economic benefits (energy savings and increased productivity). Daylighting experts have studied in detail the quantity and quality of daylighting in spaces, and have created daylighting metrics and standards to evaluate the daylighting performance based on occupants’ preferences. These standards and metrics promote successful daylighting in buildings, help designers create visually comfortable spaces, and help manufacturers develop technologies that save energy and satisfy consumer needs. [1]

In 2012, the Illuminating Engineering Society released the LM-83-12 standard [2], an approved method for Spatial Daylight Autonomy (SDA) and Annual Sunlight Exposure (ASE) metrics for daylighting performance in new and existing buildings. This standard is based on a field study of 61 spaces in six cities in the United States from the states of California, Washington and New York, within latitudes 37° to 47° for the California Energy Commission (CEC) [1]. The LEED program adopted the use of SDA and ASE as one of the two compliance paths for the daylight credit for the LEED v4, which was released in 2014. [3] The credit requires a minimum of 300 lux for SDA for at least 50% of total occupied hours of the year, for (1) 55% of floor area, for 2 LEED credits, and (2) 75% or more the occupied floor area, for 3 LEED credits (sDA-300lux, 50% hours); no more than 10% of regularly occupied spaces can exceed 1000 lux of direct sunlight for more than 250 hours per year (ASE 1000 lux, 250 hours). After LEED v4 was released, an addendum was added that increased the maximum ASE to 20%. In 2018, the U.S. Green Building Council (USGBC) called for proposals to improve the new LEED v4.1, more than 250 proposals were submitted by industry stakeholders. [4] The LEED v4.1 daylight credits [5] incorporated these proposals, lowering the requirements: the ASE metric was removed (even though the CEC study reported that occupants were less satisfied with ASE > 20%), and added 1 credit to spaces with sDA-300lux over a lower threshold of 40% of floor area. (Table 1)

Table 1: LEED v4 Metrics and Points.

<table>
<thead>
<tr>
<th>LEED v. (year)</th>
<th>Metric</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0 (2014)</td>
<td>sDA300/50% &gt; 0.55, 0.75, 0.9 ASE1000, 250 &lt; 10%</td>
<td>1-3</td>
</tr>
<tr>
<td>4.0 Add. (2017)</td>
<td>sDA300/50% &gt; 0.55, 0.75, 0.9 ASE1000, 250 &lt; 20%</td>
<td>1-3</td>
</tr>
<tr>
<td>4.1 (2019)</td>
<td>If ASE1000, 250 &gt; 10%, identify how the space is designed to address glare</td>
<td>1-3</td>
</tr>
</tbody>
</table>

This paper demonstrates that it is possible to achieve the 3 daylight credits of LEED v4 in latitudes ranging from 0° to 62° in the Northern Hemisphere.
2. METHODOLOGY

For this study, 12 locations were selected (see Table 2). These locations represented a wide variety of climates from hot and humid to cold and snowy, and from very sunny (Phoenix) to overcast skies (Anchorage). For the purpose of this study, latitudes from 0° to 25° are considered low, 26° to 50° are considered intermediate, and > 50° are considered high. The building locations in the CEC report [1] are within the intermediate latitudes of this study.

A typical office space in any of these 12 locations was modelled in Rhino 6 and linked to a Grasshopper script. Simulations were conducted with DIVA-for-Rhino v4 [6] and RADIANCE [7] in order to generate climate-based annual hourly illuminance data for 200 sensors at 0.76 m height. About half of the simulations were conducted manually using principles of effective shading design. The other half used a parametric approach.

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude</th>
<th>Sunshine hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quito</td>
<td>0.1</td>
<td>2,238</td>
</tr>
<tr>
<td>Caracas</td>
<td>10.6</td>
<td>2,507</td>
</tr>
<tr>
<td>Puerto Rico</td>
<td>18.4</td>
<td>2,701</td>
</tr>
<tr>
<td>Miami</td>
<td>25.8</td>
<td>3,154</td>
</tr>
<tr>
<td>Houston</td>
<td>30.0</td>
<td>2,578</td>
</tr>
<tr>
<td>Phoenix</td>
<td>33.4</td>
<td>3,872</td>
</tr>
<tr>
<td>San Francisco</td>
<td>37.6</td>
<td>3,062</td>
</tr>
<tr>
<td>New York</td>
<td>40.7</td>
<td>2,535</td>
</tr>
<tr>
<td>Boston</td>
<td>42.3</td>
<td>2,634</td>
</tr>
<tr>
<td>Seattle</td>
<td>47.4</td>
<td>2,170</td>
</tr>
<tr>
<td>Edmonton</td>
<td>53.6</td>
<td>2,345</td>
</tr>
<tr>
<td>Anchorage</td>
<td>61.1</td>
<td>2,061</td>
</tr>
</tbody>
</table>

2.1 sDA and ASE simulations

sDA and ASE are two important evidence-based annual daylighting performance metrics. It is the result of a six-year effort of the Illuminating Engineering Society (IES) Daylight Metrics Committee led by the Heschong Mahone Group. [9] The sDA evaluates if a space receives enough daylight (> 300 lux) during regularly occupied hours (8:00 to 18:00) on an annual basis over a horizontal work plane. ASE intends to limit excessive sunlight in a space. ASE measures the presence of sunlight using annual hourly horizontal illuminance grids rather than luminance measures.

The office space was modelled with a sidelight window on one facade that represents a section of a deep open plan office space of 3.0 m high, 6.0 m wide, and 9.1 m long. The window’s width varies from 5.5 m to 6.1 m, and the window’s height from 1.5 m to 2.3 m. The window’s visible transmittance (Tvis) is 70% and the window-to-wall ratio (WWR) ranges from 0.45 to 0.75. The interior surface reflectances are 70% for the ceiling, 70% for the walls, 70-90% for the shading, and 35% for the floor. No blinds were used in the simulations. The Radiance ambient parameters were: -aa .15 -ab 5 -ad 2048 -ar 512 -as 1024 -dr 2 -ds .2 -lr 6 -lw .004 -dj 0 -sj 1 -st 0.15.

2.2 Annual Incident Daylight

The cumulative daylight illuminance on unobstructed vertical facades facing the cardinal directions and on the flat roof of a building [10] was calculated in DIVA-for-Rhino for the 12 locations. This calculation indicates which locations and facades receive higher or lower daylight illuminance throughout the year. Data were calculated hourly using Perez skies based on EnergyPlus (EPW) weather files, considering sun, sky, and ground (20% reflectance).

2.3 Shading design, projection factor, and view angles

The Ladybug Tools [11] were used to design the shading devices for the 48 facades based on the incident solar radiation, generated from local climate EPW weather files. Fig. 1 depicts the radiation intensity distribution over a skydome for low, intermediate, and high latitudes. Angles for the horizontal and vertical shading devices were defined for the 12 locations, in order to reduce the number of iterations for the parametric runs of the east- and west-facing facades, and for the manual runs of the south- and north-facing facades.

In this paper, the dimensions of the horizontal and vertical shading devices are defined as horizontal and vertical projection factors (PF). The horizontal PF is the ratio of the horizontal depth of shading device divided by the height of the window. The vertical PF is the ratio of the vertical depth divided by the width of the window. The horizontal View Angle (hVA) is the angle measured from a normal line to the facade plane on the window sill and the edge of the horizontal shading device. The vertical view angle (vVA) is the angle measured from the edge of the window opposite to the vertical shading device and the edge of the vertical shading device.

3. RESULTS AND DISCUSSION

The results of this study are presented as the three types of variables that designers use: context variables (daylight availability), performance variables (sDA & ASE), and design variables (window size, shading geometry, and optical properties of building materials).

3.1 Context variables: daylight availability

Fig. 2 presents the cumulative incident daylight for the 12 locations. In south-facing facades, the annual incident daylight is high (108–138x10⁶ lux-hours) in intermediate (30°–50°) and high latitudes (> 50°), except in locations with predominantly overcast conditions, such as Seattle and Anchorage (83–94x10⁶ lux-hours). South-facing facades in latitude 0° receive
an annual incident daylight of $72 \times 10^6$ lux-hours, which is fairly low compared with the amount received on a flat roof, which is three times higher.

In north-facing facades, the cumulative incident daylight illuminance gradually decreases from low latitudes to high latitudes. For example, a north-facing facade in Anchorage receives one-third the daylight received in Quito. The cumulative incident daylight in south-facing facades is four times higher than in north-facing facades in Phoenix and Edmonton, while in Quito the incident daylight in north- and south-facing facades are similar. The lowest incident daylight in east- and west-facing facades are in Anchorage, which receive about half the amount received in Phoenix and Quito.

3.2 Performance variables: sDA and ASE

Fig. 3 depicts a summary of the results. sDA > 75% was achieved in all latitudes and orientations (48 cases), even though the annual incident daylight varied from $26\times10^6$ lux-hours (Anchorage, north facade) to $138\times10^6$ lux-hours (Phoenix, south façade; see Fig. 2). The lowest ASE values (almost 0) are reached in intermediate and high latitudes in northern facades, and in all other locations and orientations the ASE values were < 10%.

Fig. 4 presents the sDA and ASE distribution at low (Quito), medium (Phoenix), and high latitudes (Anchorage). Quito has the highest and most uniform sDA distribution in the north- and south-facing facades, and receives the lowest sDA in the east- and west-facing facades. As expected, the lowest ASE values are achieved in the intermediate and high latitudes of the north-facing facades. All the other facades receive 1,000 lux for more than 250 hours in areas adjacent to the window walls, except for the east-facing facade in Phoenix, where sunlight penetrates deep in the center of the space. Shading in the east- and west-facing facades are the most difficult to design to control the entrance of sunlight.

![Figure 1: Solar Radiation at Anchorage AK (top), San Francisco CA (center), and Quito, Ecuador (bottom).](image1)

![Figure 2: Total Annual Incident Daylight on different surfaces of a building of the twelve locations.](image2)
3.3 Design variables: window size, reflectances, projection factors, and view angles

Window Size: Table 3 presents the area of windows expressed as WWR. The WWR is the percentage area determined by dividing the building’s total glazed area by its exterior wall area. The size of the windows was increased from low latitudes to high latitudes to achieve sDA > 75%. North- and south-facing orientations had the smallest windows (WWR 0.45). In most cases, the window size in the east- and west-facing orientations had medium sized windows (WWR 0.57), except in high latitudes. Due to the depth of the space, the most used WWR was 0.57 in 58% of all cases, and the WWR of 0.45 was used in 25% of all cases. Larger windows were used in high latitudes (47°–53°). For example, the WWR was 0.75 in Anchorage. Large windows in high latitudes with predominantly cold climates may create a problem for energy efficiency. These locations would require advanced glazed technologies with very low U-values.

Shading Geometry and Material Properties: Fig. 5 shows horizontal and vertical PFs by orientation of all locations. PF shows to what extent a window is blocked from daylight by external shading; hence the higher the PF, the lower the sDA and ASE. It is noticeable that PFs for south-facing facades increase with the latitude from 0° to 62°. South-facing facades in low latitudes locations (0°–25°) require minimum shading devices (PF Horizontal 0.2–0.6, PF Vertical 0–0.2) to comply with the sDA and ASE metrics; intermediate latitudes (25°–50°) require extended shading (PFH 1–1.8, PFV 0–0.5); and high latitudes (>50°) require shading that would extensively block the window glass (PFH 1.8–2.4, PFV 0.3–0.4), similar to

Table 3: Window-to-Wall Ratios by latitude & orientation

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east-facing (PFH 0–2.4, PFV 0.2–1.1) and west-facing facades (PFH 0–1.6, PFV 0.2–0.8). North-facing facades do not require shading except at equatorial locations (PFH 0.2, PFV 0).

**View Angles:** As the researcher expected, the trend lines of view angles are inverted to those of the PFs (see Fig. 6). South-facing facade hVAs decrease from 79° to 29° from low to high latitudes. This is caused by the lower angles of the sun and deep shading devices. On the other hand, vVAs decrease from 90° to 68°. East- and west-facing facade hVAs decrease from 23° to 43° from low to high latitudes and the vVAs vary from 62° to 81°. North-facing facade hVA and vVA remain at 90° in all locations, except for Quito.

**Figure 5: Horizontal and Vertical Projection Factors for the four orientations.**

Table 4 presents a summary of the reflectances used in shading devices by latitude and orientation. South- and west-facing facades used mostly 70% reflectance in low and intermediate latitudes, but up to 90% in high latitudes. The north-facing facade in Quito used a 70% reflectance. The only facades that needed specular reflectors to pass the sDA > 75% requirement were the east- and west-facing facades in Anchorage.

**Figure 6: Horizontal and vertical view angles of four orientations.**
Table 4: Reflectance (%) of shading devices by latitude & orientation

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The shading geometry used in this study can be replicated using the Horizontal and Vertical PFs (PFH and PFV) and material properties presented in Fig. 5 and Table 4.

4. CONCLUSIONS
This study demonstrates that it is possible to achieve the 3 points of the LEED v4 daylight credits for north-, south-, east- and west-facing facades at locations within latitudes 0° and 62°. Although the sDA and ASE metrics were developed using spaces located in latitudes 37° to 47°, these metrics can be used in any latitude, whether skies are sunny or overcast, and in all orientations, to allow designers to predict the quantity and quality of daylight spaces.

Shading devices and windows have to be designed according to the requirements of solar geometry by orientation and weather conditions. Results demonstrate that south-facing facades in low latitudes locations (0°–25°) require minimum shading devices to comply with the sDA and ASE metrics; intermediate latitudes (30°–50°) require extended shading devices; and high latitudes (> 50°) require deep shading that would extensively block the window glass, similar to the shading for east- and west-facing facades. In summary, south-facing facades in high latitudes, and east- and west-facing facades at any latitude require the development of articulated facade integrating deep shading devices, reflectors, view windows, and large window areas.

By removing the ASE requirement and giving points to sDA-300lux to 40% of the space, the new LEED v4.1 promotes the use of large expanses of glass and does not encourage designers to harvest daylight to interior working environments. This paper concludes that IES LM-83-12 implemented in LEED v4 is a metric that can be achieved in any latitude and will be able to provide visually comfortable spaces.

Parametric runs without a clear understanding of solar geometry and local climate are not useful to design shading devices and effective windows. With few manual runs, compared to hundreds of parametric runs, we can achieve the LEED v4 sDA and ASE requirements. It is more important to have a clear shading strategy than making guesses using parametric tools.

To increase the sDA in spaces in deep floor plans, other daylighting strategies can be integrated to the daylighting system that could increase the sDA to 100%. Core sunshinging technologies are a good alternative to passively introduce natural light to distances beyond 9 m. [12]

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REFERENCES
Weather File Creation Methodology for Remote, Underserved Locations

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ABSTRACT: Measured climate data are used in many activities across different sectors including city planning and decision making, as well as in a series of applications in the architecture, engineering and construction industry. Such data is typically used in the creation of Typical Meteorological Year (TMY) weather files in order to assist with climate analysis, decision making in building design and building performance simulations. Although great advancements have been made in the past 50 years, it is still evident that underserved locations around the globe lack quality measured data and often collecting weather data in those locations becomes a challenge for several reasons. In order to exemplify this condition and evaluate any possible shortcomings in practice, summary measured onsite data in the city of Mbale in Eastern Uganda were used in order to calibrate MERRA2 Climate Reanalysis data and create a functioning and reliable TMY weather file for building analysis purposes. Observed trends over the course of the measurement period were used in order to attune the correction profiles and multiplication factors for the calibration of the different climate variables. The climate file was created to assist with decision making for the design of the New Neonatal Unit for the Mbale Referral Hospital. The installed weather station continues to collect data aiming to create a bigger pool of information for future calibrations and adjustments.

KEYWORDS: climate file, weather station, environmental data collection, underserved location, reanalysis data calibration Uganda

1. INTRODUCTION

Historical and current recorded weather and climate data can be essential in many activities across different economic and societal sectors. Decision making on a city planning level becomes easier when data are presented in reliable simple graphical representations. Planning includes energy needs, water management, budget allocation, as well as preparation for extreme weather events. Collection of climate observations are being sustained to meet short-term weather forecasting needs for water, agriculture, fisheries and disaster management, as well as a range of commercial and community activities. They are valuable for operational meteorology, identifying extreme events and assessing associated risks, development of climate informed early warning systems, planning, and research. Climate observations are also used as a baseline for assessing changes in climate, for providing the initial conditions and evaluating climate predictions [1], as well as assessing the sensitivity of disease outbreaks relative to climatic conditions [2, 3]. In the Architecture, Engineering and Construction (AEC) industry climate data have been used since the ‘70s in building performance simulations in the form of hourly hypothetical typical years (Typical Meteorological Year - TMY). Building simulations are used to inform building design decisions related but not limited to building layout, material properties, window configuration, mechanical/electrical systems such as lighting & HVAC and solar control.

TMY files for US, Canada, Western Europe, Australia, Japan, and China are widely available. However, there are many locations around the world for which the availability of weather files is scarcer. There have been several attempts to expand this database to such locations [4, 5]. The coverage, however, remains spotty, while the demand for international weather data increases among building simulation specialists.

Africa is considered to be highly vulnerable to climate change, yet the availability of observational data and derived products is limited. For Africa it was noted that the lack of adequate data and observation systems seriously hinders the ability of scientists to assess the past and current state of climate [6, 7]. Obtaining weather data is often a challenge for locations in Africa away from the major cities and the collected data are often reported of poor quality or spotty. In addition to that, the number of observation stations across Africa has been declining since the early 1980s. Possible explanations include political and economic conflicts, legal restrictions and policies, low financial investment, difficult geography and terrain, or simply data are not being collected or reported anywhere [8]. Additional challenges the authors have encountered include prioritizing data collection in vulnerable areas, procurement of...
compatible equipment, safe transportation to the site overcoming fear of private profiteering, proper installation and calibration, maintenance and periodical data collection, as well as frequent power shortages that prohibit real-time online monitoring.

2. PROBLEM STATEMENT
The need to start collecting weather data in a remote underserved location in Eastern Uganda arose from the desire to support the design and build of the New Neonatal Unit (NNU) for the Regional Referral Hospital in the city of Mbale (1.08N, 34.158E, elev. 1,143m). Mbale is a small city of 100,000 inhabitants, approximately 222 kilometers, by road, northeast of Kampala, Uganda's capital and largest metropolitan area, and 40 kilometers directly west of Mount Elgon that rises to 4,320 meters. The Köppen Climate Classification subtype for this climate is "Am" (Tropical Monsoon Climate) [9]. The climate of Mbale is influenced by its proximity to the equator and its position at the rainy windward foot of Mount Elgon. It is warm and humid without extremes and as a typical tropical climate has almost no seasonal variations in temperature throughout the year. Seasonal differences are primarily attributed to rainfall patterns and therefore the year is typically divided into wet and dry period.

Analysis of local climate conditions and building performance modelling presented a big challenge to the design team due to lack of reliable recorded weather data in the area. On a worldwide level, there is a great discrepancy between different parts of the globe in relation to the number of weather datasets available, directly related to the financial and political status of the country and region. A consolidated database of hourly surface datasets can be seen in the Integrated Surface Database (ISD) project, NOAA's (National Oceanic and Atmospheric Administration) National Climatic Data Center (NCDC) initiative. Since 1950, station coverage has been reasonable over North America, Europe, Australia, and parts of Asia, with noteworthy gaps in Africa and South America until the early 1970s, when the Global Telecommunications System came into existence (Figure 1) [10]. Although coverage was improved after that, there are still severe gaps observed in Africa.

There have been some efforts to overcome scarcity of historical data in Africa, and many other parts of the world. These include interpolation of observations from existing stations as well as the use of proxies such as satellite rainfall estimates and climate model reanalysis products [8]. However, both approaches are prone to either reducing density of stations over time or the quality deterioration of the data as discussed in the previous chapter. The Enhancing National Climate Services (ENACTS) initiative of the International Research Institute for Climate and Society (IRI) of the Columbia University is using a hybrid approach where station observations are combined with satellite data for rainfall and reanalysis data for temperature [8, 11].

As of April 2018, the closest available weather station to Mbale was found at the Tororo airport (0.68N, 34.167E), nearly 50 kilometers south of Mbale and 1.5 times further from Mount Elgon. Weather data for Tororo was obtained from the Integrated Surface Database [12] and provided 10 years of recorded data (2005-2012, 2016-2017) that was turned into a typical year weather file. This file was used in the preliminary climate analysis in 2018 and in the preliminary daylight and thermal modelling of the designed building in 2019. This analysis could only be regarded as tentative, not only because of reported climate differences between the two locations, but also because of the poor quality of the Tororo weather data, which averaged at best less than four records per day, not a sufficient number to obtain reliable daily patterns.

3. METHODOLOGY
To better determine the actual weather conditions at the site, the design team decided to install a weather station near the site of the project. This is considered a short-term solution that responds to the research question of the application at hand. The obtained field summary data collected for roughly half-the-year are combined with satellite data to create partial weather files equal in length to the obtained measurements. The created file is then compared to meteorological reanalysis data and used to calibrate them and to produce a functioning TMY weather file for the purposes of thermal modelling of buildings. Since the measured data were initially half year of length, the rest of the year was generated using the calibrated reanalysis data to go back in time for 12 years and find the most typical conditions that would complement the file. After one full year of field
data is collected, the meteorological reanalysis data will then be re-calibrated to the full year of length and compared to the initial TMY file that is created by the summary field data. This comparison provides a way to evaluate the reliability of the initial methodology in case only partial data (at least half year in length) are available.

4. WEATHER DATA COLLECTION AND CALIBRATION

4.1 Weather station specifications and installation

The selected weather station for the application is the wireless DAVIS Vantage Pro2 [13] without the optional feature of solar radiation sensors. The selection of the model was based on familiarity of the authors with the equipment, its availability in formats compatible to the regional power and radio frequency requirements, as well as its ability to operate independent from the power grid. The weather station was installed on site in early 2019 and began recording data in February 2019. Installation and data collection related decisions were made relative to the specifics and challenges of the location and the site.

The exterior equipment is solar powered and therefore self-sufficient. It measures temperature, humidity, wind direction, wind speed, barometric pressure and precipitation. Since satellite-derived solar irradiance can be downloaded near real-time for any location in Africa from Copernicus Atmosphere Monitoring Service (CAMS) [14], it was unnecessary to install instrumentation to measure solar radiation, typically the most difficult climatic parameter to measure. Temperature and humidity sensors are shielded from solar radiation. The data are transferred via radio signals to the reading console, which has additional interior sensors that measure temperature and humidity. The console runs on batteries that last up to nine months. This setting gave power independence from the unreliable grid and provided the necessary foundation to the local doctors to almost seamlessly download data periodically and supply them to the design team in the US.

Members of the design team were responsible of safely purchasing, transferring and installing the weather station. Although the core design team is based in the US, the weather station was purchased from Europe due to data transfer frequencies reciprocity with Uganda. Directed by the local hospital manager, the weather station was installed 56m away from the site and the console was placed inside the existing neonatal facility at 61m distance from the weather station sensors (figure 2). The weather station was mounted on the structural support of a water tank at 6m height (figure 3). This location was considered the safest option to avoid vandalism and curious eyes. The area is surrounded by single or double story buildings and any obstruction to the equipment is considered minimal to inexistent. The interior console is mounted at a wall at the doctor’s office, away from any window and direct solar radiation.

4.2 Data collection

The recording of data was set at half hour intervals which gave the console a capacity of 53 days in stored data. Shorter intervals would result in significantly smaller capacity of the system and therefore would require a more frequent data collection. Data was collected in metric units so local people can have a better sense of accuracy while monitoring.

Figure 2: Weather station location relative to the project site and the interior console (in meters)

Figure 3: Installed weather station in Mbale
4.3 Data calibration

To extrapolate the recorded data to a long-term record, i.e., a "typical year" weather file, MERRA2 Climate Reanalysis data were used. Climate Reanalysis refers to using climate forecast computer models in a retrospective mode to simulate actual climate conditions across the entire planet, typically on a spatial resolution of half-degree (55km) in latitude and longitude, extending back several decades. There are several such ongoing climate reanalysis efforts around the world, of which the authors are most familiar with MERRA2 [15].

Previous experiences have found that while good in capturing general weather conditions, reanalysis data is limited by the imperfections and granularity of the climate forecast models. While atmospheric modelers have used techniques such as downscaling with mesoscale climate models, this project used a simpler method of calibrating the MERRA2 data with the local weather station data, after which the calibration is applied to the MERRA2 data of the grid cell containing Mbale for the past 10 years. The advantage of this simpler method is that the calibration implicitly adjusts for all differences between the grid cell and the actual site, including those that derive from elevation, land surface characteristics, heat island effects, etc. Furthermore, by calibrating the weather parameters, i.e., temperature, humidity, and wind speed, the accuracy of the climate modeling becomes secondary. Even if the modeling is inaccurate, the calibrated climate parameters are still acceptable. The main unknown factor of this method is whether a calibration done for one period of time will extend to a different, longer, period of time. How consistent and repeatable are the differences between actual measurements and the reanalysis data over the year?

Previous work by one of the authors had found the differences between actual measurements and reanalysis data were best described as differences in the average hourly profile by month. Figures 4 and 5 show the dry-bulb and dew point temperatures and Figure 6 the wind speeds from the two data sources for the week starting March 4, 2019.

The differences in average daily temperature profiles by month between MERRA2 and measured data appear constant and repeatable. Since Mbale is very close to the Equator, the differences in average daily temperature profiles do not change very much even between different months (see Figures 7 and 8). For wind speed, a simple multiplier of 0.24 was used to reduce the MERRA2 wind speeds to match those at the onsite weather station.
Because the calibration profiles could only be calculated for only February through June, it was decided to use an averaged annual dry-bulb correction profile for the missing months, while for a single annual dew-point temperature correction profile was used for all times. Calibration is not needed for the satellite-derived solar, while for atmospheric pressure a constant fraction is used (reflecting the considerable difference in elevation between the MERRA2 grid cell (1,586m) and the actual site (1,156m). This “typical year” weather file is then used to assess the energy and comfort performance of the building over an entire year.

5. OUTCOMES AND LIMITATIONS

The authors and the design team, with the help of the local doctors and the hospital maintenance team, managed to successfully install and operate the first weather station in the city of Mbale in Uganda. For the first time, the city is seeing measured weather data that evidently can be used in the calibration of advanced reanalysis models and utilized for building performance analysis. Proper maintenance of the weather station will allow for the data pool to grow and it will be used for readjustment purposes in the future.

The rural landscape of the project site made the installation of the weather station a relatively straightforward task. Physical obstructions from adjacent structures were easy to avoid. Proper installation and security of the equipment were the primary concerns mostly due to unfamiliarity of the people with such apparatus. Development of custom manuals and instruction guidelines aiming to educate the stakeholders and the users is providing the foundation for a more sustainable and self-sufficient operation of the installed systems.

Calibration of reanalysis models using only summary data that cover most of the climate variations, with focus on the rainy and dry season, produced a reliable weather file of sufficient accuracy for design purposes. This was mostly possible due to the fact that the climate variations during the year are minimal in a location close to the Equator. Had the climate been more diverse during the year, the selection of the measured data period would have to be much more intentional and calculated in order to cover all seasonal differences. That would likely affect the calibration process that would require more than one correction profiles to calibrate dry bulb temperatures and dew point temperatures for different seasons.

The methodology of calibrating reanalysis data using summary measured data can be applied in other locations. Attention must be paid on the proper installation of the weather station and the seasonal climate variations. Proper installation must be cognizant of the extreme conditions and protect against them, i.e. extreme wind patterns, hurricane or storm seasons etc. Awareness of seasonal variations should affect the summary data collection period as well as the extrapolation of trends throughout the year.

6. CONCLUSION AND FUTURE INITIATIVES

Acknowledging the need for more reliable climate data and specifically for “typical year” weather files for building performance analysis in underserved, remote locations, a unique approach is explored to creating such files. Serving the design of the new Neonatal Unit at the Mbale Referral Hospital in Uganda, the authors invested in the development of a novel methodology in generating the file.

Summary measured climate data are used to calibrate reanalysis data. The observed trends defined the correction profiles and multipliers which were then extrapolated year round in ways that are climatically justified. Using this methodology, functioning and reliable “typical year” weather files can be created for any location with just summary data.

As more reanalysis and measured data become available, the model can be re-calibrated until it reaches a full year in length. This future initiative will allow the authors to further assess the value of the present methodology, extract additional conclusions, and apply optimized calibration techniques.

ACKNOWLEDGEMENTS

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REFERENCES


ABSTRACT: Building-integrated carbon capturing (BICC) is a mechanism capable of absorbing carbon dioxide (CO2) from the air to be stored and then converted into useful carbon-based materials without negatively impacting the environment. We intend to build upon our previous work, in which we treated building façades as artificial leaves capable of providing shade to lower solar heat gain, while simultaneously capturing CO2 through the air filters attached to the building façades by attempting a different approach capable of capturing CO2 within buildings. In this newer version of BICC, we envision buildings as CO2 reservoirs or vacuums, into which mechanical systems introduce fresh air, and through human activities, the air within the building becomes enriched with CO2 before being exhausted back to the outer environment. The design of a carbon-capture mechanism will take advantage of the ventilation side of existing HVAC systems, through which we intend to capture CO2 from the exhaust-enriched CO2 air. We believe BICC is another small piece of the puzzle to combat the rise of atmospheric CO2 levels; just like planting a tree adds to the global carbon sink, BICC takes advantage of existing structures and equipment to provide another method to capture CO2.

KEYWORDS: Carbon, Capture, CO2, Building, Integration

1. INTRODUCTION
Carbon dioxide (CO2) concentration in the atmosphere has reached a record high and has been on the rise since the industrial revolution, due to human activities such as deforestation and the burning of oil, coal, and gas. CO2, due to its physical characteristics as a heat-trapping greenhouse gas, is considered a long-living and key factor contributing to climate change [1]. Stabilizing the level of emissions is becoming less and less possible; to combat climate change and meet the targets set out in the Paris Agreement on climate change, which are aimed at ensuring the global temperature increase is no more than 2°C for this century, a host of aggressive and innovative strategies must be enforced.

To date, most strategies have focused on carbon mitigation at national levels. Carbon mitigation involves reducing human emissions of greenhouse gases or increasing the capacity of the carbon sink. For buildings, carbon mitigation focuses on energy efficiency and the implementation of renewable energy. While carbon mitigation in buildings is crucial to lower emissions, it is not enough to offset carbon emissions from buildings. Even highly efficient buildings continue to use energy to meet operational needs, and on-site renewable energy implementation has a limitation on how much energy it can generate.

Therefore, combating this challenge in the building industry through the capture and reuse of CO2 is of equal importance to lowering emissions through carbon mitigation.

This paper serves as a continual ideation toward developing an appropriate and applicable building-integrated carbon-capture (BICC) mechanism that can capture CO2 from buildings. We intend to build upon our previous BICC work, an envisioned form of biomimicry that models nature’s process of photosynthesis, in which plants capture CO2 and turn it into carbohydrates and oxygen. BICC intends to absorb CO2 from the air and turn it into useful carbon-based materials without harming the environment. The first generation of BICC was intended to create shade and carbon capture from the atmosphere, where the mechanism was designed to be placed on building facades to cast shade to lower heat gain while capturing CO2.

Figure 1: The first version of BICC.

The second generation, which is the topic of this paper, focuses on the capture of CO2 from buildings, where it can be implemented within buildings’ heating, ventilation, and air conditioning (HVAC)
systems to take advantage of the fan used for air circulation, in addition to the higher concentration of CO2 in buildings. The reason for shifting our way of thinking away from targeting the building envelope as the medium for carbon capture, into carbon capture from within building is due to the first option being considered as a costly building element that requires high maintenance due to its having lots of moving parts; moreover, its performance may not be as good as we would like. This newer approach is a more suitable option for current implementation in buildings, as it can serve as an addition (in the form of a filter-like mechanism) to a building’s existing HVAC system, and be employed for the purpose of carbon capturing and regeneration. The later sections presented in this paper showcase the potential carbon capture technologies, present the design development of integrated BICC within a building’s HVAC system, evaluate the impact of the captured carbon with regard to carbon emissions for different building types and sizes, and propose a utilization strategy for the captured carbon.

2. CARBON CAPTURE TECHNOLOGIES
The idea of carbon capture is not new; it has been used for decades in different applications, whether used in large point sources, such as natural gas fields or power plants, or in manmade enclosures to maintain liveable environments.

The first use of CO2 capture technologies appeared in the 1920s, and was intended CO2 separation from methane gas found in natural gas reservoirs [2]. In the early 1970s, the idea of carbon capture and storage was first used, when the CO2 captured from gas streams was piped and injected into oil fields to boost oil recovery, a process known as enhanced oil recovery (EOR) [2]. The idea of carbon capture and storage from large point sources did not start with the intention to offset emissions for climate change; rather, it was used for economic purposes, such as EOR [3]. When oil prices dropped in the mid-1980s, the captured CO2 was considered to be too expensive for EOR, which led some of the capture plants to produce CO2 for commercial applications [3]. Carbon capture was later used in power plants that use fossil fuels for emission reduction purposes.

Additionally, carbon capture was also used to sustain life in man-made enclosures, such as submarines and spacecraft. For such spaces to be inhabitable and livable, it is necessary to introduce engineered artificial oxygen and carbon cycles to provide oxygen and get rid of CO2. These artificial solutions vary and can be seen in a number of methods, such as ventilation, carbon capture, or a combination of both, depending on the mission’s target and the available resources found in the outer environment. Submarines, due to temporary accessibility to the atmosphere, have two methods to assure a healthy indoor space. The first is a submarine snorkel to supply the interior with fresh air when the submarine is close to the water’s surface, and the second is a mine-based carbon scrubber to capture CO2 from the submarine enclosure during submersion [4]. The second type of enclosure is spacecraft, which are highly advanced and diverse in terms of carbon capture, due to the extreme environment in which they operate, where they lack the ability to regulate the supply and consumption of oxygen and CO2 on their own. In the spacecraft industry, carbon capture involves multiple systems to ensure successful and efficient carbon capturing. There are three main types of enclosures in space: crew suits, space shuttles, and space stations. These systems range from metox and lithium hydroxide one-time use canisters in crew suits and space shuttles to a continual zeolite-based CO2-removal system in the International Space Station (ISS) to a booster fan that functions a dedicated duct system to assist the CO2-removal system by sucking air from space shuttles when attached to the ISS. The diversity of technologies and systems used in the ISS and in space shuttles allows for a continuous removal of CO2, in addition to the creation of a water and oxygen supply to ensure continual and long-duration stays for space crews [5].

Recently, the increase of global awareness of the importance of combating climate change through reducing emissions and lowering atmospheric CO2 concentrations has prompted the emergence of a number of carbon capture technologies to capture CO2 from ambient air. The first technology this paper describes is Climeworks, which is considered the first commercially available product to capture CO2 from ambient air. Climeworks’s mechanism is equipped with a fan that draws air into the device, where ambient air passes through a filter that is fitted with a CO2-sorbent material. CO2 is then chemically bound into the sorbent material. Once the filter is saturated with CO2, heat is applied at around 100°C (212°F) to facilitate the release of the CO2, which is then collected and concentrated to be stored in tanks and then used for other purposes [6].

The second technology is called moisture swing air-capture technology, developed by Dr. Klaus Lackner at Arizona State University’s Center for Negative Carbon Emissions. This technology uses an ion-exchange resin that has the ability to capture CO2 when the sorbent material is in a dry state and release it when moisture is applied. Unlike Climeworks, this technology depends on the natural flow of air, which means that it does not rely on fan power to pass ambient air through the air filter panels [7].
The third technology is direct air capture (DAC), developed by geophysicist David Keith at Carbon Engineering. DAC removes CO2 from the air using the wet scrubbing method used in industrial exhaust applications, where air is brought into contact with an alkali hydroxide CO2-absorbing sorbent. DAC captures CO2 in a closed loop, in which the only major inputs are water and energy, and the output of the process is a pure stream of compressed CO2 [8]. Air is pulled through fans into the filter-like air contactor-structured packing and CO2 is captured by the sorbent solution; the captured solution is then injected into the air contactors, releasing the carbonate solution that contains the captured CO2, which is then sent to regeneration equipment for purification [9].

That being said, all technologies and systems mentioned above provide valuable insights, as adapting one of the technologies may be possible, but pursuing one or multiple approaches may be another step toward developing an appropriate and applicable BICC mechanism.

3. CARBON DIOXIDE IN BUILDINGS

It is of high importance to have good air quality inside of a building to ensure a healthy and comfortable environment for building occupants. Poorly ventilated buildings lead to contaminant build-up and high concentrations of CO2, which can result in decreased work efficiency and increased employee sick leave, in addition to building-related illnesses [10]. Therefore, ventilation is key to assuring good indoor air quality and can be achieved through the simple process of supplying air to, and removing it from, a building’s interior.

A typical balanced heating, ventilation, and air conditioning (HVAC) system introduces to the building an amount of fresh outdoor air that it is equal to the amount of soiled air that is expelled into the atmosphere. In addition, buildings are required, by codes and standards, to maintain a certain level of CO2 concentration for acceptable indoor air quality for occupants, and typically, the maximum acceptable indoor CO2 concentration is 1,000 ppm [6]. This expelled air that is intended to exit the building through the exhaust side of the system, at a rate of almost 2.5 times the concentration of the CO2 in the ambient air, is ideal for our new version of BICC.

4. BUILDING-INTEGRATED CARBON CAPTURE 3.0

The aim is to capture carbon dioxide from commercial buildings, due to their large footprints and high occupancy ratios. According to the Commercial Buildings Energy Consumption Survey, there were 5.6 million commercial buildings in the U.S. in 2012, occupying a total of 87 billion square feet of space [11]. Most commercial buildings use a centralized HVAC system with an air-handling unit responsible for cooling and heating the air, as well as for ventilation [12]. The proposed carbon capture mechanism takes advantage of existing and centralized building components, HVAC and air duct network. Those components are responsible for conditioning and circulating air within the building and one of their functions is to direct the expended indoor air toward the exhaust. Our aim is to utilize the previously mentioned building components for carbon capture purposes. Just like typical air filters, which are placed within the HVAC unit and perform the job of removing particulates and contaminants from the air that is being recycled, the proposed mechanism can be considered an add-on filtration mechanism with one sole purpose: removing CO2 from the expended air. Figures 2 showcases the operation of a typical HVAC system, with arrows identifying the direction of airflow through the duct system.
be stored, having a dual collector allows for a continuous process of CO2 capture and regeneration within the mechanism. The damper facilitates the continuous capture and regeneration by allowing for one to perform the regeneration process, while the other performs the CO2 capture.

Figure 3: Sectional drawing representing the different components of the CO2 collector. 1) Air handling unit exhaust air connection. 2) Damper to control air flow. 3) First collector during CO2 regeneration process. 4) The second collector during CO2 capture process.

During operation, the dampers direct the exhaust air toward one of the collection chambers, where the soiled air passes through the CO2 filtration mechanism, allowing the sorbent material to collect the CO2. Once the filter is saturated with CO2, the dampers move, so that air is directed to the other CO2 collector, allowing the saturated chamber to perform the CO2 regeneration process. The collected CO2 is then evacuated and compressed into liquid, which is then converted into methane through a sabatier reactor, to be used within the building or injected into the natural gas grid as a renewable fuel.

Unlike the first two versions of BICC, this newer version is not committed to a specific CO2 capture technology at this point of the design process, as we intend to design a generic apparatus that is open to adapting any of the available carbon capture technologies.

5. POTENTIAL OF CARBON CAPTURE IN BUILDINGS

To evaluate the potential of carbon capture in buildings and its impact on buildings' overall emissions, a preliminary numerical assessment was performed. We investigated different commercial building types and sizes, with regard to carbon emissions and potential carbon-capture capacity. The evaluation process drew comparisons of the amount of carbon offset for buildings in three different energy efficiency scenarios, represented from high-energy consumption to low energy consumption: typical buildings at the turn of the century, buildings that comply with the latest energy efficiency standards, and buildings with maximum technical potential. Carbon emissions for buildings were based on the Energy Use Intensity (EUI) for each specific building type and climatic condition, while the potential carbon capture amount was calculated based on the ventilation requirements and occupancy schedules. Potential CO2 amounts passing by exhaust were estimated based on building type and size for buildings following The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard 62 for ventilation system design and acceptable indoor air quality [13]. EUI data for various building types with different energy efficiency scenarios and different climatic regions were obtained from National Renewable Energy Laboratory EnergyPlus simulations, in addition to ASHRAE 1651-RP, Development of Maximum Technically Achievable Energy Targets for Commercial Buildings [14].

We have generated a preliminary carbon emissions off-set calculator, and the calculator took into account a number of variables to estimate the amount of carbon emission offset from buildings. Those variables are building type, building size, number of floors, EUI, building properties, climatic region, occupancy, operational hours, and carbon-capture mechanism efficiency. The mechanism’s capture efficiency was left as a variable, as at this point of research we do not have an exact figure and as we aim to highlight the potential of the idea of carbon capture in buildings. Below is a sample of some of the results generated by the preliminary calculator:

<table>
<thead>
<tr>
<th>Building Type</th>
<th>EUI</th>
<th>Carbon Emissions in CO2 tons</th>
<th>BICC Capture in CO2 tons (%70)</th>
<th>BICC Capture in CO2 tons (%80)</th>
<th>BICC Capture in CO2 tons (%90)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offices</td>
<td>31</td>
<td>137</td>
<td>9</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Mall common areas</td>
<td>49</td>
<td>217</td>
<td>55</td>
<td>63</td>
<td>70</td>
</tr>
<tr>
<td>Schools</td>
<td>46</td>
<td>204</td>
<td>21</td>
<td>24</td>
<td>27</td>
</tr>
<tr>
<td>Supermarket</td>
<td>49</td>
<td>217</td>
<td>22</td>
<td>25</td>
<td>28</td>
</tr>
</tbody>
</table>

The figures presented in the table may look like they represent only a small amount of carbon emission offset, but one must perform an order of magnitude calculation to evaluate the impact that carbon capture from buildings may have on the overall carbon cycle. To do this, we performed a simple first-order calculation to determine the
number of tons of CO2 captured per year that the envisioned BICC mechanism would be able to remove from office buildings in the United States of America. There are 5.6 million commercial buildings in the U.S., which covered 87 billion square feet of floor space in 2012 [11]. Seventeen percent of this total floor space is accounted for by commercial office use [11]. The total annual U.S. carbon emission is 5.35 billion metric tons of CO2 [15]. For the sake of this calculation, we assumed that BICC would be implemented in 50% of commercial office buildings in the U.S., with a carbon capture efficiency of 70% (lowest carbon capture capacity efficiency in the table). This would offset 3.3 million tons of CO2 emissions annually, which equals 0.06% of total annual U.S. carbon emissions.

Although this may seem like a small offset, this amount must be considered alongside other carbon mitigation technologies to evaluate its impact. A good example to consider is the solar energy sector. Over the last decade, solar energy generation has increased, accounting for almost 1.4% of the total energy generated in the U.S. This energy has been generated by various solar energy applications, including residential buildings, schools, commercial buildings, utility-scale facilities, and community solar programs. The total energy generated by all sectors offsets nearly 74 million metric tons of CO2 emissions, which accounts for almost 1.5% of the total U.S. emissions [16]. This figure is almost 22 times what BICC can offset. However, taking a closer look at solar industry installations, only 2,562 MW of the total 58,000 MW of solar energy generation is installed in commercial projects, offsetting 2.4 million metric tons of CO2 each year [16]. To put the carbon offset of commercial solar projects into perspective, they only offset 0.05% of total annual U.S. carbon emissions. Therefore, the calculated potential looks promising, when viewed in terms of the small market niche of building integrated carbon-capture emission off-set solutions.

6. CARBON DIOXIDE UTILIZATION IN BUILDINGS

Although CO2 is considered a waste product from the energy and industrial points of view, CO2 can have a variety of uses in local markets, such as food production and refrigeration; it can also be used in a number of industrial applications, including metal and plastic manufacturing, or injected and stored underground for enhanced oil recovery. Yet, in all the previously mentioned applications, the amount of CO2 collected in a city would be more than what such applications require or its storage and transport to remote locations would require substantial investments in infrastructure. First, the captured CO2 must be compressed to pipeline grade, which represents a significant amount of energy and a high cost. Second, a network of pipelines must be inserted within cities’ infrastructure so that the CO2 can be captured and stored locally. Third, a local storage facility must be constructed within each urban area as a transit point, from which the carbon can be piped to the storage location. Finally, transporting the CO2 to the remote storage facility must be done through pipelines or tankers. Pipelines are an expensive investment, costing at least $50,000 for every mile on flat and dry terrain and reaching up to $700,000 per mile for offshore piping [17]. These four changes to the urban infrastructure require significant investment, except for cities that were built with CO2 capture and storage in mind. Therefore, we are proposing a utilization strategy for CO2 to be used within cities and for BICC to become a viable option for carbon capture and reuse in the building industry.

To these ends, we aim to convert the captured CO2 into methane, and then feed it as a form of renewable fuel into the existing natural gas pipeline network similar to what solar energy has done, utilizing the existing electrical network by feeding the excess energy generated by the system through the concept of net metering. The process of converting CO2 into methane requires a combination of two processes: first, electrolysis, in which water is broken down into oxygen (O2) and hydrogen (H); and second, the Sabatier reaction, in which we combine the hydrogen generated by electrolysis with captured CO2 to create methane (CH4) and water (H2O). Both processes are displayed below:

**Electrolysis reaction:**

\[ 2H_2O \rightarrow 2H_2 + O_2 \]

**Sabatier reaction:**

\[ CO_2 + 4H_2 \rightarrow CH_4 + 2H_2 O \]

The International Space Station’s regenerative environmental control and life support system relies on a similar process to provide a continuous cycle of oxygen and water [18]. Another example can be found in the power-to-gas technology that has been adapted by the European energy project, Store&Go, in which they convert surplus wind energy into methane, which can then be fed into the natural gas pipeline network as a renewable fuel or stored to be made available when needed [19].

7. DISCUSSION

Buildings account for almost 76% of electricity usage and 50% of primary energy in the U.S. and are associated with greenhouse gas emissions [20]. Reducing energy usage is essential to combating climate change. As mentioned earlier, most of the current work in the building industry has focused on carbon mitigation, though these strategies are not enough to completely offset carbon emissions from the building industry. First, commercial buildings are energy-intensive, due to their nature or to the
provision of services demanded of buildings — lighting, warmth in the winter, cooling in the summer, water heating, electronic entertainment, computing, refrigeration, and cooking [21]. Buildings also vary in terms of their EUI per square foot, which is dependent on the building type and climatic location. Each building type differs in terms of function, occupancy, and appliances used. Some building types are energy-intensive (e.g., health care facilities), while others are not (e.g., warehouses) [21]. Even for an ultra-low energy use commercial building, designed with maximum technical potential EUI, energy intensity is still present. Second, most buildings that generate their own renewable energy do so with solar Photovoltaics (PV) systems, and there are limitations on how much energy they can produce on site. Those limitations are governed by the space a building has on site to install PV rays, and that accounts for how much energy it generates. If we assume that a building has only its roof to install a PV system, then it is more likely for a single-story building to achieve net zero-energy (ZNE) than a high rise. The “Assessment of the Technical Potential for Achieving Net Zero-Energy Buildings in the Commercial Sector” report by the National Renewable Energy Lab and the U.S. Department of Energy indicated that it is extremely difficult for buildings above four stories to reach ZNE [22]. Eliminating carbon emissions through carbon mitigation strategies in the building sector is possible for some building situations, but impossible for other situations, unless they rely on off-site renewable energy sources. Therefore, carbon capture from within buildings may be another piece of the puzzle toward offsetting carbon emissions from buildings. Carbon captures hinges on the ability to take advantage of higher concentrations of CO2 within buildings, in addition to utilizing existing air circulation systems and free fan energies. Adding the ability to convert the captured CO2 into methane, which can then be fed into the natural gas network as a form of renewable fuel, BICC can serve as an additional tool that contributes to the global efforts to combat climate change through lowering CO2 levels.

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Planning Post Carbon Cities

An educational tool for learning climate responsive design
Case study applying for architectural students and engineering students

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ABSTRACT: The approach of integrated project delivery (IPD) in architecture projects gets common and the competence to communicate within the professional diversity gets essential. Thus, having literacy of both design and engineering are highly required when architects and engineers work together under the passive and low energy architecture project. The author developed the educational tool as a learning method which supports students to develop their competency of design and engineering (especially building physics) in architecture. The educational tool was applied in lectures and seminars for various target groups (bachelor level, master level) in different countries. This article describes the framework of the study kit and the results of application in the course in the department of architecture and the department of engineering in the universities in Finland and Sweden. It was found that the developed educational tool can support students to understand the reason of architectural forms considering climate profiles, learn the mechanism of function realized by the forms, and develop their aspect to see the relationship, which also can be found in modern houses. Two application cases clarified the benefit and potential for each group, and both groups utilize their advantages which are based on their major, effectively through the activity.

KEYWORDS: Educational tool, environmental design, climate analysis

1. INTRODUCTION
The approach of integrated project delivery (IPD) in architecture projects gets common and the competence to communicate within the professional diversity gets essential [1]. Thus, having literacy of both design and engineering are highly required when architects and engineers work together under passive and low energy architecture projects [2]. Besides, project team members are international with their own experience in various climate characteristics. In addition, project team has more chance to work on international architectural projects, then the team needs to develop their design considering climate profile of the project site.

In an education, it would be ideal if learning opportunities were provided for students regarding both fundamental scientific theories (such as climatology, thermodynamics, building physics, etc.) and practical design (such as environmental design, sustainability, building technology, etc.) with integrated. The author developed the educational tool as a learning method which supports students to develop their competency of environmental design and of engineering in architecture. The educational tool was applied in many lectures and seminars for various target groups (bachelor level, master level) in different countries.

This article describes the framework of the educational tool and the results of application in the courses in the department of architecture and the department of engineering in the universities in Finland and Sweden.

2. METHOD
2.1 Aim
The aim of the developed educational tool is as follow:

- Providing an opportunity for architectural students to learn building physics from practical cases.
- Providing an opportunity for engineering students to learn an environmental design with an architectural design aspect.
- Providing an opportunity to observe data with science-based attitude.

2.2 Material
The material consists of four components as climate profile datasheet (Fig 1), landscape cards (Fig 2), traditional house cards (Fig 3), and modern house cards (Fig 4). Supposing various situation to apply this tool, the contents are easy to modify and update, easy to prepare the numbers of sets depending on the class size. It means all items are based on printable format.

Climate profile datasheet
The datasheet shows the profile of the weather through the year at the target site, and it gives an
opportunity focusing on the characteristics with numerical evidence (Fig 1). The datasheet includes, average high and low temperature of outdoor air, daily chance of precipitation, day length (including the information time of sunrise and sunset) and wind rose chart. The data are collected and arranged using open weather data [3, 4]. Students overview the datasheet, pick up the feature of the local climate and consider the climatic pros and cons. Lecturer suggests them to focus on the daily difference and seasonal difference.

Figure 1: Climate Profile Datasheet (A4 format)

Landscape card
The picture of landscape includes the scene of the region and the sun path diagram (Fig 2). The Students see, seek the clue of climate feature from the picture (for example, vegetation, accessible resource and material, etc.) and find the keys to determine the houses of both traditional and modern which locate in the site. The limitation of landscape card can only show the one typical scene of a specific time. With this reason, it is difficult to show the variety of situation, for example, if the site has four seasons. To solve this problem, the sun path diagram supplies the supportive information regarding the solar situation of the time in the scene.

Figure 2: Landscape Cards (A4 format)

Traditional house card
The picture of traditional house shows the exterior on the front side and the interior on the backside of the card (Fig 3). The cards are printable format, so after printing with A4 sheets, dividing 4 sheets (A6 size).

Figure 3: Traditional House Cards (A6 format)

Modern house card
Traditional house is a good example to explain a relationship between a form of house and its function. But it can be seen in modern houses as well. For example, a modern apartment building in South Korea has floor heating system and radiative floor heating system is originated from South Korean traditional house. Thus, the tool involves the modern house cards in order to support students linking fundamental mechanism and application in modern projects. The picture of modern house shows the modern apartment building at the site (Fig 4). The format is the same with the traditional house cards, which means the exterior on the front side and the interior on the back side. The modern house cards show the typical example of a form of building envelope and the function which can be seen in the pictures. Students see and think how the details of the apartment building are functioned under the climate characteristic.

Figure 4: Modern House Cards (A6 format)
2.3 House cards

The study examples which were selected in the educational tool are shown in Table 1. Two examples are from hot climate zones and the rest of two are from cold climate zones. For the selection of study example, vernacular architecture is selected because there are many typical relationships between its form and the function. Also, the cases of the modern house are collected. The potential of modern house study case is to show the combination of passive solution and active solutions. The educational tool can expand the selection of examples depending on the contents of the course.

Table 1: Example of traditional houses

<table>
<thead>
<tr>
<th>House</th>
<th>Country</th>
<th>Koppen Climate Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yurt (Gel)</td>
<td>Mongolia</td>
<td>BSk  Cold semi-arid</td>
</tr>
<tr>
<td>Bamboo house</td>
<td>Burma (Myanmar)</td>
<td>Cwa  Humid subtropical</td>
</tr>
<tr>
<td>Wind tower house</td>
<td>Iran</td>
<td>BSk  Cold semi-arid</td>
</tr>
<tr>
<td>Wooden house</td>
<td>Estonia</td>
<td>Dfb  Warm humid continental</td>
</tr>
<tr>
<td>Straw roof house</td>
<td>South Korea</td>
<td>Dfb  Warm humid continental</td>
</tr>
</tbody>
</table>

2.4 Procedure

Instruction

Before starting group work activity, the instruction of the activity is provided. Because showing only the steps is not enough for students to understand what will be happened, one example case is demonstrated. This demonstration process is also important as a part of learning. In the application cases in this article (see Table 2), the Mongolian case is applied as a demonstration example.

Group work activity

The program proceeds with three steps (Fig 5). First, each group overviews the climate profile datasheets, analyses its climate profile and writes down the features in the worksheet. And they select the climate category from the list of Köppen Climate Classification System. Together with this, the students collect one Landscape card for each climate. The student summarizes their analysis on climate and location in the worksheet.

Secondly, the students overview the group of house cards and analyse the features of each house such as material, shape from the point of “form and function” under the climate. Then, they collect one combination of traditional and modern house cards under the target climate zone.

And the last step, they write down in the worksheet how each house performs under the target climate zone, or how the passive design and mechanical solutions are applied. In the beginning, the example case is shown and follow the steps together.

Task 1: Analyse The Climate Profile
What is the characteristic of each climate? Which scene can be seen under each climate?

Collect one Landscape card for each climate.

Task 2 Analyse The Forms
What is the found from each picture of house? Look carefully in detail and think.

Collect one combination of Traditional and Modern house cards for each climate.

Task3: Analyse Its Function
How does this house perform under the climate? Write down in the worksheet.

Follow up lecture

After the activity, the lecturer explains each case one by one through checking the correct combination. With adding various pictures (such as infrared thermal pictures, similar practices in the same climate regions, or cases of well-known architectural projects) in the slides as well as the pictures in the cards, the environmental design aspect and mechanism of the form are explained. Together with engineering aspects and design aspects, the cultural background is provided.
2.5 Application Cases

Table 2 shows the cases where the developed method in different schools, one at Department of Art, Design and Architecture in Finland (case 1) and another at Architecture and the Built Environment in Sweden (case 2). The student group in Case 1 studied architectural design and the educational tool was applied as a part of the design studio. The application in case 2 was done as a part of the course entitled “Sustainable Building” for the student group who studied building service engineering. Both groups were master level and included a variety of nationalities.

Table 2: Application cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Place of implementation</th>
<th>Major of the student group</th>
<th>Number of the students</th>
<th>Diversity of nationality</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Finland</td>
<td>Architectural Design</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>Sweden</td>
<td>Building Service Engineering</td>
<td>27</td>
<td>10</td>
</tr>
</tbody>
</table>

3. RESULTS AND DISCUSSION

3.1 Learning points

After the activity, the lecture regarding climate responsive design was done together with checking the combination of cards. The educational tool provides the following three learning points: “Climate” what is the feature of the climate, “Form” What kinds of form the architecture has due to achieve the required function, and “Function” what kinds of approach to create built environment is required.

Climate

The lecture started with using climate profile datasheet. The lecturer provided the aspect of how to get information from each graph, such as daily trend, seasonal trend or annual trend. To support deep analysis, a psychrometric chart using of each example were shown in the lecture slides. Since the architectural students in case 1 seldom have the chance to see the psychrometric chart, the chart has the advantage to deepen the understanding the profile of outdoor temperature, and humidity level. For the engineering students are familiar with using the psychrometric chart at calculating HVAC systems, it was easy for them to understand climate profile with the psychrometric chart format in the lecture.

Form

The architectural student group were good at getting information from both traditional and modern house cards, they got the climatic aspect in architectural form. On the other hand, the engineering student group were familiar with numerical graphs in climate profile datasheet, they tend to spend their time more on the first step. The engineering students started to think about the required physical element controls and extend their scope more on the design aspect.

Function

The lecture provides the chance to discuss the required function based on climate analysis in the previous step. In the review part after the activity, the architectural students mentioned that they know the house as a case but never have a chance to see them with a scientific aspect. They could integrate climate and form with function. The engineering students have fundamental theories of architectural engineering however, the less opportunity to recognize with the architectural design aspect.

Size of the group

In case 1, 9 participants were divided into 3 groups (3 students for each group), and 27 students are divided into 14 groups (2-3 students for each group). When there were only 2 students in one group, they tended to overview the climate profile.
one by one. Some groups took a long time. The advantage is to have an intensive discussion among 2 students. When the group size was 3 students, some groups overviewed the climate profiles parallelly. It can be a benefit for them to see the information with the aspect of comparison.

3.2 Feedback from the participants
The application in Case 1 (Finland), the demand for learning in terms of environmental design in architecture was investigated through the questionnaire. The questionnaire was carried out after the activity. The number of collected answer was 9 in total. Fig 8 shows the result of the demand for the contents what they want to know more and Fig 9 shows that of the demand for the way to know through the activity.

Demand to study regarding environmental design
The first question was “What do you want to know more?” The highest demand was the relationship between climate and materials (Fig 8). The students have interested in materiality as a context of sustainability in architecture, so it would be ideal if sustainability and environmental design can be integrated to study. In the lecture after the group work, the physical features of local materials are discussed, for example, wool fabric as an envelope of yurt in Mongolia, bamboo used in Burma (Myanmar).

Demand of ways to study environmental design
The highest answer against the question “How do you want to know/do?” is the request to obtain design case study (Fig. 9). This means that the students request to know the practical knowledge.

Second and third highest options are on-site environmental measurement and physical model experiment. Both are way to learn by experience based activity. Nowadays, computational tools for environmental study (such as ladybug, climate studio, etc.) get common and open for students. However, the feedback from the students showed that physical study methods are still demanded. Considering the requests, there is a potential to involve the contents based on physical exercise in this education tool.

4. CONCLUSION
Through several application cases, it was found that the developed educational tool has potentials to support students (of both architectural design field and building engineering field) to understand the reason of architectural forms considering climate profiles, learn the mechanism of function realized by the forms, and develop their aspect to see the relationship, which also can be found in modern houses. Two application cases for architectural student group and engineering student group clarified the benefit and potential for each group, and both groups utilize their advantages which are based on their major, effectively through the activity.

The features of the educational tool are exercise-based, driven by group work, and using printable materials. That’s why the flexibility of application is one of the advantages. However, considering the transition of education environment, there is the potential to develop as an online-based material and method. In case applying online, the diversity of location where students participate in can be the valuable advantage as contents of the tool. This could be the future work for further development.

REFERENCES
Understanding traditional comfort practices: 
Case-study of a low-income community in Ahmedabad, India

TANIA SHARMIN

ABSTRACT: An indoor thermal comfort study was carried out in a low-income community during the hot summer in 3 different categories of houses: Type-1: New builds, Type-2: DMU_new_builds and Type-3: Old_houses. The performance of Type-2 houses (architecturally designed with passive strategies) were significantly better than Type-1 and Type-3 houses with the former being 1.0°C cooler on average than the later. All respondents of the study expressed little concern for indoor thermal comfort as they are accustomed to sleep outdoors, either in the courtyard, roof, or balcony as a cultural practice. During daytime, they spend most of the time in outdoor shaded conditions. This is a unique example of how people can adapt through behaviour that makes us rethink the impact of immediate outdoor conditions rather than focusing solely on indoor conditions in a low-income residential context. However, the residents still use indoor spaces for cooking, eating and other social and household practices and for sleeping during the other seasons. It means there is a balance to be made. However, the attempts to incorporate courtyard in the design by the architect for improved social and environmental performance were mostly unsuccessful due to opposition from the residents. This identifies a challenge for local designers to design low-income houses in a high-density context while providing for the socio-cultural and environmental needs of the residents.

KEYWORDS: Thermal comfort, low-income house, hot-dry climate, comfort practices, developing country
1. INTRODUCTION
Recent studies by Sansaniwal et al. (Sansaniwal, Mathur, Garg, & Gupta, 2020) have identified the lack of organised thermal comfort research for the diverse climate zones in India. Their study has also identified a need for understanding the comfort practices by exogenous factors such as occupant behaviour, climate, income, and sociocultural factors. Likewise, Nicol and Roaf (Nicol & Roaf, 2012) has emphasised that people’s thermal experience and behaviour not only indicates their own personal surroundings but also the culture and climate in which they reside. Therefore, from a thermal comfort perspective it is essential to examine people in their everyday habitat amidst its complexity to ensure important variables are not overlooked (Indraganti, 2010). Indian people have a diversified culture and adaptive behaviour which needs to be acknowledged in thermal comfort studies. For instance, in hot-dry climatic zone in India, it is a common cultural practice to sleep in outdoor courtyards, roofs or semi-outdoor spaces like balconies during the summer months. Outdoor sleeping is further coupled with night ventilation and diverse seasonal and diurnal occupancy pattern as a part of living style (Rajasekar, Anupama, & Venkateswaran, 2014). This does not mean that indoor spaces are less important in terms of thermal comfort for other household activities. To provide comfortable habitat for these people, it is therefore important to gain understanding of their living style and cultural practices to ensure appropriate application of indigenous strategies to combat adversities of the local climate. Climate-responsive architecture is strongly evident in Indian traditional architectural practices that endeavours to provide comfortable indoor and climatically modified outdoor spaces. However, it is challenging to apply passive architectural solutions for providing adequate thermal comfort in a low-income setting where resources are limited. Often in such situations, the client cannot foresee the benefits of bioclimatic strategies as it often creates conflict with their trivial personal interests. In many cases they are overwhelmed by more pressing and urgent issues like hunger, poverty and natural disasters like floods, cyclones etc. In this context, this study presents a case study scenario to depict thermal comfort practices of a low-income group in a climatically harsh region in India that has implications for future design and strategic development of low-income settlements.

2. METHODOLOGY
The data collection involved questionnaire surveys, interviews, visual inspection, photographic survey, and thermal comfort survey alongside environmental measurements in the case study houses. Onsite measurements included air temperature, relative humidity, wind speed and mean radiant temperatures.

2.1 Study area
The study area is located on the outskirts of Ahmedabad, India at 22°59’58.6"N and 72°38’40.0"E which is 8.41 km south-east of Sardar Vallabhbhai Patel International Airport, Ahmedabad. Named by the Gandhi Leprosy Seva Sangh as the Loving Community, it was formed in 1968 after the land was provided by the Government of Gujarat to accommodate leprosy-affected people from all over India who were socially excluded due to the contagious nature of the disease. The community has 125 houses with a population of approximately 500 people.

Ahmedabad has a hot semi-arid climate. An average maximum temperature of 45.0°C in the pre-monsoon summer months of March-May makes Ahmedabad one of India’s hottest cities with heat posing a significant public health challenge. A diurnal temperature range of 12.0 -16.0°C throughout the year (Udaykumar & Rajasekar, 2015) makes evening temperatures somewhat tolerable during the summer months.

2.2 Measurements and thermal comfort study
An indoor thermal comfort study was carried out in the Loving community during the hot summer months of May. The study included 12 households of 3 different categories: Type-1: new-builds (New_builds - designed/ built by individual owners), Type-2: new-builds (DMU_new_builds designed/ built by local architects) and Type-3: old, existing houses (Old_houses).

A standard thermal comfort survey was carried out alongside immediate measurements of air temperature (T\text{a}), relative humidity (RH), wind speed and mean radiant temperatures (MRT) using Testo 480 with humidity/temperature probe (accuracy of up to ± 1% RH), comfort probe for turbulence measurement and globe thermometer (TC type K) for the measurement of radiant heat. Residents were asked about their thermal sensation, thermal preference, and acceptability during the survey period. Thermal sensation was recorded using ASHRAE comfort scale ranging between -3 and +3 while considering the clothing levels (0.5 clo) and metabolic rate of the occupants (1.2 met). An elaborate interview was carried out to learn about the daily activities, thermal comfort practices and satisfaction levels of the respondents in the households. Simultaneous T\text{a} and RH measurements over a 3-day period was carried out using HOBO dataloggers to investigate the thermal performance of different house types.
2.3 Building construction and environmental conditions of house-types

Type-1: New_builds – These are generally two or three-storied buildings constructed by individual owners with local contractors without any architect’s supervision/ involvement (Figure 1 a). The entire plot area of approximately 20 sq. metre is built-up with minimal cross ventilation and daylighting options. The rear room generally does not have an outside window or daylight access (Figure 1 b). Building envelop consists of brick wall with plastered finish with concrete roof slab.

Type-2: DMU_new_builds – These are typically one-storied buildings (except one two-storied building) (Figure 1 c) designed and built by SEALAB Architects. Building envelop consists of brick wall with plastered white finish with concrete roof slab. Those two-storied high, have a ferro-cement roof mesh with white tiled surface on top. Natural ventilation and daylighting have been maximised in all buildings with stack ventilation in the two-storied buildings. Courtyard has been incorporated for social as well as environmental reasons to provide mutual shading and cross ventilation (Figure 1 c).

Type-3: Old_houses – These are one-story buildings originally constructed under the government initiatives (Figure 1 e). Rear rooms do not have any natural ventilation or daylighting (Figure 1 f). The wall consists of single file brick walls with plaster finish with corrugated iron sheet roof.

2.3 Passive strategies in architecturally designed buildings

Residences in the hot–dry climatic zone of India are traditionally climate responsive (Rajasekar et al., 2014). Consequently, the use of courtyard as a climate modifier or vernacular passive cooling system is common in the hot-dry climate of Ahmedabad. Architect has incorporated front courtyards in all Type-2 houses and back courtyards in some Type-2 houses, depending on the availability of space. The front courtyard provided mutual shading and space for day-to-day social interaction with the neighbours, whereas the back courtyard served a more functional purpose such as cleaning utensils and washing and drying clothes alongside ensuring privacy of women. The other critical role of the back courtyards is to facilitate cross ventilation especially because houses were originally arranged back-to-back by sharing a common back wall. So, the only way cross ventilation could be arranged was to make provision for a back courtyard.

Additionally, the architect has incorporated roof extractor fans to increase stack ventilation alongside cross ventilation through the windows. He further used foldable window/ door (Figure 1 d) to maximise cross ventilation when necessary. These ventilation strategies are effective to maximise night ventilation and thereby, can improve comfort levels due to the large diurnal temperature swing prevalent in this region (Rajasekar et al., 2014).

3. RESULT

Figure 2 presents two and half day’s temperature data for the 12 houses. A mean is calculated for each group of house types at every 5-minutes interval. The data is then plotted, and the resultant graph is presented in Figure 2. Overall, the graph shows that the Old_houses have the greatest fluctuations and highest temperatures with an average temperature of 36.8°C (Fig. 3) over a 60-hour period. Air temperature in the New_build houses is more stable with an average temperature (36.8°C) equal to the Old_houses. DMU_new_builds, on the other hand had the lowest average temperature (35.8°C) during the above time-period, and the lowest average temperature of 33.3°C occurring at 9:30 am on the second day. It means, even in very hot conditions,
passive strategies applied in architecturally-designed buildings as in Type-2 houses, were able to reduce air temperature compared to the new buildings (Type-1) which were designed ignoring any passive strategies such as courtyard spaces, natural lighting and ventilation and appropriate thermal mass.

National Building Code of India recommends the acceptable thermal comfort limits for naturally ventilated buildings with an upper limit of 32°C and 60% relative humidity (RH), provided an air velocity (AV) of 1.6 m/s is available. Udaykumar et al. (Udaykumar & Rajasekar, 2015) suggested a local comfort range of 25 – 31°C in summer for the hot-dry climate of Ahmedabad. The average air temperature measured in all three types of houses during the survey period is well above the comfort range reported in (Udaykumar & Rajasekar, 2015). Especially, the environmental conditions in the Old_houses were found to be uninhabitable. The maximum temperature of 47.6°C was recorded at Old_house_01 on the second day and the lowest temperature (32.6°C) was recorded at DMU_new_build-03 on the first day. The maximum difference on air temperature of 12.8°C was recorded between Old_house_01 and DMU_new_build-03 at 12:50 pm on the second day.

All respondents in the DMU_new_build houses felt comfortable/ neutral during the survey period whereas TSV (Thermal Sensation Vote) for people in the New build and Old_house houses varied between neutral to warm and warm to hot, respectively (Figure 4). In the Old_houses, 100% people felt either warm (22.2%) or hot (77.8%). This corresponds with the air temperature measured in the houses. In the Type-1 houses the responses were comfortable (33.3%), slightly warm (22.2%) and hot (44.4%). There was no response in the cold, cool and slightly cool category for the extremely hot conditions.

During thermal comfort survey, average instantaneous air temperature in the three house types were 37.0°C, 37.0°C and 40.6°C for house Type-1, Type-2, and Type-3 respectively. Given the local comfort zone between 25 – 31°C as mentioned above, it is quite remarkable to see people were comfortable in the Type-1 and Type-2 houses at an average temperature of 37.0°C. It could be due to their overall satisfaction with the housing conditions as well as their ability to acclimatise with high temperature conditions linked to their daily livelihood. The responses match with the level of satisfaction reported in the self-build houses (Type-1) and DMU_new_build houses (Type-2). When asked about the 'overall living quality of the houses' 100% people in the Type-1 and Type-2 houses expressed satisfaction. Respondents in the Type-3 Old_houses,
on the other hand were fully dissatisfied. Undoubtedly, the environmental conditions with an average temperature of 40.6°C were unacceptable to most of them. Furthermore, the residents are mostly involved in outdoor-type professions such as auto or manual rickshaw driving, road cleaning, begging or factory work which indicates their acclimatisation to high air temperatures. Figure 5 shows how probability of thermal acceptability decreases with the increase of instantaneous indoor air temperature.

Figure 5: Thermal acceptability against instantaneous temperature during comfort survey across the houses

4. DISCUSSION

As discussed above, in order to deal with the extreme heat in summer, the architect incorporated front and backyard in the designed houses. The design strategy also evolved from the social need of the local community as realised from their lifestyle. However, from the interviews, none of the residents were happy about the courtyard spaces even though they appreciated the social and functional value of the courtyard spaces. To them it was more important to have additional indoor space rather than a semi-outdoor space where they could store more personal belongings.

The natural ventilation strategies adopted in the design such as cross ventilation and stack ventilation could not be utilised for night ventilation which is the most effective ventilation strategy for this climate as the windows did not have safety grills and therefore, could not be kept open during nights. Furthermore, the foldable panels were somewhat inflexible, heavy, and impractical (size unsuitable for a residential scale) and did not follow ergonomic design. Therefore, their performance to facilitate natural ventilation was somewhat reduced.

Culturally and traditionally, the people in the region are accustomed to stay outside throughout the most part of the day and sleep in the courtyards or terraces at night. The reason behind this mainly climatic as it is not possible to fully modify the indoor environment through design and building material. Therefore, people take it very naturally to come out of the house and stay outside in a nearby open field, under the shade of a tree, whenever it is uncomfortable inside the house. Even at night, it is completely normal for men and women to sleep in the open premises outside their house, for thermal reasons. In the questionnaire survey, 86% respondents chose to ‘go outside’ as the first option while feeling hot indoors. Other options mentioned were ‘turning on ceiling fans’ and ‘opening or closing of windows and doors’.

4. CONCLUSION

Analysis of the thermal comfort performance of the three different house-types for a low-income community shows that people in the architecturally designed houses (Type-2) were fully comfortable even when the temperature ranges were above the prescribed comfort ranges. The average indoor air temperature in the Type-1 and Type-3 houses was 1°C higher than the Type-2 houses. Consequently, all inhabitants (100%) in the Type-3 houses were found uncomfortable and only, 33.3% people in the Type-1 houses were found comfortable during the survey period. This implies that passive design strategies as implemented through architectural design has an important role to play for ensuring thermal comfort in low-income housing.

The residents, however, have little knowledge about the adverse effects of poor indoor thermal comfort. Therefore, they could neither fully appreciate nor exercise the full potential of the applied passive strategies. For example, use of courtyards in the design was considered to be a waste of space considering the acute space shortage and high number of occupants. Similarly, full natural ventilation potential could not be achieved during nights due to impractical window design and lack of safety features in them. It indicates that future design needs further exploration of practical aspects, usability of spaces and privacy requirements of the occupants in residential spaces to ensure passive design strategies are more effective in practice. If the drawbacks can be overcome, the passive ventilation and cooling strategies can be successfully incorporated into the design of new homes to make them less dependent on artificial cooling.

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REFERENCES


Moisture in Prefabricated Straw Bale Panels
A Post-Construction Case Study of Dwellings at LILAC Cohousing

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ABSTRACT: Concerns over the durability of straw bale walls due to moisture remains a barrier to their wider acceptance, and there is a lack of long-term data on the durability of straw bale walls in the UK climate. Offsite prefabrication provides a method by which straw bale walls can be certified and produced at greater volume. Such panels have been used in the construction of LILAC cohousing in Leeds, UK, which has been occupied since 2013. Using a probe, a series of moisture readings were taken from five prefabricated straw bale panels at two dwellings at LILAC over a six-week period from mid-February until late March 2019. Data from the original moisture monitoring in 2013-14 was also made available. Internally, hygrothermal conditions were monitored in one dwelling to assess the effect of the MVHR system. Software simulations were also carried out to compare with both the 2013-14 data and that gathered on site in 2019. Four of the panels showed average moisture levels comparable or below those expected in UK straw bale walls. Internally, relative humidity was maintained at a level that would not to be considered a problem to the straw within the panels.

KEYWORDS: Straw Bale Construction, Sustainable Materials, Offsite Construction, Balemaster, MVHR

1. INTRODUCTION
The greenhouse gas (GHG) emissions related to buildings amount to 30% of the total emitted globally [1], The construction industry also consumes a vast amount of raw materials [1].

The GHG emissions related to a building occur at different phases throughout its life cycle. Operational energy (OE), also referred to as ‘In-Use’ energy, includes that used during the buildings service life, such as for heating [2,3]. Embodied energy (EE) can include the energy used in the processes of extraction, manufacture and transport of building materials [3]. OE makes up the largest proportion of the energy use of a dwelling over its lifespan, possibly amounting to 80% or more of the total [4]. However, due to improvements in the thermal efficiency of UK buildings, the contribution of OE decreases, and the EE of materials represents an increasing proportion of the total life cycle energy use [5]. The greater use of insulation in buildings means that consideration of the environmental impacts of production and disposal of insulation materials is increasingly relevant [6].

In addition to the need to reduce the GHG emissions related to buildings, the depletion of natural resources requires that the construction industry adopts new methods and technologies with which to build affordable housing [7].

1.1 Straw Bale construction
Straw is an agricultural waste product, and is both renewable and available in vast quantities each year [8,9]. Its thermal properties also mean it is effective insulation, although it has greater variation in this regard compared to synthetic insulation [9] and the greater wall thickness it requires can be a hindrance to its use [8]. It possesses low embodied energy [10], and also sequesters CO₂ as it grows and therefore acts as a carbon store [11].

1.2 Durability and Moisture in Straw Bale Walls
Straw bale walls have been seen to be durable in certain climates, such as in Nebraska where the practice of building with straw bales began [12]. However, there is less long-term data to verify their durability in varied climates where they have only been introduced more recently [12]. Building with straw bale has generally been viewed as a niche practice [8,9] and issues surrounding the durability of straw bale construction is one of the main barriers to its wider acceptance [13]. Research carried out in the UK showed that straw bale construction elicited a low level of confidence amongst potential homeowners, with durability a major concern [14]. The assessment of moisture within straw bale walls is the ‘...fundamental step..’ in assessing their durability [9].

In-situ measurements need to be taken from existing straw bale buildings in order to improve confidence in their long-term durability [15].

It is generally recommended that the MC of straw should not exceed 25% (dry weight) for any significant length of time [16–18] The capillary saturation point of straw is reached at around 37%, at which point
degradation is expected to set in [18]. It has however been seen that such a high MC can be tolerated for short periods of time, and that walls can then recover to acceptable condition [18]. The average MC found in straw bale walls in the UK is 10% internally and 17% externally [17]. A number of factors may influence the MC, including orientation, level of shelter and also internal sources of moisture, such as kitchens and bathrooms [19].

1.3 Prefabricated Straw Bale Panels
The Farmer review recommends that the UK construction industry adopts modern methods of manufacture, or offsite construction [20]. The offsite prefabrication of timber panels filled with straw bale is a system that allows for increased production volume [3], as well as bringing the benefits of offsite construction such as improved build quality and the avoidance of rain during construction [3] as well as certification of products [8]. The construction industry is however noted as having a reluctance towards investment and use of innovative new methods [1,20]

1.4 Aims of the research
The research aimed to assess the durability of the straw bale within prefabricated panels after almost six years post-construction. This involved taking moisture measurements directly from five panels and comparing the results against recommended and typical moisture level data identified from literature.

2. THE CASE STUDY
LiLAC cohousing in Leeds was constructed in 2013 and is comprised of 20 households [21]. The dwellings are a mix of terraced two-storey houses and two blocks of six flats built from ModCell® straw bale panels [22]. LiLAC seeks “...to explore what low-impact, post-carbon values mean in practice” [21] and has been cited as an exemplar of modern sustainable construction [23]. The primary research took place in February and March 2019, approaching six years since the dwellings were occupied.

The panels used in the construction of LiLAC are comprised of 420mm straw bale within a timber frame, then finished with approximately 30mm of lime render applied to both the internal and external faces (see fig.2). These would be expected to have a U-Value of 0.19 W/m²K [ref]. The buildings on site at LiLAC (eg. Fig 1) do not possess the large roof overhangs that have previously been recommended as a standard detail to protect against direct rainfall on straw bale walls [12].

The dwellings at LiLAC achieved levels of airtightness levels between 1.54 and 4.30 m³/h·m⁻² [24] and are all fitted with mechanical ventilation with heat recovery (MVHR) systems [25]. These remove moist air from wet areas and provide fresh air to living areas [26]. In the case of the dwellings at LiLAC, raised RH internally could prove particularly problematic to the straw bale construction [25], and ideally RH should remain below 65% during the heating season [27]. It has been suggested that the use of MVHR results in ‘homogenous hygrothermal conditions’ [28], and frequently results in a mean RH of <60% during the heating season in the UK [28].

3. METHOD
Access was permitted to two dwellings on site. Dwelling A was a two-storey terraced house and dwelling B a ground floor flat. All measurements were taken from panels located at ground floor level. Neither dwelling possessed a west façade, and access to the base of north panels in dwelling B was restricted by kitchen and bathroom fittings. Potential influences on the microclimates for each panel, both internally and externally, were noted (table 1).
Table 1 – Panels selected for monitoring at dwellings A and B

<table>
<thead>
<tr>
<th>Panel</th>
<th>Room Type</th>
<th>Notable external influences</th>
<th>Notable internal influences</th>
</tr>
</thead>
<tbody>
<tr>
<td>A - East</td>
<td>Lounge/Kitchen</td>
<td>Proximity of foliage</td>
<td>Proximity of kitchen</td>
</tr>
<tr>
<td>A - South</td>
<td>Office</td>
<td>Proximity of foliage, Direct solar radiation</td>
<td>-</td>
</tr>
<tr>
<td>A - North</td>
<td>Shower</td>
<td>Absence of direct solar radiation</td>
<td>Humidity due to shower</td>
</tr>
<tr>
<td>B - East</td>
<td>Lounge/Kitchen</td>
<td>-</td>
<td>Proximity of kitchen</td>
</tr>
<tr>
<td>B - South</td>
<td>Lounge/Kitchen</td>
<td>Partial shading due to balcony</td>
<td>Proximity of kitchen</td>
</tr>
</tbody>
</table>

Direct measurements were taken from panels using a Protimeter Balemaster® probe (fig. 3). This measures the MC by means of electrical resistance to within 0.5% [29]. The probe was marked at 50mm increments beginning at 30mm from its tip, in order to allow for the 30mm render layer.

Weather data was collected from a weather station located approximately 4km away at Leeds University. Internal conditions in different rooms were monitored in dwelling A for short spells using combined relative humidity and temperature (RH/T) sensors, which recorded a measurement every 15 minutes. This was intended to identify any differences that may arise due to the internal influences noted in table 1. These sensors were also used to assess the external microclimatic conditions due to orientation and shading, and to verify the use of the weather station data for its applicability to conditions on site. Internally the sensors were placed on a suitable shelf or cupboard at heights between 1470mm and 1970mm. Externally they were placed in small shaded and ventilated plywood boxes.

Post-construction moisture monitoring originally took place at LILAC for 14 months from May 2013 until June 2014 using sensors embedded within the panels. This data was made available for the present research and was used to examine the differences between panels of different orientations. This data was also compared with simulations run using hygrothermal modelling software. The results of these simulations were also compared with the primary data gathered in 2019 using the Balemaster, but the results and analysis from this aspect of the research are beyond the scope of this paper.

4. RESULTS & DISCUSSION

4.1 Internal RH/T Monitoring

Internally, results of the RH/T monitoring at dwelling A indicated a low average RH, with a maximum of 59.2% (see table 3). This was assumed to verify the functioning of the MVHR system. The average RH/T conditions were found to be similar between any two rooms under simultaneous analysis in dwelling A, with RH maintained consistently at a level low enough to prevent growth of mould (<65%) [27].

<table>
<thead>
<tr>
<th>Room</th>
<th>Mean Temp (°C)</th>
<th>Mean RH (%)</th>
<th>High RH (%)</th>
<th>Low RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Officea</td>
<td>18.6c</td>
<td>50.1d</td>
<td>55.5d</td>
<td>43.6d</td>
</tr>
<tr>
<td>North Showera</td>
<td>18.8c</td>
<td>50.0d</td>
<td>59.2d</td>
<td>39.3d</td>
</tr>
<tr>
<td>South Officeb</td>
<td>19.3c</td>
<td>47.1d</td>
<td>52.6d</td>
<td>43.9d</td>
</tr>
<tr>
<td>East Lounge/Kitchenb</td>
<td>19.3c</td>
<td>46.1d</td>
<td>55.4d</td>
<td>41.8d</td>
</tr>
</tbody>
</table>

a 5/3/19 - 17/3/19  b 24/3/19 - 30/3/19  c Sensor accuracy ± 0.5°C  d Sensor accuracy ± 3%

4.2 External RH/T Monitoring

The external monitoring proved useful in verifying the weather data from the Leeds University weather station for its applicability to site. A similar pattern of both RH and temperature could be evident when comparing the data from the two sources. The RH/T
data recorded on site also showed a relationship with solar radiation data from the weather station, with days of prolonged solar radiation bringing about a clear difference between north and south facing microclimates.

### 4.3 Balemaster Results

The data gathered with the Balemaster were compared with the MC and gradient suggested as ‘typical’ for UK straw bale walls [17]. There is no indication of how these ‘typical’ values relate to specific depths of the internal or external faces or to different thicknesses of walls, or orientation. They do however provide a useful basis for comparison and are assumed to represent the points that the straw bale meets the render, at 0mm internally and 420mm externally in the case of the panels. Readings often did not register on the Balemaster at the internal face (0mm), and those taken at 50mm fluctuated and were considered the least reliable.

The average MC results from dwelling A show north and east panels to have an MC similar comparable, although slightly below, that typically found in UK straw bale walls (fig. 4). The south panel shows a noticeably lower MC. This panel was largely sheltered by an adjacent shrub (fig. 5), which may be responsible for influencing this.

<table>
<thead>
<tr>
<th>Dwelling</th>
<th>Panel</th>
<th>Max MC (%)</th>
<th>Min MC (%)</th>
<th>Average MC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>South</td>
<td>12.7</td>
<td>10.9</td>
<td>11.6</td>
</tr>
<tr>
<td>A</td>
<td>East</td>
<td>16.5</td>
<td>14.7</td>
<td>15.4</td>
</tr>
<tr>
<td>A</td>
<td>North</td>
<td>16.1</td>
<td>15.0</td>
<td>15.5</td>
</tr>
<tr>
<td>B</td>
<td>South</td>
<td>25.0</td>
<td>18.8</td>
<td>20.8</td>
</tr>
<tr>
<td>B</td>
<td>East</td>
<td>17.6</td>
<td>14.2</td>
<td>16.0</td>
</tr>
</tbody>
</table>

The average MC results for dwelling B are shown in figure 6. In common with dwelling A, the east panel shows a profile not unlike that considered typical for UK straw bale wall. The south panel in this case shows a profile that mostly lies above the typical profile, with a high MC becoming more noticeable towards the external face of the straw. The reason for this was not identified but seemed to be an isolated issue causing a damp area on the external render at the point where one of the sets of readings was taken. This panel was the only one of the five monitored that was sheltered by a balcony, such as can be seen in figure 1.

The highest average MC reading of 25% was recorded at dwelling B on 26th February, visible as a peak in figure 7. The highest MC readings in each panel were generally found at the outer face, and it can be seen from table 2 that at this depth four of the five monitored panels had an average MC below that considered typical (17%) for UK straw bale walls.
4.2 Moisture Content and Weather Conditions

Over the course of the monitoring, MC readings fluctuated, particularly towards the outer face of panels. The MC data from the panels was analysed alongside the weather data from Leeds University weather station. Figure 7 shows the average MC measurements taken closest to the external face of the straw over the monitoring period, along with the daily rainfall measurements and daily high and low temperatures. It is evident that the MC in all panels follows a similar pattern in response to the conditions, most noticeable following a day of heavy rainfall (21mm) on March 16th. Although not evident on March 17th, an increase in MC is noticeable in panels of all orientations four days after the day of heavy rainfall. The reason for sharp rise in MC early in the monitoring period in the south panel at dwelling B is not clear, and it is not preceded by significant rainfall. An unusually warm and dry week at the end of February brought about a general lowering of MC in all panels. The drop in MC in all panels noticeable between the 20th and 26th March also followed a day with a high daytime temperature. These responses to the weather were generally seen across the full depth of panels, although to a decreasing extent moving towards the internal face.

5. CONCLUSION

The research found that the four of the five panels that were monitored had an average MC similar or below that considered typical in UK straw bale walls. Two east facing panels and one north facing panels were found to have similar moisture profiles to each other, and most similar to that expected in UK straw bale walls.

The lowest MC was found in a south facing panel that was partially shaded by an adjacent shrub. Another south facing panel had a raised MC particularly towards the outer face, although the reason for this was not clear. This panel was sheltered by a balcony. Internal monitoring indicated that all panels were subject to similar hygrothermal conditions internally, and RH was consistently at a level low enough to prevent the growth of mould.

The data and analysis from this research indicate that the straw within prefabricated panels can prove durable after almost six years, even in the absence of roof overhangs to protect them from direct rainfall. The data from internal monitoring also suggests that a functioning MVHR system in a straw bale dwelling built to a high level of airtightness should prove effective in maintaining RH at a safe level for the building fabric.

LIMITATIONS

The research provides insight into the moisture behaviour of the panels over the timeframe of data collection and so only offers a limited indication of moisture behaviour at other times of year. Visual inspection of the straw was not possible to verify its condition.

ACKNOWLEDGEMENTS

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Methodological framework for establishing a global database for outdoor thermal comfort survey: Progress of data acquisition and harmonisation

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ABSTRACT: Studies of subjective thermal comfort have been widely conducted in the urban environment in the last twenty years, covering different socio-economic, cultural and climatic regions. There are inconsistencies among protocols used due to constraints at field sites and the availability of instruments, making it difficult for inter-comparisons between studies and climatic regions, calibrations of thermal indices and a true understanding of people’s thermal perception in outdoor settings. There is a need for standardisation of methodology and guidance for conducting field surveys in outdoor spaces with implications to climate-sensitive urban design, public health measures and adaptation of humans to a changing climate. The paper presents the pilot stage of the research initiative of a global database of outdoor thermal comfort studies. The methodological framework of the research is described and the latest progress is reported in this paper. It compares the various components across the studies included and presents the initial results of the data harmonisation process. It also identifies the inconsistencies of the studies which will be addressed in the next stages. This forms the basis for the broader objectives of the development of the global database of outdoor thermal comfort studies.

KEYWORDS: Outdoor thermal comfort, global database, standardised methodology, data harmonisation

1. INTRODUCTION

The shorter time spent (e.g. in the range of minutes) in the outdoor environment influences the thermal exposure. Höppe (2002) suggested that the steady-state assumption of indoor thermal comfort does not provide realistic assessments for outdoor settings. His previous study based on the Instationary Munich Energy-Balance Model (Höppe, 1989) showed that thermo-physiological parameters such as skin and core temperatures take at least one hour in outdoors to achieve the steady-state level. The complex outdoor environment also creates large variations in thermal conditions that the outdoor space users are exposed to. Lau et al. (2019a) showed that subjective thermal sensation changes considerably when pedestrians commute outdoors and suggested that the environmental conditions exposed have a lag effect on thermal perception of pedestrians. Therefore, the assessment of human thermal comfort in outdoor environment requires a different methodological framework and analytical approach in order to address the distinctive relationship between subjective thermal sensation and environmental conditions experienced by outdoor space users.

Currently there are no standard guidelines for subjective assessment of the outdoor thermal environment, so the use of questions and measurement scales vary across studies. The ASHRAE 7-point scale was commonly used (Krüger and Rossi, 2011; Lau et al., 2019b) while 5-point (Nikolopoulou and Lykoudis, 2006; Metje et al., 2008) and 9-point scales (Kántor et al., 2012) were also used in some studies. Moreover, the personal state of thermal comfort and thermal preference was sometimes included in the thermal assessment (Oliveira and Andrade, 2007; Ng and Cheng, 2012). The inconsistencies in subjective scales and wordings used lead to possible errors in comparison between the results of different studies.

This paper presents the pilot stage of the research initiative of a global database of outdoor thermal comfort studies. The methodological framework of the research is described and the latest progress is reported in this paper. It compares the various components across the studies included and presents the initial results of the data harmonisation process. It also identifies the inconsistencies of the studies which will be addressed in the next stages. This forms the basis for the broader objectives of the development of the global database of outdoor thermal comfort studies.

2. METHODOLOGY

2.1 Study area and data acquisition

In this pilot stage, 11 studies were included in this pilot study with three studies from Europe (Szeged, Warsaw and Athens), two studies from South
America (Guayaquil and Curitiba), two studies from Australia (Melbourne), and three studies from Asia (Hong Kong) (Figure 1). They cover different background climates according to the Köppen-Geiger’s climate classification (Kottek et al., 2006), ranging from Group A (tropical climate), Group B (dry climate), Group C (temperate climate), to Group D (continental climate), so this pilot study provides a variety of physiological acclimatisation and psychological adaptation. A total of 21,254 data entries were obtained. Details of the data sets are listed in Table 1.

Figure 1: Locations of the studies in the pilot stage.

Table 1: Details of the studies included in the pilot stage.

<table>
<thead>
<tr>
<th>Study</th>
<th>Study Area</th>
<th>Climate Zone</th>
<th>Survey Location</th>
<th>Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARMI16</td>
<td>Tempe, US</td>
<td>Bwh</td>
<td>Campus</td>
<td>1284</td>
</tr>
<tr>
<td>ATKO12</td>
<td>Szeged, Hungary</td>
<td>Dfb</td>
<td>Park, square, street</td>
<td>5288; 517</td>
</tr>
<tr>
<td>CHLA17</td>
<td>Melbourne, Australia</td>
<td>Cfb</td>
<td>Park</td>
<td>3293</td>
</tr>
<tr>
<td>ERJO18</td>
<td>Guayaquil, Ecuador</td>
<td>Aw</td>
<td>Arcade, square, park, waterfront</td>
<td>544</td>
</tr>
<tr>
<td>ESYU19</td>
<td>Hong Kong</td>
<td>Cwa</td>
<td>Park</td>
<td>454</td>
</tr>
<tr>
<td>KALI13</td>
<td>Warsaw, Poland</td>
<td>Dfb</td>
<td>Square</td>
<td>818</td>
</tr>
<tr>
<td>KAPA13</td>
<td>Athens, Greece</td>
<td>Csa</td>
<td>Square, street</td>
<td>1706</td>
</tr>
<tr>
<td>SASH16</td>
<td>Melbourne, Australia</td>
<td>Cfb</td>
<td>Campus</td>
<td>1023</td>
</tr>
<tr>
<td>EDNG12</td>
<td>Hong Kong</td>
<td>Cwa</td>
<td>Park, Street, Residential</td>
<td>2674</td>
</tr>
<tr>
<td>KELA18</td>
<td>Hong Kong</td>
<td>Cwa</td>
<td>Park, Street, Residential</td>
<td>1998</td>
</tr>
<tr>
<td>EDKR11</td>
<td>Curitiba, Brazil</td>
<td>Cfb</td>
<td>Street, Square, Crossroads</td>
<td>1655</td>
</tr>
</tbody>
</table>

The study sites of all surveys were public spaces commonly visited, including public squares, pedestrian streets, urban parks, university campuses, and residential districts. Structured questionnaires were administered to study people’s subjective assessment of the thermal comfort conditions while micro-meteorological measurements were simultaneously performed. Questionnaire surveys were conducted in summer for all studies and in winter for six studies, with seven of them covering transitional seasons. In Guayaquil, surveys were conducted in wet and dry seasons due to the insignificant seasonal differences in air temperature.

### 2.2 Field and Survey Data

Field measurements of micro-meteorological conditions included air temperature (Ta; °C), relative humidity (RH; %) and wind speed (v; ms⁻¹) in all studies. Measurements of thermal radiation, in terms of globe temperature (Tg; °C) and/or global solar radiation, were also conducted for the estimation of mean radiant temperature (Tmrt; °C). Sensors were placed close to the respondents with the same exposure to solar radiation and at about 1.1 m above ground surface in most cases, which corresponds to the average height of the centre of gravity of a standing man (Mayer and Höppe 1987).

The software RayMan (Matzarakis et al., 2007) and BioKlima (Blążejczyk, 2011) were used to calculate PET and UTCI, respectively. RayMan is developed for the calculation of short- and long-wave radiation fluxes on the human body. It takes into account the complex geometry of urban structures and can be applied in urban planning and street design. The output of the model includes Tmrt for the assessment of the urban bioclimate by using thermal comfort indices such as PMV, PET, SET*. BioKlima consists of different methods of bioclimatic studies and provides easy calculations of more than 60 various biometeorological and thermophysiological indices. The mandatory inputs of meteorological variables include air temperature, relative humidity, globe temperature, wind speed, metabolic rate and clothing level (thermal insulation). Personal factors such as height and weight can also be included for the calculation of the thermal comfort indices.

Structured questionnaires were conducted to obtain information about subjective assessment of the thermal environment, as well as personal parameters and behaviours, usage of outdoor spaces. Although the overall content of the questionnaires was adjusted to local contexts, this pilot study focuses on the subjective assessment of the thermal environment.

Table 2 describes the thermal assessment scales used in the 11 studies included in this pilot stage. Eight studies adopted the ASHRAE 7-point scale for the respondents to report their thermal sensation vote (TSV). It was originally designed for indoor studies but has been widely used for outdoor studies (Spagnolo and de Dear, 2003; Knez and Thorsson, 2006; Lin et al., 2009; Lau et al., 2018). Previous studies used this scale to correspond to the PET categories particularly developed for Central Europe (Matzarakis and Mayer, 1996; Matzarakis et al., 2009). In three of the studies (ARMI16, ATKO12, and ERJO18), two additional votes (‘very cold’ and ‘very hot’) were used to represent the wider range of thermal sensations.
thermal conditions in the outdoor environment. In particular, the respondents in Szeged were asked to report TSV on a 9-point scale with a 0.1 increment.

### 2.3 Data harmonisation

Subjective thermal perception is often compared to objective micrometeorological measurements in order to understand the subjective-objective relationship of thermal assessment. As different assessment scales (e.g. number of points on the scales) were adopted by previous studies, there is a need to harmonise the datasets obtained from different studies.

**Table 2: Thermal assessment scales used in the 11 studies.**

<table>
<thead>
<tr>
<th>Study</th>
<th>Thermal Sensation</th>
<th>Thermal Comfort</th>
<th>Thermal Pref</th>
<th>Thermal Accept</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARM16</td>
<td>9-point</td>
<td>4-point</td>
<td>7-point</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>(0 to -3)</td>
<td>(-3 to +3)</td>
<td>(-1 to +1)</td>
<td></td>
</tr>
<tr>
<td>ATKO12</td>
<td>9-point</td>
<td>7-point</td>
<td>3-point</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>(-3 to +3)</td>
<td>(-1 to +1)</td>
<td>(-1 to +1)</td>
<td></td>
</tr>
<tr>
<td>CHLA17</td>
<td>7-point</td>
<td>N/A</td>
<td>3-point</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>(-1 to +1)</td>
<td></td>
<td>(-1 to +1)</td>
<td></td>
</tr>
<tr>
<td>ERJO18</td>
<td>9-point</td>
<td>N/A</td>
<td>3-point</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>(-1 to +1)</td>
<td></td>
<td>(-1 to +1)</td>
<td></td>
</tr>
<tr>
<td>ESYU19</td>
<td>9-point</td>
<td>6-point</td>
<td>7-point</td>
<td>6-point</td>
</tr>
<tr>
<td></td>
<td>(-3 to +3)</td>
<td>(-3 to +3)</td>
<td>(-3 to +3)</td>
<td>(-3 to +3)</td>
</tr>
<tr>
<td>KAL13</td>
<td>7-point</td>
<td>N/A</td>
<td>3-point</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>(-1 to +1)</td>
<td></td>
<td>(-1 to +1)</td>
<td></td>
</tr>
<tr>
<td>KAPA13</td>
<td>7-point</td>
<td>5-point</td>
<td>3-point</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>(-2 to +2)</td>
<td>(-1 to +1)</td>
<td>(-1 to +1)</td>
<td></td>
</tr>
<tr>
<td>SASH17</td>
<td>7-point</td>
<td>7-point</td>
<td>3-point</td>
<td>2-point</td>
</tr>
<tr>
<td></td>
<td>(-3 to +3)</td>
<td>(-1 to +1)</td>
<td>(0 or 1)</td>
<td></td>
</tr>
<tr>
<td>EDNG12</td>
<td>7-point</td>
<td>4-point</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>(-2 to +2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KELA18</td>
<td>7-point</td>
<td>4-point</td>
<td>3-point</td>
<td>2-point</td>
</tr>
<tr>
<td></td>
<td>(-2 to +2)</td>
<td>(-1 to +1)</td>
<td>(0 or 1)</td>
<td></td>
</tr>
<tr>
<td>EDKR11</td>
<td>7-point</td>
<td>4-point</td>
<td>7-point</td>
<td>2-point</td>
</tr>
<tr>
<td></td>
<td>(-2 to +2)</td>
<td>(-1 to +1)</td>
<td>(0 or 1)</td>
<td></td>
</tr>
</tbody>
</table>

In this study, the method proposed by Dawes (2002) was adopted to rescale the data obtained by different assessment scales since it produces similar mean and variance values. For instance, the data obtained from 9-point scale were rescaled by applying a rescaling factor to reduce the spread from nine to seven classes. The rescaled data were evaluated against the original data based on the mean, standard deviation, kurtosis and skewness values.

### 3. RESULTS AND DISCUSSION

#### 3.1 Original data vs transformed data

The 9-point scale data from three studies (ARM16, ATKO12, ERJO18) were transformed into 7-point scale. Table 3 shows that the mean and standard deviation was reduced by three-fourth due to the scaling factor applied. Skewness remained unchanged after the transformation for normally distributed (ARM16), positively skewed (ERJO18) and negatively skewed (ATKO12) data. Kurtosis remains the same, indicating that there were no significant outliers and the transformation did not affect the spread of data and outliers.

Figure 2 shows the scatterplot between mean TSV and PET for the original and transformed data. The transformation did not affect the proportion of the variance for the mean TSV explained by the PET (i.e. R²-values). However, the slope was reduced by three-fourth due to the scaling factor. It implies that the overall relationship between subjective thermal sensation and objective thermal indices remained unchanged after transformation but respondents’ interpretation of the questions (i.e. 9-point vs 7-point scales) was unclear, i.e. the perception of extreme values (e.g. +4 in 9-point scale and +3 in 7-point scale) may be different. This requires further field data from the same sampling group to confirm the validity of both scales in the assessment of outdoor thermal environment.

**Table 3: Mean, SD, skewness and kurtosis of the data before and after transformation.**

<table>
<thead>
<tr>
<th>Study</th>
<th>Mean 9-point</th>
<th>Mean 7-point</th>
<th>Standard Deviation 9-point</th>
<th>Standard Deviation 7-point</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARM16</td>
<td>0.32</td>
<td>0.24</td>
<td>1.87</td>
<td>1.40</td>
</tr>
<tr>
<td>ATKO12</td>
<td>0.61</td>
<td>0.46</td>
<td>1.43</td>
<td>1.07</td>
</tr>
<tr>
<td>ERJO18</td>
<td>1.00</td>
<td>0.75</td>
<td>1.28</td>
<td>0.96</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Study</th>
<th>Skewness 9-point</th>
<th>Skewness 7-point</th>
<th>Kurtosis 9-point</th>
<th>Kurtosis 7-point</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARM16</td>
<td>0.07</td>
<td>0.07</td>
<td>2.32</td>
<td>2.33</td>
</tr>
<tr>
<td>ATKO12</td>
<td>-0.42</td>
<td>-0.42</td>
<td>2.73</td>
<td>2.73</td>
</tr>
<tr>
<td>ERJO18</td>
<td>0.57</td>
<td>0.57</td>
<td>2.72</td>
<td>2.72</td>
</tr>
</tbody>
</table>

#### 3.2 Thermal sensation vote vs thermal indices

The relationship between subjective thermal sensation and objective thermal comfort conditions as expressed by the PET index was compared across the studies (Figure 3). TSVs were averaged for each 1°C-PET bin in all studies and the linear relationship was determined for each study. In general, there were strong linear relationships (R² > 0.9) between the mean TSV and PET across the studies due to the large variations in the micro-meteorological conditions except the study in Guayaquil (R² = 0.84).
Six studies had slopes around 0.07-0.08 while three other studies (ESYU19, KAPA13, SASH16) showed nearly doubled slopes up to 0.15. In ESYU19, the respondents were all above 65 years old so it was likely that they were more sensitive to changes in thermal conditions. Moreover, responses in SASH16 were mostly obtained in a university campus that the respondents may have been influenced by indoor conditions. As such, they may also be less tolerant to the warmer outdoors and take certain time to acclimatize. It showed that the sensitivity of subjective responses varies across different climatic regions.

Another thermal index, UTCI, was also compared to the subjective thermal perception (TSV). It was found that most of the slopes of the regression line were higher than those of the TSV-PET relationship (Figure 4). The highest increase (61.6%) of the regression line was found in ERJO18 with a slope of 0.12. Four other studies, including ARM16, ATK12, CHLA17 and EDKR11, were found to have slopes increased by 37.8-44.4%. The slopes of two studies, namely KAPA13 and EDNG12, were slightly increased by 12.0% and 13.3% respectively. SASH16 showed a similar slope to that of the PET. The R^2-values of the regression for these studies were all above 0.9, indicating strong linear relationships between mean TSV and UTCI. In the two studies (KALI13 and KELA19) with only UTCI calculated, the slopes were small than others (0.07 and 0.06 respectively), indicating that the respondents were less sensitive to the changes in thermal conditions.

The values of neutral PET, which were calculated when mean TSV equals to 0 in the regression equations, vary significantly across the studies (Table 4). The highest neutral PET was observed in Tempe, Arizona (29.23°C), followed by Guayaquil (26.82°C) and Melbourne (SASH16; 21.08°C). However, the neutral PET in another study also conducted in Melbourne (CHLA17) was considerably lower (16.92°C). It was likely because CHLA17 conducted the survey in a botanic garden while the survey in SASH16 was conducted in university campus. The neutral PETs of the other studies were generally below 20°C but there were no considerable differences in the neutral PET values. It suggests that this method of determining neutral PET was influenced by not only climatic factors but also local contexts that the respondents were exposed to.

Neutral PETs of the comfort and discomfort groups were listed. Four of the studies showed slight increases in the neutral PET with the largest increase observed in KAPA13 (2.23°C). Two studies (ARM16 and EDNG12) exhibited a decrease in neutral PET (2.16°C and 0.55°C respectively). There is no
comparison between the comfort and discomfort groups in ESYU19 since the relationship between mean TSV and PET is not significant for the discomfort group. Complex responses in perceived comfort to subjective thermal sensation suggested that there is a need for a standard scale for affective evaluation of thermal comfort in outdoor studies.

Table 5: Regression equations for the comfort and discomfort groups.

<table>
<thead>
<tr>
<th>Study</th>
<th>Comfort Group</th>
<th>Discomfort Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMRI16</td>
<td>(y = 0.0508x - 1.5287; R^2 = 0.83)</td>
<td>(y = 0.0912x - 2.5477; R^2 = 0.86)</td>
</tr>
<tr>
<td>ATKO12</td>
<td>(y = 0.0738x - 1.3948; R^2 = 0.92)</td>
<td>(y = 0.1251x - 2.4977; R^2 = 0.95)</td>
</tr>
<tr>
<td>ESYU19</td>
<td>(y = 0.0918x - 1.9092; R^2 = 0.83)</td>
<td>Not significant</td>
</tr>
<tr>
<td>KAPA13</td>
<td>(y = 0.1016x - 1.8807; R^2 = 0.95)</td>
<td>(y = 0.1554x - 3.2231; R^2 = 0.99)</td>
</tr>
<tr>
<td>SASH16</td>
<td>(y = 0.1605x - 3.2171; R^2 = 0.96)</td>
<td>(y = 0.2395x - 5.0978; R^2 = 0.93)</td>
</tr>
<tr>
<td>EDNG12</td>
<td>(y = 0.0552x - 1.0738; R^2 = 0.92)</td>
<td>(y = 0.1049x - 1.9826; R^2 = 0.89)</td>
</tr>
<tr>
<td>EDKR11</td>
<td>(y = 0.0531x - 1.0075; R^2 = 0.86)</td>
<td>(y = 0.1211x - 2.4129; R^2 = 0.96)</td>
</tr>
</tbody>
</table>

### 3.4 Inconsistencies between studies

There are large variations in the elements of the questionnaire surveys across the studies included in this pilot stage. Only two studies were conducted in all seasons while two studies were carried out in summer, autumn and winter. They cover a relatively wide range of air temperature and thermal conditions to present a comprehensive understanding of how subjective thermal sensation and objective meteorological conditions. Five studies did not cover winter season and it requires further information for the design of outdoor spaces for the use in different seasons.

Personal factors are also important to the determination of thermal comfort conditions. There are only two studies asking the respondents for their height and weight, which are required for the calculation of PET. As such, most of the studies used default values and this may affect the accuracy of the thermal indices. Different definitions of age groups were adopted in the studies while only two studies asked the exact age of the respondents. It is therefore necessary to define certain major age groups in order to facilitate the comparison between studies of different climatic conditions and urban contexts.

The immediate thermal history of the respondents was asked in most of the studies included in the present study. However, there are no standard answers or options for the responses. It is generally classified based on the presence in outdoor or indoor environment, i.e. whether shaded or sunlit for outdoor, or non-air-conditioned or air-conditioned for indoor environment. One study accepted free answers which can be categorised into indoor and outdoor environment without specifically detailed the conditions such as air-conditioning and shading that the respondents were exposed to.

### 4. WAY FORWARD

The primary objective of developing the global database for outdoor thermal comfort survey is to provide the empirical basis for establishing outdoor thermal comfort models by understanding the influential elements of human thermal comfort in the outdoor environment. However, the content of the database has a large potential beyond this due to the large amount of high-quality field data that can be used to explore the issues regarding human thermal comfort in the outdoor environment. The followings are some examples of potential applications of this global database.

The database provides numerous possibilities for developing empirical relationships between different assessment scales of subjective thermal perception. Human thermal comfort research has been using a wide range of subjective assessment scales, for example, the seven-point ASHRAE thermal sensation scale, thermal acceptability and preference assessment. The database therefore provides a platform for evaluating the assumptions behind different assessments and the applicability in outdoor settings.

The contextual effects were studied in some previous work but there have been no comprehensive understandings of how these effects influence subjective thermal perception in different climates. Therefore, there are opportunities for researchers to investigate the characteristics of the outdoor environment and their relationship with human thermal comfort of pedestrians and users of outdoor spaces. Urban planning and design professionals can be informed with the findings and they can enhance the design of outdoor spaces in order to encourage their usage, which in turn has implications on human health and well-being, as well as energy consumption of buildings.

Since the data provided by researchers have been previously published in peer-reviewed academic journals and undergone the process of quality check, they are reliable and ready to use for scientific and design work. The database also allows professional practitioners to extract relevant information for their design. For example, design professionals can acquire the understanding of thermal comfort requirements for specific urban contexts and climatic regions without conducting the field work themselves.

The long-term goal of the database is to establish a standard methodology for conducting outdoor thermal comfort research. The draft version of the standard methodology provided in the later stages of the development of the database allows robust testing of the methodology. It also facilitates...
comparison of results between different climatic regions and urban settings in order to enhance the understanding of outdoor thermal comfort. This potentially contributes to the discussion of the difference between indoor and outdoor studies, which has been widely discussed in the last two decades.

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Sustainable Communities and energy poverty
The role of building performance to ensure affordable comfort conditions

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ABSTRACT: Huge efforts have been spent during the last decade to strongly reduce energy demand in the building sector. However, the related implications due to Climate Change issue represents a very relevant challenge not only in terms of emission trends and environmental impacts but also of quality of life in the built environment (and not only). The attention given to the topic in the last years opened the discussion to a broader vision including the possible social impacts according to the possible future scenarios. Within this general context, the development of sustainable communities - assumed as communities able to act for lowering their impacts on climate, energy demand and related issues - is to be considered a priority. Despite the number of actions promoted to foster the process, a very critical phenomenon called energy poverty - typically connected with very poor people in developing countries - still involves a limited, but relevant, number of low-income people in developed countries cities living in an energy poverty status. This paper reports a study on the role of buildings and cities quality in influencing the energy poverty condition while, possibly, addressing solutions to support sustainable communities development able to effectively contrast this phenomenon.

KEYWORDS: Energy poverty, quality of life, energy efficiency, comfort, urban transition.

1. INTRODUCTION

The evidences reported by the IPCC estimations [1] on the increase of global temperature of 1.5°C have been considered a serious warning within the scientific community and more recently the global debate about the impacts of Climate Change, generated by “Greta Thumberg speech” at the United Nation [2] and the related Friday for future strike for climate of 27th September 2019 [3] confirmed the media and the general attention on this topic.

The very recent events projected the Climate Change issue in a wider arena which is no more simply the field for experts dealing with Sustainable Communities, urban climate, policies and future city vision but a global concern about the social impacts according to the possible future scenarios.

Within this general context, the development of sustainable communities - assumed as communities able to act for lowering their impacts on climate, energy demand and related issues - is to be considered a priority from the very small scale of a village to the largest one of the so called megalopolis. IPCC 2018 report [1] highlights the connections between the effects of climate change and the food scarcity, migratory phenomena and also conflicts in developing countries.

However, an already existing related effect is still increasing in relevance and urgency in the developed countries: the so called energy poverty. This phenomenon - clearly connected with very poor people with no access to energy and any other kind of services in developing countries - involves a limited, but relevant, number of low-income people in developed countries cities living in an energy poverty status: in other words, without the money needed to pay the energy bills and therefore living in unsuitable and unhealthy conditions.

The paper reports a study on the role of buildings and cities quality in influencing the energy poverty condition while, possibly, addressing solutions to support sustainable communities development able to effectively contrast this phenomenon.

A possible solution lies in looking at the energy issue at community level instead simply focusing at building level, thus connecting the quality of the built environment with the behaviour of end users intended as a community of people sharing similar needs, expectations, lifestyles. The energy issue is typically addressed working at the building scale looking at effective solutions to strongly reduce dispersions and improve the production capacity from Renewable Energy Sources (RES), however this largely depends on the stock quality and construction characteristics as well as on the inhabitants commitment (and interest) in investing money to meet the required updates. An innovative approach has been recently explored with the purpose to develop the so called Energy Communities dealing with RES generation from solution totally or partially owned by local communities. The Energy Communities definition is quite open and flexible including a number of different administrative and juridical models – that depend on...
the local context – where many different actors, such as citizens, local enterprises, charities and public institutions, may be involved. It must be said that the idea itself is not completely new being this Tvindkraft model applied to a wind turbine collectively built from hundred people in 1978 in Ulfborg, Denmark. After this pioneering experience, energy communities largely grew in Denmark, UK and Germany where in 2012 the 34% of renewable energy production was owned by energy communities.

That said, Energy Poverty is a very complex issue and the estimation of its diffusion and impacts on everyday life in EU citizens is certainly a hard job [4]. According to a rough estimation one citizen over ten is affected by energy poverty. Data provided by the Energy Poverty Observatory clearly evidence that:
- 57 million people are not in the condition to heat their houses during winter;
- 104 million people are not in the condition to make their houses comfortable enough during summer;
- 57 million people pay their energy bills after the deadline.

Considering this issue a relevant emergency and a priority within the “Clean Energy” access for European citizens regulation framework, the European Commission created the Energy Poverty Observatory in 2018 with the purpose to monitor the trends in the EU countries and share knowledge, experiences and viable solution in order to mitigate and manage the energy poverty issue while remarkably increasing the awareness level among relevant institutions.

Energy Poverty definition has been introduced for the first time in 2009 within the Third Energy Package (Directive 2009/72/EC; Directive 2009/73/EC): “Member States shall take appropriate measures to protect final customers, and shall, in particular, ensure that there are adequate safeguards to protect vulnerable customers. In this context, each Member State shall define the concept of vulnerable customers which may refer to energy poverty and, inter alia, to the prohibition of disconnection of electricity (gas) to such customers in critical times”. The Clean Energy Package approved on May 22nd 2019 [5] explicitly refers to the “customer vulnerability” and to the “poverty” concept. The related measures deal with energy bill support and social tariffs as well as with technical solutions such as building envelope insulation, the replacement of heating systems, the adoption of RES, the energy audit targeting.

The EU Vulnerable Consumer Working Group (VCGW) points out four main possible drivers of Energy Poverty:
- The structure of the energy market (final energy prices – and consequently indirectly the concurrency level – market regulation models, taxation levels and system costs)
- The structure and characteristics of the families (income level, health conditions, age, education level, access to technologies, etc.)
- Housing conditions (age of the building, house typology, maintenance level and energy efficiency, technological system conditions)
- Context conditions (environmental, social and cultural conditions, economy trends at country level, geographical location).

2. ENERGY POVERTY

The scientific literature provides several definitions of energy or fuel poverty which can be briefly summarised as the condition that “occurs when households have insufficient funds to pay for the most basic levels of energy needed to provide them with heating, lighting, cooking, and appliance use” [6-7] as reported by Victoria Pellicier [8]. The relation between building energy consumption, population and income is the focus of several political choices and studies as already evidenced in previous studies by Fabbri K [9] and Besani & Bogarelli [10, 11] about Italy. Other researches regard the effect of energy poverty [12] on health and policy implication [13 - 15]. Among the elements affecting the energy poverty within the urban context the energy infrastructure and the energy price - including the rate of penetration of the liberalisation in the energy markets - represent one of the first factor to be considered. The social distribution with relation to the quality of the urban fabric, is another relevant issue which can drive to segregation phenomena, degradation, marginalization and which can strongly influence the real estate value, consequently impacting on the maintenance capacity of both buildings and outdoor spaces. The use of these spaces is another key aspect dealing with cultural, climatic and local factors.

2.1 Building role

Most of the people, included the low-income ones, spend a huge part of their time inside buildings and particularly the quality of residential buildings represents a very relevant factor in contributing (or not) in the Energy Poverty condition. Renovation actions aimed to meet energy efficiency targets are particularly necessary to reduce energy poverty in those places where adverse environmental conditions last for almost the time on a yearly basis (northern European regions, Alpine regions, etc.), however much more can be done in the direction of energy savings in many other areas. During the last decade a number of different solutions were introduced to improve energy efficiency in a wide range of situations. The most frequently adopted measures in the housing sector can be listed as follows:

a. the introduction of dedicated regulations with specific standards (i. e. for insulation and glazings) in new buildings;

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b. the introduction of subsides dedicated to energy improvement interventions (often higher for low income people with the extra budget assumed as a collective social cost);

c. the introduction of new models where more efficient heating systems are ensured by the service providers and the costs are paid by the consumers during the time within their energy bills (Energy Performance Contractor (EPC) or Energy Services Company (ESCO));

d. the introduction of specific actions for households to reduce the required investment for energy improvements (eco-bonus) or to qualify the investment done (energy labelling).

2.2 Building energy performance and energy poverty

The building energy performance (EP index) – that derives from the combination of factors such as the building construction characteristics, the heating/cooling systems, the quality of the glazings, etc. – strongly influences energy bills and consequently the occupants can only reduce costs reducing the number of hours the heating system is switched on or renouncing to have a cooling system for the summer period.

It is therefore very relevant to understand the potential Energy Poverty risk. The study focuses on identifying a risk threshold, the so called Building Energy Poverty Index (BEP) [16] defined as:

$$B_{EP} = 1 - \left( \frac{l_{av}}{l_{av}+I_{EP}} \right) \% \quad (1)$$

where

- $B_{EP}$ is the Building Energy Poverty Index (%)
- $l_{av}$ is average Income, according to national statistics institutes
- $I_{EP}$ is the Income from Energy Poverty (€/year) evaluated according following formula (2)

$$I_{EP} = \frac{B_{EC}}{t_{EP}} \quad (2)$$

where

- $B_{EC}$ is the annual building energy cost (€/year), which includes the cost of heating, electricity, etc.;
- $t_{EP}$ is the energy poverty threshold, determined in accordance with the choices and the policies adopted to tackle energy poverty.

The annual building energy cost is:

$$B_{EC} = EP_{index} \cdot C \quad (3)$$

where

- $EP_{index}$ is the energy need, in kWh/m²/year
- $C$ is the Energy cost (tariff) in €/kWh

The Above formulas allow to correlate building energy performance with energy cost and geometry in order to define a building energy vulnerability, based on average income and energy poverty income values.

Figure 1a reports the relation between $B_{EP}$ and the usable area (UA in m²) with an energy poverty threshold of 10% and a $l_{av} = 20,000€$. It can be noted that with a $EP = 140$ kWh/m²/year a house with UA = 100 m² presents a higher risk of energy poverty; thus (figure 1b) in order to obtain a $B_{EP} = 20\%$, $EP$ must range between 50 kWh/m²/year and 120 kWh/m²/year.

In other words, figure 1 allows to define building energy vulnerability, based on geometry and apartment floor area. In case of small apartments energy performance has a minor role compared to wider apartments (i.e. 100m²) where building energy poverty risk is 40%. So, if policy-makers want to concretely tackle energy poverty larger dwellings are to be preferably targeted. In this case EP index should be under 50 kWh/m²/year.

![Figure 1a,b: Building Energy Poverty Index and usable area (UA in m²)](image)

Figure 2 reports the relation between $B_{EP}$ and Energy cost (€/kWh). It can be noted (figure 2a) that when $EP = 140$ kWh/m²/year, $B_{EP}$ ranges between 30 % and 45%; thus in order to ensure (figure 2b) $B_{EP} = 20\%$, $EP$ must range between 45 kWh/m²/year and 80 kWh/m²/year. This second example (figure 2) allows to correlate energy cost, expressed in €/kWh of primary energy, and building energy poverty risk; e.g. with energy cost equal to 0.12 €/kWh, correlated energy vulnerability is equal to 40%, that corresponds to a high risk of energy poverty in case of very low income tenants. Vice versa if energy cost is less than 0.07 €/kWh building energy poverty risk is equal to 20%. So in case of energy cost 0.12 €/kWh building energy performance must be less than 50 kWh/m²/year, while if energy cost is less of 0.12 it is enough a $EP$ equal to 80 kWh/m²/year. Above graphics should be used to support policy decision maker in order to define priority action in policy to reduce energy poverty.
The annual unit consumption per m² for residential buildings of the existing stock across EU can be assumed around 200 kWh/m² (with relevant variations country by country due to climatic reasons), the main objective of the majority of renovation and retrofitting actions is to strongly reduce the total amount of energy demand bridging the gap with the standards fixed for new constructions that still account for a low percentage of the built environment. However, this aim can be translated into very different design options that drive the renovation intensity and the related investment required despite the target is the same: to bring the building EP under the estimated energy poverty threshold (BEP < 20%).

2.3 Buildings technologies

The recurrent reaction to low quality in the building stock is to foster renovation or retrofitting actions to improve the energy behaviour.

The age and typology of the building under renovation may of course influence the design approach and the related objectives: on the one hand, it is quite clear that a relevant saving potential can be achieved by renovating older buildings assuming they are affected by a wider gap in terms of compliance to current standards and requirements, on the other one these buildings often own some cultural, symbolic, social values that may influence the priorities and shift from the energy issue to other possible deficits the perspective a renovation action is considered [17]. The objectives and drivers of renovation initiatives concerns:

- building envelope improvements;
- equipments and energy system updating
- expected effects and renovation trends

However, when a building enters in a renovation process a limited number of critical factors (replacement of windows, poor insulation of walls, etc.) typically influencing the thermal and energy building behaviour are considered at the same time. This often depends on budget constraints or on the very conventional approach adopted at the design stage (which not frequently envisages improvements within a timeline).

Building performance depends on the original constructions system and may vary according to technological choices and construction period. Therefore, the starting configuration of the existing building strongly influence all the parameters related to indoor and outdoor climatic conditions and accurate evaluations have to be performed at design stage to carefully consider some key factors such as the orientation of the building, insulating conditions, wind direction and ventilation as well as other specific environmental features.

3. APPROACHES TO RENOVATION

In order to increase the attention towards the thermo-economic implications and the energy poverty risk, this paper provides a synthetic overview of a methodological approach aimed at considering the main relevant variable supporting designers and decision makers to explore viable and effective solutions. A case study application is also provided as a concrete example of the defined methodology based on progressive renovation scenarios.

When the building envelope is conventionally designed and the construction quality is quite low, negatively contributing to the energy performance level, the overall building behaviour becomes highly dependent on services and installations (especially for heating) requiring more energy (and money to pay the related bills) for operating. The observed reaction of low income households is usually to progressively reduce consumption related to electricity, cooling, sanitary hot water, and finally heating falling into very unsuitable and unhealthy living conditions.

Thus, when the budget for renovation is limited, strategic decisions on how to invest the money for improving the building EP are required.

3.1 Progressive renovation scenarios (envelope)

The major trend in building renovation is to provide a more efficient building envelope, insulating the existing façades and correcting – where this is possible – the thermal bridges and other critical elements in terms of thermal dispersion. However, this approach may vary according to the features of the building, the original construction system and the façade configuration. The main difference deals with the positioning of the insulation layer that can be located on the inner or the outer side of the walls. The first
case occurs when preserving the original façade is mandatory or a collective consensus on the decision to work on the entire surface is not achieved. Consequently, each household proceeds autonomously in any single flat producing limited effects on the building as a whole. The second is usually aimed to maximize the potential positive impacts but it requires an overall agreement among the tenants and it is generally more expensive. Furthermore, the first solution can be obtained without the use of external structures accepting to reduce a bit the inner net surface. The second requires instead a scaffolding and a more expensive site preparation, but strongly reduces the disruption for the end users. In both cases, many design variations can be defined: from the addition of a very simple insulation layer to a more complex envelope over-cladding, according to the targeted energy performance level, the budget constraints and the building starting conditions (Ferrari, 2016).

The proposed methodology can be divided into four main phases:
- Phase 1 dealing with diagnostic activities, data collection and systematization;
- Phase 2 dealing with modelling activities and simulation of possible solutions according to pre-defined performance thresholds;
- Phase 3 dealing with scenarios creation and possible outcomes and impact evaluation;
- Phase 4 dealing with results visualization for supporting the proper communication to the main players, actors and decision makers involved in the process [10].

Each phase requires several steps useful to set a coherent and organic process with a cyclic assessment for ensuring the design strategy can be checked, re-addressed or refined at any time.

3.2 Case study application

In order to make the understanding of the methodology easier and the different phases clear a case study application is provided. The selected case study is a medium size social housing complex located in Ravenna, a small city near the Adriatic coast in Emilia Romagna Region, where the Public Administration and the Housing Association proposed a study to evaluate the renovation intensity of the residential stock to explore the feasibility of a retrofitting initiative. The project was developed in cooperation with these institutions which provided most of the necessary background and context information as well as the contacts to meet and engage the residents in the preliminary analyses and survey. The buildings to be renovated belong to a wider neighbourhood, dating back to the 1970s, built following a quite conventional construction technique based on bearing concrete walls, 15 cm thick, supporting concrete slabs to create modular boxes of different size and depth (tunnel system). The façades were completed using pre-casted lightweight concrete panels (25 cm thick). The seven storey buildings are not insulated and are affected by diffused obsolescence phenomena dealing both with services and equipments as well as with the quality of the building envelope. Furthermore, some of the buildings suffer of an unfavourable orientation that compromises natural lighting conditions. Also the size of the units is often no more compliant with the current market demand. After performing all the diagnostic steps and preliminary analysis, a general framework of the deficits was obtained and the general energy performance was estimated in approximately 200 kWh/m² year. 24% of dispersions depends on the external walls, 49% on the windows, 16% on the roof and the residual 11% on the ground floor and the staircase.

Once Phase 1 was completed, a number of possible technological options were considered to develop the renovation project and, considering the huge amount of dispersion affecting the building envelope, some different combinations were explored to renovate and insulate the façades. When a couple of more convincing solutions were developed the deriving scenarios have been evaluated using the software Termolog EpiX7 [18] and the achievable performances compared with the starting conditions.

As figure 03 summarizes, three scenarios were considered and compared:
- the first one, the “low intensity” renovation scenario completely replaces the windows, adds an insulation layer over-cladding the existing façades, adopts a new boiler and distribution for the heating system in order to obtain an overall energy performance of 63 kWh/m² year;
- the second one, the “high intensity” renovation scenario replaces the entire external pre-casted wall with a new highly insulated one to which a shading system to control solar radiation is also added. The new boiler and distribution for the heating system is combined with thermal and photovoltaic panels to feed heat pumps and fan coils achieving an overall energy performance of 23 kWh/m² year;
- the third one, the optimized scenario, combined the two strategies to reduce a bit the costs maintaining the new service system and limiting the façade replacement where strictly needed and over-cladding the residual parts. The overall achievable energy performance is 36 kWh/m² year.
Quite similar results were obtained by another alternative project, following the same methodological approach, in the same housing complex where a massive over-cladding was used to completely re-design the building elevations and increase the energy performance to 22 kWh/m² year with a saving of more than 47 k€ per year.

Comparing the payback time of interventions, it is possible to point out that the first one is not suitable while the other two are almost aligned despite the optimized one is a bit less expensive while preserving most of the benefits. Both the options meet the B_EP threshold and can be therefore considered viable solutions to reduce the energy poverty risk in the specific context.

4. CONCLUSION

This paper offers a dedicated perspective considering energy poverty risk in renovation strategies. It particularly focuses on evidencing the role owned by the building envelope in contributing or avoiding this risk depending on the construction characteristics and the related contribute to the overall building Energy Performance. The proposed approach does not require huge additional efforts for delivering a renovation, but simply addresses the design stage of the process, it can be considered a useful way to guide designers, stakeholders and decision makers in achieving more effective measures to cope with energy poverty and ensure affordable living conditions for low-income people within sustainable communities. Considering the United Nations Sustainable Development Goals (SDGs) framework, the eradication of (energy) poverty and the access to primary services and quality of life certainly represent a major challenge for the near future.

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ABSTRACT: This paper shows part of the international research experience of developing a software prototype for energy simulation at neighbourhood/urban scale, called URBAN-4S (Sustainable and Suitable Social Scale), a revision and adapted to Latin American context of the original Spanish URSUS, created originally by professor José Antonio Turégano’s team from the Energy and Buildings Group of the University of Zaragoza. This first challenge of this new version was to redevelop a free software that would assist the design of neighbourhoods under sustainability criteria adapted to the Latin American urban context. In order to re-elaborate this digital tool, summarized models of thermal calculus were developed, in terms to optimize the time calculation and to obtain results quickly at the sketch and drafts stages. In addition, also a new structure for simple urban sustainability indicators and energy at scale of neighbourhood were generated, with the possibilities to characterize a complete urban area. Neighbourhood scale was prioritized as an innovative approach for an energy simulation software. Consequently URBAN-4S represents a new tool for design and evaluation of urban areas, both for designers, local authorities and developers, that can evaluate from the first design stages, the optimal solutions for new development or reform of an existing urban area from the double point from an energy and environmental point of view.

KEYWORDS: Sustainability, Neighbourhood scale, Free Software, Energy Simulation, Design assistance, Urban Indicators.

1. INTRODUCTION
The Millennium Development Goals, agreed targets by United Nations, specifically Objective No. 7, which seeks to ensure environmental sustainability, establish priority guidelines for cities to be on focal point in the current global scenarios, given their significant role as important impacts on ecosystems, use of resources and waste.

In developed countries, discussions are set on issues like patterns consumption and global resources access, while developing countries are still focused on urban and spatial structures efficiency, economic growth, inequity reduction, and poverty overcoming [1]. It is very important to combine series of design criteria and adapt benchmarks towards these goals. Assessment and adaptation at the local level of the broad concept of urban sustainability is an urgent challenge today [2]. The trends that our cities will follow in the coming years and the typologies of growth and implantation, with which they will develop and transform our neighbourhoods, will be decisive to face the challenge of urban sustainability in the future.

We understand that still there is much more needs to be done in terms of designing our neighbourhoods, improving energy efficiency, and also giving better quality to the housing developments, with distributions and densities that could create complexity and diversity [3]. It should be mentioned that both urbanization projects carried out for the traditional real estate market as well as with public contributions and subsidies, at any stage of the design, are actually in Chile considering issues of evaluation of the quality of the whole project [4].

2. OBJECTIVES
The main objective was to develop a software that would assist the design of neighbourhoods under sustainability criteria adapted to the regional and Chilean context. In order to elaborate this digital tool, summarized models of thermal calculus were developed, in terms to optimize the time and to obtain results quickly at the sketch and drafts stages. In addition, a new structure of indicators for urban sustainability and energy at scale of neighbourhood were generated, with the possibilities to characterize a complete urban area [5].

3. ABOUT THE SOFTWARE
Software, still in prototype stage, is called URBAN-4S, meaning “Sustainable and Suitable Social Scale”. The software intends to explore and assist for an
optimal neighbourhood design, focusing on combine the most adequate and convenient solutions, keeping in mind the relevance of framing sustainability in its intermediate scale between building and neighbourhood[6,7]. This step involves work and calculation resources for improving our indexes precision and adjustable scales depending on contexts, together with the goals we intend to achieve in our future urban environments. Our ambitious goal to become a reference tool for neighbourhood scale designs involves covering different approaches that complement final energy and sustainability vision, getting fed from planning and other disciplines involving urban context.

3.1 Already accomplished goals

Along our first stage, already developed, URBAN-4S Project achieved the different objectives as far as software features are concerned. Which are already working in our first free software prototype:

- Creation and launching of our software tool, validated by international experts (what was mandatory for CONICYT[8]) for calculating a whole urban planning energy demands and different sustainability indexes based on urban regulation accomplishment[9], international references and experiences [10,11], climate conditions and specific Chilean urban legal requirements and housings conditions. In order to achieve that, the program includes tools for modelling streets, plots or ground lots, buildings, etc.(Figure 01).

- Advances over traditional static models and incorporation of neighbourhood level with a semi-dynamic methodology that includes state-of-the-art solar radiation models and modifications in their calculations for anisotropic diffuse radiation or sky view factors. This aspects surpass currently used tools precision, while they allow quick calculations with any user’s home or professional computer.

- Initial version for normative accomplishment:
  - Local regulations (housing density, heights, distances, etc.). [12]
  - National energy efficiency regulations[13].
  - Normalized streets and sizes according to Chilean normative.

- Automatic calculations for distance to relevant public services like hospitals, sports zones, trash cans, public transport stops, leisure zones, parks, and several other conditions,[14-18].

- Climate data insertion system adapted to Chilean climates and databases[19,20].

3.2 Calculations

The energy calculation are, with the sustainability indicators, the software core of URBAN-4S, and its original purpose in the versions. The calculation method arises from the experience accumulated by the Energy and Building Group of the University of Zaragoza led by Doctor José Antonio Turégano and is reflected in the doctoral thesis of Hernández [21], which is the basis of the program calculation engine. In the thesis itself the role of the inertia of the building is analysed, which must be discussed in some detail. Figure 1 shows a layout of how energy calculations are working:

The program’s input data is shown in grey, while the magnitudes in blue are calculations made by Urban-4S. Finally, the insolation of the location is shown in yellow since it is not a required value but optional in case properly irradiation data is not available. Obviously there is no influence of elements such as vials, streets materials or plots on energy demands but all these data are considered for sustainability indicators calculation. Once the necessary inputs for the program have been entered, the option of carrying out energy calculations can be activated, which obviously also take place independently from sustainability indicators of the urbanization.

The process of the previous figure is carried out for each of the buildings under study and consists of the following main steps:
Processes and models of solar radiation calculations.
- Assessing of shadowing between the different elements.
- Calculation of incident radiation on each enclosure.
- Evaluation of effective solar gains.
- Evaluation of other (internal) gains in the building.
- Calculation of losses for each enclosure.
- Carrying out the energy balance and obtaining the energy demands.

The starting point of the calculations regarding solar irradiation is the set of data required from the user, which consists of monthly average data of daily global irradiation on the horizontal plane. However, the purpose of the program requires the availability of discretized data at least hourly and with which both the solar position (height and azimuth) and the value of solar irradiation on different planes are available at those times. Urban-4S performs these calculations every 15 minutes. To do this, the method of Gopinathan [22], contrasted with other models in Miguel Ángel Hernández’s doctoral thesis “Model for evaluating energy demand in urban planning” and which turns out to be the best evaluated in comparative terms with other several models of solar irradiation. This model also uses expressions from Collares-Pereira [23]. As a summary, a calculation of the global radiation for overcast sky according to Dogniaux et al [24], which is based on:

\[
H_{GHH}/H_{GHOH} = 0.37022 + (0.00506 \times \sigma - 0.00313) \times L + 0.32029 \times \sigma
\]  

(1)

where:
- \(H_{GHH}\) - is the Average daily global radiation monthly over horizontal for overcast sky (Wh/m²day).
- \(H_{GHOH}\) - is the Average daily extraterrestrial global irradiation over horizontal plane(Wh/m²day) for every monthly representative day.
- \(L\) - is the project location Latitude in Urban-4S in degrees.
- \(\sigma\) - is the insolation factor de insolación, Iqbal [25].

After that is already possible to calculate the global daily average monthly irradiation over horizontal, Collares-Pereira, [23]:

\[
H_{GHH}/H_{GH} = \pi/24 \times (a+b \times \cos\omega) \times (\cos\omega-\cos\omega_s)/(\sin\omega_s- (2 \times \pi \times \omega_s \times \cos\omega_s)/360)
\]  

(2)

Where:
- \(H_{GHH}\) - is global hourly irradiation for overcast sky
- \(H_{GH}\) - is the monthly average daily global irradiation over horizontal for overcast sky.
- \(\omega_s\) - is the estimated hour angle for sunrise (in degrees).
- \(\omega\) - is the hour angle for the analyzed hour (in degrees).

The values of \(a\) and \(b\) are obtained according to:
- \(a = 0.409 + 0.5016 \sin(\omega - 60)\)
- \(b = 0.6609 - 0.4767 \sin(\omega - 60)\)

The next step is the decomposition of the global irradiation into the direct and diffuse components. According to Gopinathan [21], two models can be used, the one that contains both radiation and insolation data being more precise. In the case of Urban-4S, the model that contains the radiation data is used solely for the user’s convenience. This model is:

\[
H_{DHH}/H_{GH} = 0.91138 - 0.96225 \times K_t
\]  

(3)

where:
- \(K_t\) - is a cloud index previously calculated based on the information entered, whose value is \(H_{GHH}/H_{GHOH}\) (ratio between global monthly average daily radiation over horizontal plane, and extraterrestrial global monthly average daily radiation).

\(H_{DHH}\) - is the monthly average daily diffuse radiation for overcast sky.

For the hourly calculation of this diffuse radiation, the following expression is used according to Collarés-Pereira [23]:

\[
H_{DHH}/H_{D} = \pi/24 \times (a+b \times \cos\omega) \times (\cos\omega-\cos\omega_s)/(\sin\omega_s- (2 \times \pi \times \omega_s \times \cos\omega_s)/360)
\]  

(4)

In this case, the hourly diffuse radiation for the overcast sky is obtained directly, the hourly direct radiation being the difference between the value of the global and diffuse radiation for each moment analyzed.

In the case of inclined surfaces, it is first necessary to calculate the angle of incidence value, whose value is according to Markus et al[26]:

\[
\cos(i)=\cos(h)\times\cos(\gamma)\times\sin(s)+\sin(h)\times\cos(s)
\]  

(5)

Where:
- \(i\) - is the angle of incidence sought.
- \(H\) - is the solar height
- \(\gamma\) - is the angle between the azimuth and the projection of the normal of the inclined surface on the horizontal.
- \(S\) - is the inclination of the surface on the horizontal.

Sun position values (as height and azimuth) are calculated in Urban-4S according to the widely accepted model of Iqbal M. [25]. Finally, the hourly direct radiation on an inclined surface is:

\[
D_h= H_{DH} \times (\cos(i))/(\sin(h))
\]  

(6)

Where:
- \(i\) - is the angle of incidence sought.
- \(H\) - is the solar height
\( \gamma \) - is the angle between the azimuth and the projection of the normal of the inclined surface on the horizontal.

\( S \) - is the inclination of the surface on the horizontal.

Finally, global irradiation for a sloped surface is calculated like:

\[ H_{Gh} = H_{Dh} + H_{dh}, \quad (6) \]

In case that the surface or dot to study is shadowed in the calculation moment, \( H_{Dh} = 0 \). For this reason, the role of solar irradiation over façade has special importance in URBAN-4S(Figure 3). Also another method is integrated to this calculation [27].

![Figure 03: Different shadows on an enclosure at a specific time. Screenshot of Urban-4S software. The authors.](image)

### 3.3. The role of building inertia

The variability in the results of energy demands arising from using the 5000 method with different zoning strategies by the calculators leads to the development of a methodology that allows simplified calculations of cooling and heating, abandoning the aforementioned zoning and taking as a starting point the inertia of the building.

This property allows energy storage in buildings without overheating, which would imply that part of the profits are not useful for its use, an effect described by Givoni [28]. This inertia is characterized by a time constant \( \tau \), measured in hours, the value of which is generally calculated using the expression:

\[ \tau = \frac{C_t}{3600 \times CGP} \quad (1) \]

where:

- \( C_t \) - is the total thermal capacity of the building (J / K)
- \( CGP \) - Global Building Loss Coefficient (W / K) including losses through all closings and air renovations.

Once the program calculations have been seen, a brief description of the different elements involved in the energy balance (obviously static) to be carried out for each building is shown:

### 3.4. Gains of the building system

The program includes calculations of two types of gains:

- **Internal gains in the building:** They are included as a single factor, whose default value is 0.15 kWh/m².day. This magnitude includes an average home use in terms of household appliances, lighting and human metabolism.
- **Solar gains:** There is a whole process of evaluation of the useful gains that are integrated into the balance and come from solar radiation. Starting with the gain through the semi-transparent enclosures (openings), the following algorithm is carried out:
  - Firstly, calculations of solar position and relative position of each enclosure allow obtaining the incident radiation on the holes.
  - Next, the different shadows that said gaps suffer due to different origins (horizon, shape of the building, obstacles and nearby buildings or eaves) must be observed, which generates a decrease in the direct component of the incident radiation.
  - Subsequently, the incident radiation suffers various losses depending on user-configurable variables (solar factor or optical transmittance) or that have default values in the program (frame percentages, presence of carpeting, etc.). This step results in the maximum solar gains, which represent the energy entering to the building.
  - Finally, solar gains are converted into useful (effective) gain through an algorithm that takes into account the inertia of the building. This useful gain is the result that enters the energy balance of the building.

### 3.5. Losses of the building system

The losses in buildings have two clearly differentiated sources: losses by conduction-convection through the enclosures and losses generated by the renewal of air by introducing outside air.

- **Convection conduction losses:**
  - Firstly, the losses coefficient is calculated, which supposes a summation of the \( U \times A \) factors (thermal transmittance multiplied by area) for each of the opaque or hollow elements of the building.
  - Subsequently, for each of the times of the year, this coefficient is multiplied by the difference in interior and exterior temperatures, obtaining losses through the enclosures.
  - It is noteworthy that this term can be negative in the case of high outdoor temperatures above the summer reference. In that case, this term will effectively end as a gain.

- **Losses due to air renewals:** The program allows the insertion of a value of hourly air renewals. This value includes both those produced voluntarily (ventilation of the rooms) and involuntary (infiltrations through gaps and other construction defects).
  - Once this value has been entered, the program performs a calculation similar to that of the previous section, taking into account the difference in indoor and outdoor temperatures.
- These losses can be negative and turn into gains in the aforementioned case that the outside temperatures exceed the summer reference.

Effective realization of the energy balance: After obtaining all its elements, the energy balance is made by adding all of them, both for the heating and cooling seasons.

3.6. Simplification of weather data and assumptions.
A simplification of weather data to evaluate daily and monthly energy needs of residential buildings was based on Bahadori model [29]. Another several models are programmed under algorithms in Java language and used to configure all the calculations given, and for space reasons are as references[30-37].

3.7. Testing the models
Sensitivity analyses were performed to determine the best models to include in the calculation engine, from the point of view of speed and precision. This is due to the special characteristics of the neighbourhood study as object, which can normally involve series of different typologies of buildings(Figure 04) and configurators, that in an non-adapted software can take many hours of calculation. Adapted models were estimated based on a compromise required precision-speed. The second part of the work was the configuration of this battery of indicators adapted to the regional and national context, which was one of the main challenges in an indicator system, especially in Chile, where there are no objective bases at urban design practices level. No applicable to some scale beyond the dwelling, indeed.

4. NEXT STAGES AGENDA
At this time, the team is planning to continue developing the URBAN-4S software, whose prototype stage is already completed, including different aspects and technological advances in the software, to obtain a new, marketable version that is a first internationally validated tool to move towards criteria for voluntary urbanization evaluation. To do this, we must continue to develop the software based mainly on three aspects; we must carry out different tasks in the field of programming, secondly review and validate the applied energy theory and third, collect the latest advances in evaluation in terms of sustainability and Circular

5. CONCLUSIONS
Numerous international standards and experiences that have set the agenda and standard in Chile, but often these imported criteria lose their validity since they have been developed within realities and frameworks that historically are foreign. The urgent needs to anticipate us to the slow evolution of regulations deserves special attention, and already to define a series of restrictors and urban quality indicators adapted to the Chilean urban areas that could bring added quality beyond the O.G.U.C.(Urban and Buildings national normative provisions) and current regulations, responding to the undeniable current problems of Chilean cities [38,39].
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REFERENCES
1. INTRODUCTION

The abundant use of highly reflective cladding in dense urban areas is causing severe visual discomfort because of reflection of the sunlight that falls on those surfaces. These intense reflections can cause a disabling glare that impairs the vision of the occupants of surrounding buildings [1–3].

Glare impairs visual performance and well-being, leading to premature fatigue, headaches, blurred vision, and eyestrain. Glare problems can worsen in office environments in which there is a need for frequent and extended computer usage. The increasing use of various digital technologies in offices can create substantial challenges for office occupants in processing information and performing visual tasks throughout the day [4–9], and creating a visually comfortable environment in office areas could help reduce the strain on workers’ eyes that must constantly adapt to different visual tasks and thus ultimately increase workers’ productivity.

In addition to the glare problem, reflective building elements reflect sunlight onto surrounding vegetation, causing burn damage. An example of reflective building cladding causing glare and vegetation burn was experienced in Dallas, Texas, where the façade of a 42-story high-rise residential tower, which was fitted with a highly reflective glazing, caused intense specular reflections into the Nasher sculpture museum. This resulted in overheating of the interior spaces of the museum, leading to the damage and deterioration of the sculptures on display [10,11]. The sunlight was also reflected onto the Nasher museum’s garden, creating hot spots in both exposed and shaded sections of the garden. Daily readings by museum officials recorded temperatures at those hot spots that were approximately 40 degrees higher than the air temperature [10].

Glare in buildings is usually assessed by analyzing the luminance values in 180-degree fisheye high dynamic range (HDR) images or renderings. The analysis outputs the daylight glare probability (DGP) value and highlights glare sources on reflective surfaces. However, the highlighted glare sources’ actual locations on the reflective surface are difficult to determine using the analyzed images due to the skewed fisheye projection.

This research paper proposes a methodology that facilitates the determination of the exact location of glare-causing façade panels using OpenCV (Open Source Computer Vision Library), an open source computer vision and machine learning software library [12]. In addition to being an automated method, it can be applied to large-scale glare simulations that consist of hundreds or even thousands of glare images.

In this study, 15 views inside a small building that faced a tower fitted with a reflective façade were analyzed for glare over the course of an entire year. The HDR renderings produced were further examined using custom software written in Python, a programming language [13] that utilizes computer vision recognition.

2. GLARE ANALYSIS USING HDR RENDERINGS

180-degree fisheye HDR renderings have been used in assessing glares caused by a high ratio of luminance between the task that is being looked at and the glare source. HDR rendering can represent the full dynamic range from the brightest light (direct sunlight) to the darkest spots, such as deep shadow, in the examined scene, making it one of the best tools to assess glare [14–16]. Glare simulations and HDR renderings usually use CIE standard clear sky [17].

The HDR images are usually analyzed using Radiance, which is an open source software for accurate lighting simulation and visualization based on a backward ray-tracing algorithm [18].

3. METHODOLOGY

As noted, this paper proposes an computer vision recognition based method to accurately determine the patches on a specific reflective façade that cause glare during every hour of the year. Glare analysis was
performed from 15 views inside a small building located across from a 11-story tower. The geometric model of both buildings, the glare analysis process, and the computer vision recognition algorithm are explained in the next three sections.

3.1 THE GEOMETRIC MODEL

A geometric model of two buildings—a three-floor building and a tower—was created with the Rhinoceros 3D modeling software [19]. The location of the buildings was set to Houston, Texas, in the United States. The latitude of Houston is 29.76°N, the longitude is -95.36°W, and its elevation is 80 ft (24.4 m) above sea level.

The tower consists of 11 floors, and it is 108 ft (33 m) tall and 59 ft (18 m) wide. Each floor has seven rooms measuring 16 x 13 ft (5 x 4 m) with a ceiling height of 9.8 ft (3 m). The smaller building consists of three floors, and it is 29.5 ft (9 m) tall and 42.7 ft (13 m) wide. Each floor has five rooms measuring 16 x 13 ft (5 x 4 m) with a ceiling height of 9.8 ft (3 m). The street width between the buildings is 98.5 ft (30 m) (Figure 4). The reflective façade is oriented toward the south. Figure 1 shows the geometric model that includes context buildings on both sides of the tower to mimic an urban context.

In the modeled buildings, the façade of the tower is considered to be a glare-causing surface due to its high reflectance and its orientation toward the south.

![Figure 1. The modeled 11-story tower (blue), the three-floor building (red), and the context buildings (brown).](image)

3.2 GLARE ANALYSIS

A view inside each room in the small building was created at a height of 5’6” and located in the center of the room as one looks toward the reflective building façade. The total number of views was 15. In order to assess and quantify the glare caused by the reflective façade, each view was rendered to HDR 180-fisheye images, which were further analyzed to obtain the DGP value for each hour of the year (HoY). Several glare indices have been developed over the past decade to assess glare in views within interior spaces, but it was determined that DGP was the most suitable metric to use for this study. DGP was developed by Wienold and Christoffersen and based on laboratory studies in daylit spaces in two different locations (Freiburg, Germany, and Copenhagen, Denmark) in order to assess glare. That study tested 72 different objects under various daylighting conditions, and DGP showed a remarkably high correlation with users’ glare perceptions [20].

In addition to calculating the DGP, the HDR renderings were used to visualize the glare sources in each scene. Glare sources in HDR renderings are usually highlighted in random colors by Radiance. Figure 2 shows an example of the HDR renderings produced of the 15 views, with the glare sources automatically highlighted in different colors by Radiance.

![Figure 2. HDR 180-fisheye renderings of 15 views inside the three-story building looking outward. The HDR renderings are used for glare analysis. Glare sources are automatically highlighted by Radiance in random colors, such as magenta, yellow, or cyan.](image)

3.3 High Performance Computing

The total number of HDR renderings needed to analyze glare in all 15 views for every HoY was 65,000. Each rendering took about 111 seconds to complete on a high-end desktop computer [21], meaning that running the glare simulations could take about 83 days. It is evident that carrying out such large-scale hourly glare simulations can be a complicated process due to the intensive computing power that is required. Furthermore, running such simulations manually is impossible because of the enormous number of files that are needed for the simulation process. To mitigate these challenges, the simulations were automated with Python, and executed on a high performance computing (HPC) environment using the parallel computing framework proposed by Labib and Baltazar [21]. HPC facilitated the execution of such large number of files on
powerful computing nodes that run in parallel to speed up the process of running such a large-scale simulation in just a few hours.

3.4 COMPUTER VISION RECOGNITION

Because of the enormous number of HDR renderings produced following the glare analysis and considering their skewed projection, it is evident that locating the glare-causing façade panels manually would be impossible. It was therefore determined that an artificial intelligence-based method—specifically, computer vision recognition—would be necessary for this step, the workflow for which is shown in figure 3.

Figure 3. The workflow for locating the façade panels causing glare for every HoY using computer vision recognition.

The 180-degree fisheye images that resulted from the glare analysis were further examined by custom-written Python software that utilized advanced features of OpenCV. To facilitate locating the glare-causing façade panels by OpenCV, each view was rendered to produce images containing a green mask on the reflective façade. In addition to the mask, the façade was also divided into a 5 x 3 m grid. To produce these images, each view (total 15 views) was rendered using custom Radiance materials that were assigned to the interior of the room, the outside ground, and the façade, which was given a Radiance plastic material with the RGB value of (0,255,0). To produce a grid system, black-colored mullions were modeled and rendered on top of the façade using a Radiance material with an RGB value of (0,0,0). The mullion system was used to divide the façade into patches that were 5m wide and 3m high; see figure 4.

The Python script overlaid each HDR rendering produced for every view for every HoY from the initial set of glare simulations onto the corresponding rendering that was prepared with a grid on top of the reflective façade, as shown in figure 5. The program looked for glare sources only in the green-masked grid (the reflective façade) and located the glare sources in each view inside the grid units. Each grid unit was assigned a unique identification number (ID) by the Python program. The software package that was used to write and send the files to Radiance originally included instructions to output the HDR images with randomly colored highlighting, as shown in figure 2. However, the Python script was designed to look for one specific color (magenta), so it was necessary for the commands sent to Radiance to be customized so that Radiance output the glare in magenta only, with an RGB value of (255, 0, 255).

Figure 4. A custom HDR rendering of one view showing the reflective façade, which was assigned a green Radiance material, with a 5 x 3m mullion system modeled on top of it.
After the pictures were overlaid, Python’s OpenCV tools facilitated locating the magenta color inside each grid.

Figure 5 shows a visualization of the output of the Python script. A grid with the letter P indicates that the façade panel represented by the grid causes glare at that HoY, and a grid with the letter N indicates that it does not.

**Figure 5.** A visualization of the results of the Python/OpenCV code that facilitated the overlaying of an image from the glare simulations (set 1) with the corresponding mask (set 2). P in each grid unit indicates the presence of a glare source (magenta color) in that unit. N indicates no glare sources in the grid unit.

Finally, the results from the glare-causing panel program were output and the data stored in a SQL database for easy access. The data included the view, HoY, and ID of the grid unit; see figure 6.

**4. RESULTS**

Upon executing the Python/OpenCV program, a SQL database was created. The database contained the location of the glare sources in each of the 15 examined views for every HoY, for a total of 65,000 views. The locations of the glare sources were expressed by the façade grid ID.

**5. CONCLUSION**

The Python program facilitated the determination of the exact locations of the glare-causing panels on a reflective façade, a process that has never been possible before using traditional fisheye HDR images due to their skewed projection. The Python program also executes in an automated manner, thus eliminating manual processing efforts, making the proposed method time-efficient, especially for large-scale analyses that consist of thousands of images. Furthermore, the proposed computer vision process outputs the results of the glare analysis in an easy-to-read manner, making it an easy and quick process to search for and extract glare information about a specific view at a specific HoY. Because the obtained information locates the glare sources in occupants’ views, it becomes a great asset, especially in the early design process when architects...
and designers make decisions on the design of the building façade in terms of its material and geometry.

6. LIMITATIONS AND FUTURE STUDIES

Although this proposed workflow has been proven to be extremely beneficial for the purpose of locating the building elements that cause glare, the execution of such a workflow requires knowledge of various disciplines, including architecture design and computer science. It is therefore clear that the methodology introduced in this paper could be difficult for the regular user, and further studies are required to devise an alternative workflow for non-programmers. A better approach for such users could be achieved using Grasshopper components, which use an easy-to-understand graphical user interface and hide complicated code from entry-level users.

6. REFERENCES


Thermo-Spatial Performances of Eight Responsive Envelopes
Simulation Studies Benchmarking Built Active Solar Shading Envelopes

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This study examines the thermo-spatial performances of eight responsive building envelopes from the built environment. The objective is to understand and compare each of the envelopes for their thermal comfort/sensation performances, and their capacities for creating visual transparent conditions through the envelope. Through extensive simulations, based on annual hourly simulations in two geographic locations and with a series of envelope movements, a large dataset is created for further analysis. The envelopes are then compared through comparative graphs, showing that one design strategy perform better than the rest. The paper includes the framing of the study, the methods used to convey the investigations and the results obtained. Lastly, specific findings are presented in the conclusion, with additional discussion for intended future studies.

KEYWORDS: Adaptive Envelopes, Thermal Sensation, Energy, Comfort, Simulation

1. INTRODUCTION

As an approach to increase the thermal quality of indoor environments and thereby decrease energy costs for cooling and heating spaces, solar shading responsive envelopes are designed, built and integrated across the world. Yet, little data, nor comparative studies of these often ‘high-profile’ projects exist. In contrast, one study suggest that an international renowned responsive building does not increase thermal performance as a consequence of the responsive envelope (1).

This study examines the thermal and spatial performances of eight selected built envelopes, which have a significant impact on the architectural language and how the projects are communicated as responsive sustainable architectures. The projects combined represent a large part of the responsive envelopes currently designed and built, and is therefore strongly indicative of the general performances of solar responsive envelopes. The projects studied include two scales of Al Bahr Tower by AEDAS, two segments of Copenhagen Business School by Lundgaard and Tranberg Architects, Kiefer Showroom by Ernst Giselbrecht + Partner, Chicken Point Cabin by Olson Kundig Architects, UN City by 3XN Architects and Mærsk Tower by C.F. Møller Architects. The studies are conducted through comprehensive simulation studies, to allow side-by-side comparison of the designed envelopes, and then benchmarking them against each other in two different geographic locations.

Figure 1. Mærsk Tower (copper elements) and CBS Kilen (wood, metal and glass elements) projects, including vertical oriented movable devices with different mechanisms and expressions and performances. Photos by author.
Previous studies of mechanical-based responsive envelopes, studying solar shading performances, have focused on the classification of the responsive mechanisms and structural makeup (2–4) or the individual and non-comparable data from projects focused on potential energy savings, rather than human focal points, such as thermal sensations and view to context conditions.

This experimental simulation-based study identity, catalogue, model, simulate and explore how the eight responsive designs perform when they are extensively analyzed for their capacities to create thermal sensations, comfort conditions and these relations to allowing visual contact to the outdoor context and environment.

The paper presents the experimental computational studies, the methods used, the responsive behavioural results of the built envelopes and their performances for both thermal and visual relation to context aspects.

2. METHODS

Given that the eight existing solar shading responsive envelopes are located around the world, and with variances in local climate, context and occupancy, simulation methods are used to enable comparative studies. This support a study which benchmarks isolated on the capacities to shade, influence perceived thermal comfort and to understand visual relation to the outdoor environment.

2.1 Simulation Studies

The eight responsive envelope geometries are parametrically modelled in the Rhino/Grasshopper + Ladybug/Honeybee software, including the movement mechanisms of the individual envelope designs. Movements have a ten-step sequence from closed to open. The space simulated is an 8x8x4 meter geometry, fig. 2, with a simulation mesh, where 9 reference points are assessed hourly across a year for thermal comfort based on the Heat Balance Model (5), and an Isovist analysis providing metrics on how much of the context that can be viewed from the 9 reference points and at different envelope opening degrees, fig. 3. This in turn allow not only an understanding of the thermal performance, but also the spatial and context relation performance of a responsive envelope, which when shading typically reduces the view and relation to contextual elements.

Simulations are then conducted for each hour of the year and compared graphically for summer, winter, equinox, and, for Copenhagen and Barcelona. In total, millions of data points are created during simulation as basis for assessing and comparing the eight responsive envelopes.

2.2 Comparative Analysis Studies

Based on the extracted simulation data, an extensive comparative graph analysis is made by cross referencing the thermal and spatial performances. At each spatial reference point thermal averaging, thermal comfort maxima, thermal comfort minima, view factor and comfort-to-view ratio is mapped and compared allowing the reading and identification of absolute and relative performances between the eight responsive designs, and how these vary according to year, location, spatial reference and envelope opening position.


Figure 3. Cone of vision analysis view properties from different spatial simulation positions seen in plan view.
3. RESULTS

With a very large data set of points, the study identifies and visualize how the eight different responsive designs influence thermal sensations and view-to-outside properties in a comparative and targeted study. To structure the data set, 6 graphs are made, 3 for Copenhagen and 3 for Barcelona, in summer, equinox and winter conditions. Each graph includes the 8 envelope studies, with the comfort sensation coefficient (0-100 %) in relation to the opening of the envelope (0-100%). Each curve represents the averaged values from the 9 simulation-view-points in the aforementioned space. Additionally, the maximum and minimum comfort coefficients are included, showing the large thermal sensation variation based on the human position in the space.

3.1 Copenhagen Thermal Comfort Sensations

In summer, the light blue line, representing the Chicken Point Cabin, with its singular large opening element, comes out with the averaged highest comfort coefficient, particularly when opened 20-60%. In addition, interestingly it represents the greatest comfort spreading across the space, with values from 53-84%. Less dominant is the Kiefer envelope, with a higher comfort in the more open state, but also with high variance across the spatial positions, ranging from 48-82%. The Mærsk Tower shows the lowest gain in comfort sensations based on the envelope, and also the lowest variance across the space, from 47-57%.

At Equinox, the pattern is similar to the summer performances. Here, Chicken Point and Kiefer are closed matched for both averaged values and spatial variance. The Mærsk Tower and UN City are in the lower performance range, with a steady decline the more closed the envelope becomes. This is also seen in the summer and winter. Interestingly, the CBS Kilen project has an almost uniform performance across its opening range, and across seasons in Copenhagen. With thermal comfort sensation variance from 48-75% based on spatial position, the effect of human spatial positioning has a much higher effect than the operation and performance on the dynamic envelope.

Figure 4. Thermal comfort graph in summer (21 June) period in Copenhagen.

Figure 5. Thermal comfort graph at Equinox (21 March) period in Copenhagen.

Figure 6. Thermal comfort graph at Winter (21 December) period in Copenhagen.

3.2 Barcelona Thermal Comfort Sensations

In Barcelona, similar results to Copenhagen is found during summer, figure 7. The solar vector is steeper at 60 degrees compared to Copenhagen’s 55 degrees, which also alters the geometric relations between envelope design and movements and the resulting thermal contribution from radiation. Higher thermal comfort sensations are achieved with more closed conditions of the envelopes in general, and particularly with the highest performance design of the Chicken Point project. At both the Kiefer and Chicken Point envelopes, variance from spatial positions are very high from 0-50% closed, ranging from approx. 48-78% in both cases. CBS Kilen is relatively steady across opening conditions and spatial positions, while the UN City and Mærsk Tower has very low impact from spatial position when closed more than 50%.
Across all seasons, when referring to Chicken Point and Kiefer envelopes, large variation is found when combining spatial position and envelope opening degree. For equinox in Barcelona, figure 8, this is mostly outspoken, with a significant difference if comparing the Chicken Point at envelope 20% open and minimum comfort sensation with the envelope 30% and the maximum comfort sensation. The difference ranges from 30-88%, providing a 58% comfort sensation variance if just changing 10% opening degree and moving the human to another position in the space. Another very significant variance is found in the Mærsk Tower. The averaged comfort sensation is steady around 50% across opening levels, but the spatial variance is very high from 0-40% opening, ranging from 21-52%. In this case, envelope open 0-40%, the envelope has little to no impact, while the placing of the human has very impact. Closing the envelope above 40% then removes the importance of spatial positioning.

In winter, the registered high variance based on spatial positioning is limited to closing degrees around 40-50% for the two top performing envelopes, the Kiefer and Chicken Point, figure 9. In similarity, the otherwise uniform performing CBS Kilen also shows increased variance from spatial position around 50% opening, while the remaining envelopes do not have this performance behaviour. For instance, the Al Bahar Tower, grey line, has relatively low performance, but a uniform impact across the opening levels and little delta, approximately 10%, variance based on spatial positioning.

The trends across the results show that the largest difference between envelope performances, in respect to thermal comfort sensations, is found in the mid-open region, from 30-60% open and that above 70% closed, envelope performances start to converge into domains where the spatial position has more impact than what dynamic envelope design that is acting. The mid-open region (30-60%) is also registering the by far largest deviations between thermal sensations based on spatial position. When observing across locations, seasons and envelope designs, the comfort sensation is 69% (21-90%). When filtered for season and location variation, we find a variation of 64% (21-85%), figure 8, showing a significant impact on the combination of design and spatial position of the human in the test space.

3.3 Vision Analysis

The outward view is defined by the spatial position, figure 3, and the envelope construction, which obstructs and reduces the area of view from inside to the outside. Much in similarity to the performances of the thermal sensations, has the Chicken Point and Kiefer the highest view ratios, but also the largest variance according to spatial position. In particular the Chicken Point has an advantage in that no frames of non-movable elements are in the sightlines during any open/close conditions, while the Mærsk Tower and the Al Bahar includes a significant amount of construction, which independently from movement blocks the view performances. CBS Kilen includes also a significant non-dynamic construction, but here, the geometries and opening mechanisms provide a homogeneous view ratio performance, albeit lower than both Chicken Point and Kiefer.
Figure 10-17. Vision to outside through envelope in relation to opening percentage. Fig. 10. Maersk Tower, Fig 11. CBS 90-180, Fig. 12. CBS 0-90, Fig. 13 Chicken Point, Fig. 14 Kiefer, Fig. 15 Al Bahar Large, Fig. 16. Al Bahar Small, Fig. 17 UN City.

4. CONCLUSIONS
The magnitude of thermal sensation simulation results and graph mapping has allowed the comparative analysis and results finding between locations, seasons, designs and human spatial positioning. From these datasets the following conclusions has been made.

4.1 Human spatial position is very important
In all analysed cases, a high difference in thermal sensation exist between the spatial reference points. In several cases, the position of a person in the space has higher impact on thermal sensation than the type of envelope design and the operation of the envelope. This also means that the shading has hyperlocal impact on thermal comfort with the space and that responsive behavior of the envelope should be steered towards individual thermal assessments.
4.2 Small envelope elements greater uniformity
The smaller the responsive elements of the envelope, the more stable comfort sensations across degrees of openings. This is both true for the uniformity across envelope opening level (sunlight permeability) and the relational impact on human spatial positioning. The Chicken Point envelope with one large element has a drastic change in performance depending on degree of permeability, compared to the CBS Kilen envelope. The smaller elements thereby also serve to create higher spatial uniformity, which decreases the impact of human spatial positioning.

From an architectural point of view, which looks to sensations, and not only generalized comfort conditions, each of the envelope performances can be activated according to thermal design strategies.

4.3 Simple structures higher thermal performance
Across all the studies, Chicken Point followed by Kiefer envelopes perform highest for thermal comfort creation. Chicken Point is by far the simplest mechanism and geometry, with one pivoting planar element with a single drivetrain. When comparing the results from the geometrically and mechanically complex envelope of the Al Bahar project with the low-tech simple envelope of the Chicken Point envelope, the performance differences are significant in favour of a simpler design.

In contrast, envelopes with high resolution in terms of elements per area has the capacity to regulate locally across the envelope and perform counter measures, or increase certain sensations, by closing regions of the envelope, rather than uniformly open and close the building envelope of the individual spaces.

4.4 Thermal and Vision Relations
View the singular large opening of the Chicken Point, without any other construction in the sightline, it provides as higher view ratio performance over the envelopes which rely on additional, and often, significant amount of other static construction. The disadvantage is the near occlusion taking place at higher closing percentages. When related to the thermal performances of the envelopes described above, Chicken Point and Kiefer comes out as the best performing envelope designs in the framework of this study. That said, in particularly the Chicken Point, has a very mono-functional performance, where hyperlocal calibrations are not possible. In this sense, the Chicken Point design approach relies more on the spatial positioning of people, as can also be seen in the high variance between maxima and minima values.

5. DISCUSSION
Through a large data set, based on simulations, and analytical mapping and comparative analysis, it is clear that there are significant conclusions and trends, as presented. Yet, it is also clear that the thermal and spatial performances of a building envelope is a large, dynamic, subjectively linked complex, where the actions and positions of the individual human have great impact on perceived performances of a design.

Therefore, when the generalized human plays such a central role in the performance of the envelope, it seems difficult to exclude these aspects in future envelope designs. If we then consider a non-generalised human, but includes the specifics of gender, age, health, behaviour, clothing etc, the human appears to stand as the centre point of building envelope designs and their assessment in higher degree than is currently practiced in both research and academia. Our future studies will address in higher degree how the human can engage and be integrated into design models for the development of adaptive architectural envelopes. It points to new studies that address tempi of sensations, subjective conditions, hyperlocal microclimates in relation to the envelope operation and subjective actions with dynamic envelopes.

This study also questions the prevailing approach of complex mechanical systems, as these appear to have a lower thermal and view performance capacities. Beyond this study, questions of usage and maintenance also adds to these aspects and we can then ask for future studies, what are the direct energy to run these mechanical envelopes? What are the in-direct energy to maintain and renovate mechanics? And of course, what are the alternative approaches? From an architectural and phenomenological perspective, we will ask how we can understand and use the presented high variance across the studies. Can this increase higher subjective comfort potentials?

And, lastly, how to account for thermal sensations tempi in relation to human perceived temperatures?

REFERENCES
A Process-oriented Approach to Tackling the Problem of Forest Migration under Climate Change

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ABSTRACT: Rapid climate change is expected to result in migration lags in many tree species. Large-scale urbanization will impede the process of forest migration by reducing landscape connectivity. This study proposed a process-oriented approach to tackling the problem of forest migration. The focus of this approach was placed on improving the connectivity of urban landscapes for effective seed dispersal. The process-oriented approach was conducted through an iterative process of designing, testing, and refining to explore effective afforestation strategies in urban areas to increase landscape connectivity. Graph theory-based indices were used to test the effectiveness of afforestation strategies. Greater Manchester, UK was used as a case study area. The results indicated that the effectiveness of urban afforestation is strongly related to the spatial arrangement of trees across the urban matrix. In general, trees should be planted in highly connected greenspaces and high-density residential areas. The study revealed the potential of urban afforestation to facilitate forest migration and called for more attention to the importance of urban landscapes in biodiversity conservation under climate change.

KEYWORDS: Urban afforestation, Landscape Connectivity, Forest Migration, Climate Change, Seed Dispersal

1. INTRODUCTION

Global climate warming is expected to shift the geographical distribution of tree species worldwide [1]. Climate defines the geographic range of modern biomes and plays an essential part in defining the ecological niche of species [2]. Increasing empirical evidence has emerged showing that many tree species are already moving toward higher latitudes to track suitable climatic conditions [3]. Yet, such movement cannot guarantee their survival, especially if the accessibility of suitable climates is highly constrained by species dispersal capabilities and human-created barriers. Large-scale urbanization will impede the process of forest migration by reducing landscape connectivity for seed dispersal between habitats [4]. Moreover, anthropogenic habitat fragmentation extinguishes or drastically reduces the populations of the birds and mammals responsible for long-distance seed dispersal [5]. If appropriate seed dispersal agents are absent, it is likely that seed dispersal between distant habitats will not occur. The mismatch between climate shifts and species responses will increase species mortality and susceptibility to insect attacks and diseases, even resulting in their extinction.

Within this context, conventional habitat-based conservation strategies which rely on fixed protected areas cannot ensure species’ long-term persistence. Habitat-based conservation strategies aim to maintain population viability and biotic integrity of ecosystems. In the absence of climate change, protecting habitat areas could mitigate the negative impact of habitat loss and fragmentation and minimize the risk of species extinction. However, this will not be the case in a rapidly changing climate. To avoid the extinction of forest trees, more active forest management strategies with human interventions are needed to assist the migration of tree populations.

Recently, assisted migration is gaining increased acceptance as an important strategy to facilitate forest migration. Assisted migration refers to the intentional translocation of species, populations or genotypes from their natural ranges (current habitats) to locations where the climate is projected to be favourable to them in the future [6]. As a response to climate change, assisted migration has already been practised and incorporated into forest management in many regions and countries. In England, the Forestry Commission recommends using seed sources from slightly warmer climates from 2 to 5 degrees of latitude further south than the site [7]. Similar recommendations are made in Canada: British Columbia, Alberta and Quebec have extended current seed-transfer guidelines northward to compensate for recent and future climate warming [8].

Despite the rising interest in assisted migration, there are concerns that the translocation of species may not be successful and may lead to unpredictable adverse consequences. Current prescriptions of assisted migration most often rely on the identification of areas where the climate is projected to become suitable in the future, using species distribution models. However, due to limitations and uncertainties in the models, there is a risk of moving species too far or not far enough [9]. Besides, cold adaptation in tree
populations constrains seedling recruitment and seed production in translocation sites. Poleward planting of warm-adapted seeds or seedlings may expose them to frost damage, resulting in poor seedling survival and slow growth, as well as serious risks of death and dieback [10].

Here, we proposed a process-oriented approach to facilitate the process of forest migration through urban areas. The focus lies on increasing the connectivity of urban landscapes for effective seed dispersal. Increasing landscape connectivity is often suggested to be a necessary action to offset the negative impact of landscape fragmentation and assist tree species to traverse human-created barriers [11]. Since the migration of trees is a continuing process that does not rely on their future distributions, a process-oriented approach could avoid projections of species’ future distributions and thus might be more robust to future climate change than current ‘goal-oriented’ efforts in assisted migration. Moreover, it could be easier to promote the process of forest migration than to maintain a translocated species at a given site, especially in urban areas where human activities are intense and implementing large continuous reserves is not feasible.

The process-oriented approach was conducted through an iterative process of designing, testing, and refining to explore effective urban afforestation strategies to increase landscape connectivity for seed dispersal. Graph theory-based indices were used to test the effectiveness of urban afforestation strategies. Greater Manchester, UK was used as a case study area. Frugivorous birds are considered as major seed dispersal agents in the study given their outstanding mobility, adaptability, and effectiveness in urban environments [12]. Three frugivorous birds—Eurasian jays, Eurasian siskins, and coal tits—were selected as the main seed dispersal agents in the study area because they represent contrasting agent groups with respect to dispersal abilities (Table 1): Eurasian jay is a large-sized species that has a large habitat requirement and relatively long flight distances; Eurasian siskin is a medium-sized species that has a large habitat requirement and medium flight distances; and, coal tit is a small-sized species that has a small habitat requirement but relatively long flight distances. It was therefore expected that test outcomes for the three frugivorous birds could reveal the effectiveness of urban afforestation in general.

Table 1. Key parameters of the three frugivorous birds in Greater Manchester [13].

<table>
<thead>
<tr>
<th>Bird species</th>
<th>Habitat size</th>
<th>Daily dispersal</th>
<th>Long-distance dispersal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eurasian Jay</td>
<td>≥ 4 ha</td>
<td>≤ 1 km</td>
<td>1 km - 5 km</td>
</tr>
<tr>
<td>Eurasian Siskin</td>
<td>≥ 4 ha</td>
<td>≤ 0.5 km</td>
<td>0.5 km - 3 km</td>
</tr>
<tr>
<td>Coal Tit</td>
<td>≥ 1 ha</td>
<td>≤ 0.4 km</td>
<td>0.4 km - 5 km</td>
</tr>
</tbody>
</table>

2. METHODOLOGY

2.1 Designing afforestation strategies

‘Greening’ existing areas of the built environment is an effective way to increase landscape connectivity in dense urban areas [14]. In Greater Manchester, domestic gardens, roadsides, and non-woodland greenspaces were selected as potential afforestation sites. Other urban areas were not defined as being appropriate for planting, given considerable cost and constraints, especially in the city centre. We proposed the following urban afforestation strategies to increase landscape connectivity. The two strategies represent different spatial arrangements of afforestation sites and were designed as general as possible so that they can be applied to other cities.

Strategy A was planting trees in large, non-woodland greenspaces (including public parks and gardens, community gardens, unmanaged lands, natural lands, and other landscape areas). This strategy intended to form habitat patches that could serve as population sources for seed dispersal. We simulated 30% tree canopy cover per hectare of the non-woodland greenspaces to achieve 30% tree canopy cover [15, 16]. Green spaces smaller than 1 ha were not considered in the strategy.

Strategy B was planting trees in domestic gardens and roadides. This strategy aimed to form a large number of small woodland patches as stepping stones for the movement of birds [17]. Although small woodland patches are unable to support viable populations of frugivorous birds in the long-term due to the scarcity of resources, they could provide stopover points, offering temporary shelter and food for the movement of birds between large habitat fragments, thereby increasing the permeability of the urban matrix to forest migration [18-20]. We simulated 30% tree canopy cover in each private garden [21] with a minimum canopy area of 3.14 m² (canopy radius of 1 m) [22] and a maximum area of 0.3 ha, as well as street trees planted at 8-meter intervals along roadsides [23]. The crown width of the street trees was assumed to be 6 m, which is the most common crown size for urban trees with a stem diameter of 25 cm [24].

The simulation of urban afforestation was done in ArcGIS 10.6. The geospatial data of urban greenspaces (including domestic gardens) and streets were obtained from the 2019 Ordnance Survey MasterMap in Digimap (https://digimap.edina.ac.uk/) and the European Urban Atlas geodatabase (https://land.copernicus.eu/local/urban-atlas/urban-atlas-2012/view), respectively.

2.2 Testing afforestation strategies

The minimum habitat sizes of the frugivorous birds were taken as grain sizes to change the resolution of woodland maps. Cells were assigned to the class of
woodland when tree canopies cover more than 30% of their area [15, 16]. As a result, small, scattered urban woodland fragments were aggregated into large, contiguous woodland patches. Patches that formed by urban greenspaces were defined as habitat patches for birds, while those formed by garden and/or street trees were defined as stepping-stone patches.

We used two graph theory-based indices, the probability of connectivity index (PC) and the choice index (in Space Syntax), to measure the improvement in landscape connectivity due to the newly added habitat and stepping-stone patches, respectively. PC was employed to assess the possibility of seed dispersal by frugivorous birds across the study area before and after strategy A. It is a probabilistic index that integrates both patch area and inter-patch distance in one measure, with the degree of connectivity increasing as the area gets bigger while decreasing as the distance gets longer [25]. Empirical evidence has indicated that PC relates significantly to actual movements and occurrence patterns of species [26, 27]. We assumed that urban landscapes with a high PC value might have a high frequency of visitation by frugivorous birds and thus a high probability of seed dispersal.

The choice index in Space Syntax was used to measure the permeability of the urban matrix to forest migration before and after strategy B. The stepping stones formed by garden and street trees were expected to connect currently fragmented habitat patches by forming new dispersal paths between patches. Choice calculated the frequency that a dispersal path is located in the shortest routes between all pairs of patches [28]. The choice value of each path was then taken as a weight to calculate the density of dispersal paths within a radius of species’ daily dispersal distance, using the kernel density tool in ArcGIS 10.6 Spatial Analyst. The average link density of the urban matrix could indicate the frequency that urban areas are traversed by frugivorous birds in their search for new habitats and thus can be considered as urban permeability to forest migration.

### 2.3 Refining afforestation strategies

To achieve a cost-effective afforestation strategy in urban greenspaces, we used a patch addition method in Conefor 2.6 to prioritize the new habitat patches formed in strategy A, according to the connectivity gain they provide [29]. The patch addition method calculates the PC value of a landscape before and after the addition of patch $i$:

$$dPC_i = \frac{(PC_{add,i} - PC)}{PC} \times 100\%$$

where $PC$ is the connectivity value of the present landscape and $PC_{add,i}$ is the connectivity value of the landscape after the addition of patch $i$.

We calculated the proportion of garden trees (in strategy B) in each built-up density level that could form stepping-stone patches. The potential of trees to form patches is directly influenced by their size and spatial aggregation. In general, trees planted in high built-up density areas have small canopies but appear high degrees of aggregation, while those planted in low density areas have large canopies but low degrees of aggregation. It can thus be expected that trees planted in different built-up density areas will have varying degrees of potential for forming patches. Here, the data of built-up density was obtained from the European Urban Atlas, which classify urban blocks into five categories based on the percentage of built-up areas: very-low density (< 10%), low density (10-30%), medium density (30-50%), high density (50-80%), and very-high density (> 80%).

According to the above analyses, we proposed a refined afforestation strategy which brings together the advantages of strategy A and B to form highly connected habitat patches and stepping stones for seed dispersal. We then tested the effectiveness of the refined strategy using graph theory-based indices.

![Strategy A](image1.png)

![Strategy B](image2.png)

*Figure 1: The spatial distribution of urban woodlands after strategy A and B.*

### 3. RESULT

#### 3.1 Simulation results
Both strategies contributed to a significant increase in the city's tree cover (Figure 1). Strategy A established 2,914 ha woodlands in urban greenspaces. The new woodlands connected some small, fragmented woodlands in the present urban matrix. In strategy B, the afforestation program resulted in an increase of 13,443 ha in urban tree canopies, including 5,513 ha garden trees and 2,806,059 street trees.

3.2 Test outcomes

According to the requirement of habitat size (≥ 4 ha), we identified 464 new habitat patches for Eurasian jays and siskins in the simulation of strategy A, which resulted in an increase of 3,412 ha (27.9%) in their overall habitat area. Comparatively, in the case of coal tits, which have a much smaller habitat requirement (≥ 1 hectare), strategy A generated 1,234 new habitat patches, which increased their habitat area by 4,321 ha (30.4%). These new habitat patches led to remarkable improvements in the overall landscape connectivity for seed dispersal. Our calculation of PC showed that the possibility of seed dispersal was increased by 100.8% in the case of Eurasian jays, 119.2% in Eurasian siskins, and 120.1% in coal tits.

Figure 2: The choice value of dispersal paths before and after strategy B for Eurasian jays, Eurasian siskins, and coal tits.

As a result of strategy B, the aggregation of garden and street trees yielded 712 stepping-stone patches for Eurasian jays and siskins and 1912 for coal tits. These stepping stones formed 2,999, 2,973, and 8,197 new dispersal paths for the movement of Eurasian jays, Eurasian siskins, and coal tits (Figure 2), which increased urban permeability by 557.11%, 745.47%, and 424.00%, respectively.

3.3 Refined strategy

Based on the calculation of dPC in Conefor 2.6, we prioritized the new habitat patches formed in strategy A based on their potential to increase landscape connectivity (Figure 3). It appears that for all the three frugivorous birds, only a handful of the new patches showed great potential to increase the connectivity of urban woodlands for seed dispersal. The majority of the patches had little contribution to the overall landscape connectivity. Here, the top 20% most connected patches for each of the birds were selected as the most important sites for afforestation.

Figure 3: The dPC values of the new habitat patches formed in Strategy A for three frugivorous birds.

Only 23% and 39.3% of the garden trees planted in strategy B formed stepping stones for the movement of Eurasian jays (and siskins) and coal tits, respectively. The proportions vary greatly across the five built-up
density categories (Figure 4). On average, trees planted in high-density areas have relatively high potential to form stepping stones for all the three frugivorous birds. The difference can be due to different degrees of tree canopy aggregation. On average, trees planted in high-density residential areas formed highly aggregated canopies due to the high density of afforestation sites. In contrast, although low-density areas usually accommodate more garden trees, the low aggregation of trees led to low potential for forming patches.

![Graph showing percentage of trees in patches across different density categories.

Figure 4: The percentage of trees that formed habitat patches in five built-up density categories.]

According to the above analyses, we proposed a refined afforestation strategy to increase landscape connectivity in a more cost-effective way—that is, planting trees in the top 20% most connected non-woodland greenspaces to form habitat patches, and planting garden and street trees in urban blocks with built-up densities of more than 30% to create stepping-stone patches. The simulation of this strategy resulted in a total of 12,061 ha trees planted in Greater Manchester, including 1,299 ha woodlands in 4,329 ha urban greenspaces, 5,071 ha garden trees and 2,015,150 street trees. Our calculation of PC index showed that the new woodlands contributed to a significant increase of 113.79% in landscape connectivity for Eurasian siskins, which was slightly higher than the increase of 90.39% and 103.03% for Eurasian jays and coal tits, respectively. The garden and street trees improved the permeability of the ‘average’ landscape to forest migration by 496.42%, 670.37%, and 351.29%, respectively.

4. CONCLUSION

This study explored a process-oriented approach to facilitating forest migration. Our results revealed the potential of urban afforestation to increase landscape connectivity for seed dispersal: establishing large woodlands in urban greenspaces could increase the possibility of seed dispersal by providing population sources, whilst trees planted in domestic gardens and roadsides could act a large number of stepping stones for the movement of frugivorous birds across the urban matrix. We found that the effectiveness of urban afforestation varies greatly across seed dispersal agents. This is because different agents may have diverse habitat requirements and dispersal abilities, and thus may respond very differently to a landscape.

While planting trees in cities can improve the connectivity of urban landscapes for seed dispersal, the degree of improvement was strongly influenced by the spatial arrangement of afforestation sites. Based on the test outcomes of strategy A and B, we identified the afforestation sites that have great potential to increase landscape connectivity and then proposed a refined afforestation strategy in Greater Manchester. The refined strategy achieved remarkable increases in both the possibility of seed dispersal and the urban permeability to forest migration for all the three frugivorous birds, which were slightly lower (10.7% and 5.1% on average) than the increases after strategy A and B, respectively. Moreover, the refined strategy only requires 73.7% of the total number of trees planted in strategy A and B and thus can be considered as a more cost-effective strategy.

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Planning Post Carbon Cities

Designing and Building for Extreme Environments
A multi-criteria decision model to evaluate architecture for extreme temperatures

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ABSTRACT: The purpose of this research is to present an assessment methodology that validates architecture designs for environments with extreme temperatures, considering structural and energy demands, as well as sustainability-related concerns. This is achieved using multi-criteria decision analysis modelling. This study presents the results of a MCDA model built for this purpose, and evaluated through four variations representing different project scenarios. A total of 11 criteria (regarding energy efficiency, material performance, architectural performance and circularity) are used to analyse four building assemblies, in order to understand which is more appropriate for an environment with extremely cold and extremely hot temperatures. This allows the validation of the proposed multi-criteria analysis framework, which will lead to further research on extreme climate design.

KEYWORDS: Extreme Environments; Sustainable Architecture; Multi-criteria Evaluation.

1. INTRODUCTION
This paper is part of an on-going research that aims at optimizing the mediation between extreme environmental conditions and the architectural habitat. This requires an evaluation methodology for the validation of the architectural design proposals for extreme temperatures. This paper briefly presents the groundwork already undertaken related to designing for extreme environments and describes a new methodology to evaluate architectural designs for extreme temperatures. The evaluation methodology is based on a multi-criteria decision analysis (MCDA) framework, including a set of criteria grouped according to energy efficiency, material performance, architectural performance, and circularity. This paper is focused on the MCDA modelling structure and on an application for preliminary evaluation purposes.

2. DESIGNING FOR EXTREME ENVIRONMENTS
An extreme environment can be considered as any environmental setting in which human life is hard or even impossible. Such extreme characteristics can be temperature, humidity, pressure, salinity, lack of oxygen or no air quality, extreme pH values (mainly acidity) and dangerous levels of radiation [1]. This study is focused only on extreme temperatures and because of this, two locations among those with the lowest and highest temperatures on permanently inhabited places on earth have been selected. The two locations with the lowest and highest temperatures ever recorded on earth are Oymyakon, in Siberia, Russia [2], with -62°C recorded in 2018, and Furnace Creek in Death Valley, California, United States [3], with a temperature of +57°C recorded in 1913. Due to the lack of accurate annual climate data for these locations, similar places were chosen for this study instead. For the coldest climate Yakutsk, in Russia, was selected, being one of the coldest large cities in the world, where the lowest temperature ever recorded was -64°C [4], and Needles in California, close to Death Valley, USA, with the highest recorded temperature of +52°C. It also holds the record for the highest minimum temperature in the world, +38°C [5].

Due to previous research [6], three types of characteristics of architectural design were considered as crucial for extreme design: the building morphology for the optimization of energy requirements; the building materials and construction assemblies that are able to effectively withstand these extreme conditions; and the internal spatial configuration for an effective use of space, integrating minimal space requirements and functionality.

2.1 Building Morphology
Building morphology is addressed through the heat transfer form factor of the architectural form. The form factor is used to assess the compactness of a building and may be obtained by dividing the external envelope surface area by either the internal volume of the building or the internal treated floor area. In this research, the second option was chosen because, for a given functional floor area, larger volumes mean more energy to keep the internal volume comfortable. Therefore, it was considered that the floor area should be the reference to
calculate the form factor [7]. The lower the form factor, the lesser the heat transfer. Previous work carried out in this project led to the conclusion that the best outside shape for a building in an extreme environment would be either a prism or semi-ellipsoid; this latter shape would be better for aerodynamic purposes, taking into account environments with high wind speeds [6]. In this paper, the prismatic shape is used to validate the proposed multi-criteria model.

2.2 Materials
The materials and construction assemblies used in this preliminary application of the MCDA model were selected among the default set included in the EnergyPlus software material library [8] (the engine used for the energy performance simulations). These material assemblies cover brick, concrete, steel and wood-based construction and are recommended for the climates included in the study, according to ASHRAE Standard 189.1, “Standard for the Design of High-Performance Green Buildings” [9] (climate zone 2 for Needles and climate zone 8 to represent Yakutsk climate [10]).

The full set of material assemblies considers 21 solutions, grouped in four types, designated as follows: ‘Generic’ (brick-based); ‘Mass’ (concrete-based); ‘Metal’ (steel-based); and ‘Wood’ (wood-based). Each type includes floors, walls and roofs, and the recommended thickness of each material layer depends on climate.

2.3 Interior Spatial Configuration
In extreme environments, the interior habitat has an increased importance. In these circumstances, inhabitants are more psychologically dependent on the indoor environment. Certain elements such as lightning conditions, colour, perception of safety, separation between public and private spaces, noise and flexibility become essential for people living in these realities [11].

Also, minimum area requirements need to be ensured. Outer space being the ultimate extreme environment, a sound reference for the threshold values for 'minimum area' is NASA’s reference for space crews. According to these requirements, a habitat of six people must have a minimum area of 55m² and a habitable volume of 150m³ [12]. In extreme conditions, architectural design must integrate improved effectiveness with functionality and aesthetics to assure a holistic well-being of the inhabitants. This leads to selecting three essential morphology qualities: floor area (it must ensure the minimal requirements while trying to remain as small as possible); height (must also ensure a minimal comfortable height but the smallest the better), and space organization (which must ensure all the requirements presented by NASA to guarantee the most comfortable living experience possible).

3. Methodology
Designing for extreme environments is a peculiar task and it must respond to distinct requirements other than the usual contemporary standards. As mentioned above, there are specific technical, material, and spatial attributes that inform the design process. It seems therefore that an evaluation methodology may be of great interest to validate design proposals for these environments. This study aims at developing a proposal for such an evaluation methodology, based on a multi-criteria decision analysis (MCDA) framework [13].

3.1 MCDA Model Criteria
Based on the insights from other research and from previous phases of this project (vd. section 2), a set of four categories (grouping a total of 11 criteria) was established for the evaluation methodology: energy efficiency (including criteria ‘energy consumption’ and ‘free-floating mean internal operative temperature’); material performance (including criteria ‘service temperature’, ‘fracture toughness’, ‘weight’, ‘carbon footprint’ and ‘end-of-life’); architectural performance (including criteria ‘minimum areas’, ‘internal spatial height’ and ‘space organization’); and circularity. It should be noted that heat transfer properties are not considered individually because these will be the most conditioning factors for the energy performance simulations. Circularity is introduced as a way of including sustainability-related concerns in the design options; it is an index-type criterion built upon energy efficiency, carbon footprint and end-of-life.

3.2 Energy Efficiency
The data for this criterion (energy consumption and average free-floating internal temperature) was obtained from EnergyPlus using Ladybug and Honeybee running on a Grasshopper parametric model [14].

For the purpose of this study, data relative to the indoor temperature of the building (for each material assembly presented previously) is retrieved, both in free-floating and within comfort targets, to know how much energy would be necessary to achieve comfort conditions. The indoor comfort target temperatures used in the study are common references for low-energy indoor environments [15]: 16-18 °C for Yakutsk and 26-28 °C for Needles.

In order to run the simulation, it is also required to provide Honeybee other types of information, specially related to space usage, occupancy schedules, lightning conditions, and equipment load. Space usage is in this case six people; the occupancy
schedule is defined for a 24-hours period, considering that, in an extreme environment, inhabitants would live and work within the building; the lighting load density is defined at 3 W/m², which corresponds to efficient LED bulbs; and lastly, equipment load density is defined at 7 W/m², corresponding to a mid-scale load density (between 2 W/m² for one laptop and 15 W/m² for a heavy-equipped office). As the building would have both a work area and sleeping areas where little to no electronic equipment would be required, maintaining the load at half the scale was considered an adequate depiction of the equipment load. Simulations were run for the most extreme period in each climate: June to August for the hot climate, and December to February for the cold climate. Simulation results were then analysed through Ladybug visualization tools and exported to the MCDA model.

### 3.3 Material Performance
Regarding the data for Material Performance, the first criterion of Service Temperature was only used for the extreme cold temperature scenario, because all the materials could successfully handle the extreme hot temperatures. High resistance to cold temperatures is indeed a mandatory feature for very cold environments. Material fracture toughness was selected as a baseline indicator of mechanical strength and durability. Based on data retrieved from a previous study (a library of 52 materials studied for the range of climate conditions selected in this study [16]) each construction assembly was given a qualitative assessment within a 5-level scale ranging from ‘very low’ to ‘very high’. The weight of each construction assembly was assessed by its total weight computing the sum of each layer weight calculated using density from the EnergyPlus library and volume of material used. Carbon footprint is assessed through the total embodied carbon of the construction assembly, considering the system boundary of cradle-to-gate. Unit values for embodied carbon were retrieved from the Inventory of Carbon & Energy (ICE) [17]. The criterion end-of-life characterizes the reuse and recycle potential of each construction assembly.

### 3.4 Architectural Performance
For this specific group of criteria, in order to facilitate the testing of the model, just one example of architectural morphology and internal design was used: a habitat planned for up to 6 people. The 3D digital model was replicated in Rhinoceros 3D, a prism with interior dimensions of 4.80m per 11.80m, with 56.64m² of internal area. The height was defined at 2.40m, as it is the minimum height for residential spaces [18]. The interior spatial configuration was defined considering the functional distribution advised by NASA. Therefore, in the MCDA model used for this paper, there is no variation in this criterion, all the options rating very good. The sleeping quarters and the hygiene quarters are on opposite sides of the prism; a social/eating zone and the workspace occupy the central area of the plan; this offers both privacy and noise reduction. Sleeping and workspace zones have the same area, while the social area is the largest space, and the hygiene quarter was divided into two smaller areas, one for bathing and another one for various uses (Fig.1). Category ‘architectural performance’ is divided in three criteria: Area, Height and Space Organization. The first two criteria are assessed quantitatively against the references recommended by NASA. The last criterion is qualitative, and it refers to the internal organization of the different functionalities; as a proposal based of the directives of NASA, it rates High on a scale of Low, Medium and High.

![Figure 1: Floor plan of the base prism with sleeping quarters (green), social area (yellow), workspace (orange) and hygiene quarters (blue).](image)

### 3.5 Circularity
The circularity criterion was envisaged as a mean to have a single indicator expressing the environmental impact of the options being evaluated by the MCDA model. Following an index-type procedure, it puts together energy consumption, average internal free-floating temperature, carbon footprint and end-of-life data. The assessment of each construction assembly for this criterion was performed in a dedicated MCDA sub-model, and then the results exported to the main MCDA assessment model.

### 3.6 MCDA Model Creation
The main advantage of a multi-criteria decision analysis methodology to evaluate a set of architectural proposals is the easiness with which design scenarios may be represented through the relative weighing of each criterion. For the purpose of this study, the MACBETH approach is used [18], through the computational tool M-MACBETH, offering the ability to include qualitative judgments based on differences of attractiveness.
The first step when planning the M-MACBETH model is to define the value tree composed of the set of criteria that will be used to evaluate the group of options (in this case, options are the material assemblies). The basis for comparison in each criterion may be the options themselves (using or not reference values), qualitative performance levels or quantitative performance levels. Then, the options to assess are uploaded to the model and characterised against each criterion. The difference of attractiveness between criteria is then used to include judgements related to the objective of the assessment process. Further fine-tuning may be accomplished through changing the difference of attractiveness between the performance levels of each criterion, what may prove useful to represent different project scenarios.

The base value tree includes 11 criteria: energy consumption and free-floating mean internal operative temperature (energy efficiency category); service temperature, fracture toughness, weight, carbon footprint and end-of-life (material performance category); minimum areas, height and space organization (architecture performance category); and circularity (as above described).

At the actual stage of the research, it was decided to use a single base architecture morphology and configuration. Therefore, the options being assessed to test the model are the four types of construction assembly above described: ‘Generic’, ‘Mass’, ‘Metal’ and ‘Wood’.

Options characterization for energy consumption and free-floating mean internal operative temperature comes from the simulations using Ladybug and Honeybee. The performance levels, in each case, are set within the range of actual values for the set of options. Energy consumption was measured for the whole 3-month period per unit surface area [kWh/m²].

The performance related to the resistance to extreme low temperatures was characterized through a qualitative basis for comparison using a 3-level scale (low, medium, high). As previously mentioned, mechanical strength and durability, as assessed by the fracture toughness, was also characterized using a 5-level qualitative scale ranging from ‘very low’ to ‘very high’; in this case, the need for a wider qualitative scale arose from a wide range between the best and the least performing options. Weight is a quantitative criterion considering the total weight of each construction assembly [kg]. Carbon footprint is also a quantitative criterion assessing the comparative climate change potential of each option, computed as the total embodied greenhouse gas emissions [kgCO₂e]. The reuse and recycle potential (criterion end-of-life) of each option is compared through a qualitative 3-level scale (low, medium and high).

In what concerns the architecture performance category, minimum areas and height are quantitative criteria ([m²] and [m], respectively); for this specific study the dimensions of the model are the same for all four options, 56.64m² in area and 2.4m in height. Space organization is again a 3-level scale qualitative criterion (low, medium, high).

As above described, the circularity criterion is an index-type assessment using a MCDA sub-model, with scores attributed in the range 0-100. The performances of all options in all criteria are shown in table 1 (Needles) and table 2 (Yakutsk). The two values for ‘Circularity’ are for model variations A and B, respectively (please, refer to next paragraph).

Table 1: Options performance in each criterion for the hot climate (Needles).

<table>
<thead>
<tr>
<th>Criteria / Assemblies</th>
<th>Generic</th>
<th>Mass</th>
<th>Metal</th>
<th>Wood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Consumption (kWh/m²)</td>
<td>202.5</td>
<td>65.4</td>
<td>61.5</td>
<td>55.6</td>
</tr>
<tr>
<td>Free-floating temperature (°C)</td>
<td>-38</td>
<td>-32</td>
<td>-33</td>
<td>-32</td>
</tr>
<tr>
<td>Service Temperature (-)</td>
<td>L</td>
<td>L</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>Fracture Toughness (-)</td>
<td>VL</td>
<td>VL</td>
<td>VH</td>
<td>VL</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>86865</td>
<td>45898</td>
<td>7239</td>
<td>6904</td>
</tr>
<tr>
<td>Carbon footprint (kgCO₂e)</td>
<td>21800</td>
<td>17379</td>
<td>9184</td>
<td>7805</td>
</tr>
<tr>
<td>End-of-life (-)</td>
<td>L</td>
<td>L</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Minimum Areas (m²)</td>
<td>56.64</td>
<td>56.64</td>
<td>56.64</td>
<td>56.64</td>
</tr>
<tr>
<td>Height (m)</td>
<td>2.40</td>
<td>2.40</td>
<td>2.40</td>
<td>2.40</td>
</tr>
<tr>
<td>Space Organization (-)</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>Circularity (-)</td>
<td>25%/5%</td>
<td>17%/12%</td>
<td>71%/48%</td>
<td>63%/48%</td>
</tr>
</tbody>
</table>

Table 2: Options performance in each criterion for the cold climate (Yakutsk).

<table>
<thead>
<tr>
<th>Criteria / Assemblies</th>
<th>Generic</th>
<th>Mass</th>
<th>Metal</th>
<th>Wood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Consumption (kWh/m²)</td>
<td>202.5</td>
<td>65.4</td>
<td>61.5</td>
<td>55.6</td>
</tr>
<tr>
<td>Free-floating temperature (°C)</td>
<td>-38</td>
<td>-32</td>
<td>-33</td>
<td>-32</td>
</tr>
<tr>
<td>Service Temperature (-)</td>
<td>L</td>
<td>L</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>Fracture Toughness (-)</td>
<td>VL</td>
<td>VL</td>
<td>VH</td>
<td>VL</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>86865</td>
<td>45898</td>
<td>7239</td>
<td>6904</td>
</tr>
<tr>
<td>Carbon footprint (kgCO₂e)</td>
<td>21800</td>
<td>17379</td>
<td>9184</td>
<td>7805</td>
</tr>
<tr>
<td>End-of-life (-)</td>
<td>L</td>
<td>L</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Minimum Areas (m²)</td>
<td>56.64</td>
<td>56.64</td>
<td>56.64</td>
<td>56.64</td>
</tr>
<tr>
<td>Height (m)</td>
<td>2.40</td>
<td>2.40</td>
<td>2.40</td>
<td>2.40</td>
</tr>
<tr>
<td>Space Organization (-)</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>Circularity (-)</td>
<td>0%/0%</td>
<td>55%/27%</td>
<td>80%/56%</td>
<td>88%/59%</td>
</tr>
</tbody>
</table>

Four variations of the base MCDA model were considered. Model A corresponds to the base model, in which the difference of attractiveness between each criterion was given by an equitable distribution among the four categories (25%). In each category, the weighting factors are evenly distributed: the 25% are divided among the number of criterions within the category, meaning that if one category has more criteria, each will value less than what is the case in another category with less criteria.
In model B, the sub-model for calculating the scores related to the ‘circularity’ criterion was changed in how it compares options for the energy consumption and the free-float operative temperature. While in the first case (MCDA model A), this circularity sub-model used the actual values in the range as low and high reference scores, in the MCDA model B the references used correspond to energy efficiency good practices in Europe. In the case of energy consumption, a reference of 11 kWh/m² final energy was used for the highest score. In what concerns operative temperature, 18°C and 28°C were used for the cold and the hot climates, respectively.

MCDA models C and D represent a change in the assessment approach, from a general evaluation methodology to a more realistic approach related to project scenarios. The criteria ‘free-float operative temperature’ and ‘circularity’ are now disregarded. In the first case, because the values are so extreme and out of the comfort zone that it would not make sense to consider it as an evaluation criterion in real conditions; on the other hand, the differences between options are too small to be significant (from -38°C to -32°C for the cold climate, and from 43° to 46°C for the hot climate). The option of removing ‘circularity’ was related to the fact that in these two new models (C and D) the difference of attractiveness between criteria now corresponds to real conditions project scenarios and thus the redundancy effect associated with using circularity as an independent criteria is no longer useful. Another important change implemented in these two models (C and D) is that the value scale for evaluating the resistance to extreme low temperatures was modified so that the ‘Wood’ option rates higher in the cold climate than in the hot one. The ‘Metal’ construction assembly rates higher, followed by ‘Wood’, then ‘Generic’ and ‘Mass’. For the model related to the cold climate however, the ‘Wood’ option rates higher than the best option for the hot climate, followed closely by the ‘Metal’ assembly, then ‘Mass’ and then ‘Generic’ at the bottom of the scale.

4. RESULTS

The ratings of each construction assembly, in the four MCDA models, are presented below in tables 3 and 4 in a 0-100 scale.

MCDA model A, with all the categories having the same relative importance, delivered different results between the extreme hot and the extreme cold climates. In the first case, the ‘Metal’ construction assembly rates higher, followed by ‘Wood’, then ‘Generic’ and ‘Mass’. For the model related to the cold climate however, the ‘Wood’ option rates higher than the best option for the hot climate, followed closely by the ‘Metal’ assembly, then ‘Mass’ and then ‘Generic’ at the bottom of the scale.

### Table 3: Ratings of the four construction assemblies in the four MCDA models, for the hot climate (Needles).

<table>
<thead>
<tr>
<th></th>
<th>Model A</th>
<th>Model B</th>
<th>Model C</th>
<th>Model D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generic</td>
<td>25%</td>
<td>15%</td>
<td>11%</td>
<td>10%</td>
</tr>
<tr>
<td>Mass</td>
<td>19%</td>
<td>16%</td>
<td>31%</td>
<td>31%</td>
</tr>
<tr>
<td>Metal</td>
<td>76%</td>
<td>64%</td>
<td>85%</td>
<td>91%</td>
</tr>
<tr>
<td>Wood</td>
<td>61%</td>
<td>53%</td>
<td>77%</td>
<td>67%</td>
</tr>
</tbody>
</table>

### Table 4: Ratings of the four construction assemblies in the four MCDA models, for the cold climate (Yakutsk).

<table>
<thead>
<tr>
<th></th>
<th>Model A</th>
<th>Model B</th>
<th>Model C</th>
<th>Model D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generic</td>
<td>1%</td>
<td>1%</td>
<td>9%</td>
<td>8%</td>
</tr>
<tr>
<td>Mass</td>
<td>56%</td>
<td>42%</td>
<td>30%</td>
<td>28%</td>
</tr>
<tr>
<td>Metal</td>
<td>85%</td>
<td>73%</td>
<td>88%</td>
<td>92%</td>
</tr>
<tr>
<td>Wood</td>
<td>87%</td>
<td>73%</td>
<td>83%</td>
<td>76%</td>
</tr>
</tbody>
</table>

In model B, all the assemblies rated lower than in the previous model A but generally kept the same relative position in the overall scale.

In MCDA model C and D, the assemblies rated similarly in the two environments, both models following the same organization of ratings: ‘Metal’, ‘Wood’, ‘Mass’ and ‘Generic’.

5. DISCUSSION

Considering all the simulations run through the four MCDA models it may be concluded that construction assemblies ‘Mass’ and ‘Generic’ are the worst for extreme climates, being that they aren’t prepared to handle this environments within controlled parameters, even if the Mass assemblies rates higher in the cold climate than in the hot one. For hot climates, the ‘Metal’ and ‘Wood’ are preferential, although ‘Metal’ rates higher, the biggest difference between the ratings being in model D. This is due to the fact that mechanical properties are given priority in this case, and ‘Wood’ fracture toughness is much lower than ‘Metal’. On model C ‘Wood’ rated higher due to environmental concerns (with the end-of-life and embodied carbon criteria).
Regarding the cold environment, ‘Wood’ rates higher in model A, when all criteria have the same weight, and in Model B, where high-performance benchmarks were used for the criterion ‘Circularity’, ‘Wood’ and ‘Metal’ rate very similarly. Relative to model C and D, ‘Wood’ rates higher in model C, and lower in model D, exactly for the same reasons as in the hot climate scenario.

It is important to remark that these construction assemblies are preliminary since they were chosen from a default database, and thus are not yet customized. Future work will include running the models with customized construction assemblies to reach a better understanding about the influence of each material.

The ultimate purpose of this study is to validate a multi-criteria approach to evaluate architecture building proposals for extreme environments. The models proposed in this paper, including their capacity to be adapted to different project scenarios, seem to be a valid framework. Further research will include custom materials and assemblies, other types of architectural morphologies (with different areas and heights) and other climate scenarios. This will add to the existent knowledge on architecture for extreme environments, hopefully providing a new methodology for evaluating future building proposals and opening the way for new research.

ACKNOWLEDGEMENTS

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REFERENCES

A Comparative Monitoring Study of Indoor and Outdoor Heat Stress in Four Different Urban Typologies in Cairo

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2Heidelberg University, Heidelberg, Germany
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ABSTRACT: Rapid urbanization and increasing heat exposure from climate change in combination with the urban heat island effect has become a contemporary pervasive threat to human health. We monitored four urban typologies with temperature and humidity sensors during the 2015 summer peak in Cairo, Egypt to evaluate which typologies could potentially reduce adverse impacts on human health. Our mixed methods approach included qualitative surveys to gauge how people perceived heat stress. While our monitoring revealed that indoor temperatures were cooler by 1.64°C in the low-density typology relative to outdoor temperatures, the minor indoor temperature differences revealed that building envelopes had little impact on protecting inhabitants. The study points to the urgent need for more comprehensive empirical monitoring of indoor heat stress in urban areas. Future research would benefit from greater interdisciplinarity so that a more inclusive range of heat stress scenarios, particularly in urban areas in the Global South, can be anticipated, and thereby monitored, mitigated and potentially avoided in order to reduce human health insecurity impacts from climate change.

KEYWORDS: Heat stress, urban heat island effect, urban green space, urban density, human health

1. INTRODUCTION

Anthropogenic greenhouse gas emissions are increasing average global temperatures, which will continue to rise if left unmitigated to fuel climate change [1,2]. The World Health Organization (WHO) sounded the alarm in 2015 by declaring climate change to be “the greatest threat to global health in the 21st century” [3].

To understand what the WHO means by “health” in this context, one need only look to the WHO constitution (1948; 2005) [4] which claims human health as “a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity.”

Climate change scenarios for the Middle East indicate severe temperature increases, with particularly dire scenarios for Egypt in particular as Cairo, with a population of over 20 million inhabitants, is ranked as the most densely populated city in the Middle East [5]. Several climate models estimate a steady increase in air surface temperatures for Egypt [6]. We chose to study Cairo as a densely populated urban centre in the Global South that is already facing human health impacts from extreme heat.

Our interdisciplinary study heeds earlier calls for research that combines the methodological rigour of biometeorology with a contextual understanding of culturally embedded risk factors by applying a social anthropological lens to not only consider the ‘what’ but also the ‘why’ in order to examine the risks within the specific context. As such, we have combined bioclimatic science with architectural design, while also doing preliminary work to illustrate the value of considering both direct and indirect risks when examining climate risks to health.

1.1 Direct and Indirect risks

Health researchers tend to focus on direct health risks when evaluating possible climate change impacts on individuals and communities, such as the potential direct health risks of climate change on respiratory health. One direct health risk study focused on concentrations of all health-related air pollutants in relation to allergic airway diseases such as asthma and rhinitis [7]. Our study evaluates the direct health risks of heat stress.

However, to apply the kind of holistic approach to human health urged by the WHO, researchers must evaluate both direct and indirect risks to human health faced by people living in megacities. Our study took
initial steps to begin to capture some indirect health risks faced by people living in Cairo by using qualitative interviews to capture how people perceived heat stress is affecting them personally, including their challenges trying to escape heat stress indoors, as well as in urban green space (UGS).

Scholars and security analysts describe climate change as a “threat multiplier” that can lead to “many second order effects” including migration and “health insecurity” [8], as well as trigger civil unrest, armed conflict and even war. We discuss opportunities for future research to expand on our preliminary findings in the final discussion section.

1.2 Regional climate vulnerability

High ambient air temperature is a leading cause of weather-related mortality in many regions of the world [9,10]. If increasing temperatures continue unabated, some parts of the world, including the Middle East, will become uninhabitable [11]. Therefore, our health risk assessment of Cairo includes a mid-range climate change scenario (IPCC RCP 6.0).

1.3 Local urban heat island effect

Urbanization exacerbates the negative impacts of increasing heat [12]. Urban areas, dominated by heat retaining structures, such as buildings and roadways (while having very few green spaces), can create an urban heat island effect characterized by elevated air temperatures compared to surroundings areas, even during night-time, leaving urban dwellers unable to escape both the physical and psychological risks associated with high heat [13].

Cairenes face this exact scenario in their dense city, and the situation is worsened by both climate change and by Cairenes having abandoned their older vernacular and traditional building practices that were intentionally designed to incorporate heat reducing features [14]. For example, one of Cairo’s renowned older building practices were the Cairene courtyard houses, featuring two cooling architectural features, specifically “the Durqa’a” as an uncarpeted high roofed circulation space that provided light and enhanced ventilation, and the “Maka’ad” as a square or rectangular shaped covered loggia, opened with its entire façade onto the court, “essentially oriented to the north in grasp of the soft breeze” [15]. Today, Cairo has few urban green spaces and an abundance of substandard housing with poor roofing and entire building envelopes designed without any intentional features to reduce heat exposure [16].

There is a well-established body of research on the relationship between hot outdoor temperatures and mortality [9,10,17]. However, studies presenting empirically measured differences between indoor and outdoor temperatures during heat episodes remain comparatively scarce. Our study starts filling this gap.

2. METHODOLOGY

We selected Cairo, a dry, hot city in the Global South where people live and work in. We applied a case study methodology [18] (Yin,2003) to intensively monitor and analyse four case site locations in Cairo. Each case site represented one of four specific urban typologies, namely: high density, medium density, low density and an urban green space (UGS) that we also refer to as a park environment. Three of the four typologies pivot on urban density as a proxy for evaluating the microclimatic impact correlated with a lack of green space. Using urban density as a way of denoting when urban green space is absent enabled UGSs to be viewed with a new lens when factoring in how UGSs influence indoor and outdoor air temperatures.

2.1 Monitoring and thermal comfort collection methods

We collected data in four typologies in four different locations using air temperature measurements during the peak of summer heat between the 12th of July and the 22nd of August 2015. One location is a high-density typology with limited UGSs and represents an informal settlement. In Cairo, 40% of the housing is informal [5]. The medium density typology represents a more typical middle-income housing location with a mix of roads, buildings and UGSs. The low-density typology is representative of a high-income gated community featuring 60% UGSs, with only 40% containing buildings and streets. The park typology was used to gauge how UGSs impact temperatures and thermal comfort among respondents.

The rooms selected for the monitoring within the three building typologies were all living rooms. Construction materials used for the building envelope are similar in the four cases. During the monitoring we asked the occupants not to use any air-conditioning to reduce bias in the results. Occupant schedules, age, gender, and clothing were also accounted for in this study.

Environmental monitoring of temperature and humidity was performed using LASCAR EL-USB-2-LCD+ (accuracy of air temperature: +0.3C; relative humidity: +2%) data loggers. Two loggers were placed in each urban typology - one inside the building and one outside in the shade, with protection from rain, wind and direct sunlight. In the park, we placed the indoor logger in a housing facility used by the park officers. Environmental data was collected at one-hour intervals. On the last day of each of the monitoring periods, the thermal...
environment satisfaction survey [19] was used together with a qualitative questionnaire to evaluate how residents perceived their indoor comfort. Two residents (one male and one female) at each indoor typology participated in the survey. At the outdoor park typology, it was only possible to ask two male respondents.

2.2 Data analysis methods

We conducted linear regression to quantify the difference (also called the delta) between indoor and outdoor air temperatures and relative humidity. These deltas were used as our indicator of heat stress based on empirical data collected in the four typologies. We calculated the mean change in coefficient for temperature and humidity indoors relative to the same type of data gathered outdoors. We considered effect estimates with \( p \)-values below 0.05 to be statistically significant. We both performed statistical analyses using \( R \) v. 3.3.3, and also quantified climate change projections for outdoor heat stress in Cairo based on the IPCC RCP 6.0 mid-range future scenario from among five global climate models visualized within the Climate CHIP analysis tool (Climate CHIP, 2019).

3. RESULTS

The air temperature (AT), relative humidity (RH) and dew point (DP) were measured for each urban typology. The typologies have been abbreviated in Figure 1, Tables 1 and 2 as: “high dense” for high-density, “medium dense” for medium-density, “low dense” for low-density and “park” for UGS.

Indoor air temperature measurements revealed buffered results relative to outdoor temperatures, as illustrated by the differing diurnal fluctuations at each typology (Figure 1). We did not observe a statistically significant difference between indoor and outdoor temperatures in the park. However, being the peak of summer, it should be noted that in all four typologies, air temperatures remained above 30°C, risking persistent heat stress day and night for residents.

We observed slightly higher indoor temperatures relative to the outdoor temperatures in both the high- and medium-density typologies by 0.07°C and 0.87°C respectively. The difference in temperature for the medium-density typology was statistically significant at the 5% level. Only the low-density typology had indoor temperature readings that were cooler than outdoor temperatures. The low-density typology had the largest temperature delta with indoor readings 1.64°C below outdoor temperature. Relative humidity observations in all four typologies were lower indoors than outdoors. However, both the high-density and low-density typologies were slightly more humid inside than outside by 0.59% and 2.72% respectively. However, this difference falls within the margin of error specified for the LASCAR devices used.

Table 1: Monitoring results for four urban typologies in Cairo

<table>
<thead>
<tr>
<th>Parameter</th>
<th>High dense</th>
<th>Medium dense</th>
<th>Low dense</th>
<th>Park</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT (°C)</td>
<td>33.38 (3.71)</td>
<td>33.16 (3.63)</td>
<td>34.33 (3.79)</td>
<td>36.28 (3.76)</td>
</tr>
<tr>
<td>RH (%)</td>
<td>55.54 (11.90)</td>
<td>55.13 (10.87)</td>
<td>43.83 (10.82)</td>
<td>45.54 (9.78)</td>
</tr>
<tr>
<td>DP (°C)</td>
<td>22.86 (2.28)</td>
<td>22.48 (2.31)</td>
<td>20.98 (1.98)</td>
<td>21.96 (2.47)</td>
</tr>
</tbody>
</table>

The thermal environment satisfaction survey, which was used alongside a qualitative questionnaire to evaluate the perception of respondents about their thermal comfort, provided additional insights. Respondents indoors at the high- and medium-density typologies said they felt inconvenienced by the high heat indoors. In contrast, respondents both indoors at the low-density typology, as well as outdoors at the UGS typology expressed satisfaction with their thermal comfort, thanks to shade trees perceived as providing cooling. Respondents at the low-density typology expressed satisfaction at the convenient proximity of their housing to the UGSSs, particularly since the UGSSs created wide spaces around their homes to reduce the density of the area. However, one respondent at the low-density typology expressed concern that their building is more exposed to direct sunrays from all directions, which they had perceived as creating the need for continuous daytime air conditioning to reduce indoor temperatures. Both respondents at the low-density typology said they tend to turn off air conditioning in favour of opening windows for ventilation and cooling. They also conceded that during high humidity, they use their air conditioning continuously day and night.

Table 2: Linear regression indicating the mean temperature and humidity differences in four urban typologies in Cairo, Egypt. The differences presented are for indoor temperature or humidity relative to outdoor temperature or humidity. *** indicates statistical significance at 0.05 or lower.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Temperature difference</th>
<th>Humidity difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>High density</td>
<td>0.07 (0.00 to 0.15)</td>
<td>0.59 (0.36 to 0.82) ***</td>
</tr>
<tr>
<td>Medium density</td>
<td>0.87 (0.81 to 0.93) ***</td>
<td>-1.84 (-2.04 to -1.65) ***</td>
</tr>
<tr>
<td>Low density</td>
<td>-1.64 (-1.72 to -1.56) ***</td>
<td>2.72 (2.41 to 3.03) ***</td>
</tr>
<tr>
<td>Park</td>
<td>0.00 (-0.20 to 0.20)</td>
<td>0.00 (-0.66 to 0.66)</td>
</tr>
</tbody>
</table>
Respondents at the high-density typology perceived the shade cast by buildings as potentially providing relief from the sun for their building facades. These same respondents attributed the lack of space between buildings as reducing indoor air flow, which they perceived as worsening heat stress, and voiced their belief that having more UGSs would provide spaces where they could escape their feeling of overheating during summer. Similarly, respondents at the medium density typology expressed dissatisfaction with the lack of UGSs in their neighbourhood, and concern that densification due to low rise buildings being replaced by high rise buildings would worsen heat stress by cutting off access to night-time breezes through open windows and increase air conditioning dependency.

3.1 Climate Change projections

The historical air temperatures measured onsite at Cairo airport over a twenty-year period from 1980-2020 reveal an upward trend, namely a 0.51 degrees Celsius temperature rise each decade (Climate CHIP, 2019), as illustrated in Figure 2. Forecasts for future heat stress in Cairo project further increases, even if using the modest mid-range future scenario model for the IPCC’s RCP 6.0. We selected the IPCC RCP 6.0 from among the five global climate models we viewed through the Climate CHIP analysis tools (Climate CHIP, 2019), as shown in Figure 3. July outdoor temperatures in Cairo are already frequently above 35 degrees and are expected to rise higher under the IPCC RCP 6.0 mid-range model forecasts. This is alarming given that thermal comfort between 18-26 degrees Celsius is a prerequisite for mental and physical health [20-21].
4. DISCUSSION

Only the low-density typology had indoor temperatures measured at 1.64°C less than outdoors. This difference could be attributed to the abundance of trees around the building that provided shade over the building envelope, and adequate ventilation from air moving between homes. Respondents both at the indoor low-density typology, and at the UGS typology, also attributed their reduced feeling of heat to the available shade trees.

These responses are consistent with previous findings [22]. Evergreen trees with wide canopies were appreciated by survey respondents due to the shadows cast on building facades, sidewalks and on streets, thus providing a more comfortable pedestrian experience. Trees were most prominent in both the low-density and the UGS typology, both of which revealed lower temperatures and thus less risk of heat stresses.

However, the higher indoor temperature readings in both the high- and low-density typologies can be attributed to the UHI effect. The UHI effect is prominent in high-density structures that retain heat and have insufficient ventilation to cool indoor spaces [23]. We found that the conditions most vulnerable to heat stress were at both the high and low-density typologies, albeit due to different design flaws. Even though the low-density typology had more UGSs, its horizontal areas had abundant asphalt and concrete surfaces, while much of the vertical building surfaces were glazed facades exposed to direct sun, resulting in heat gain throughout the day. Meanwhile, the heat stress in the high-density typology could be attributed to poor building envelopes lacking adequate ventilation, and a lack of UGSs. Incorporating design elements that reduce heat, such as incorporating UGSs of over 10ha, or the vernacular architectural features used traditionally to ventilate Cairene houses, could contribute significantly towards reducing the impact of extreme urban heat. We can also learn from useful design features the high-density typology in which the clustering of the buildings cast shadows that reduced heat gains via facades while providing more sidewalk shade for pedestrians. The high-density typology also had better window-to-wall ratios, which helped to reduce heat gains from glazing.

Both health and urban planning professionals alike could help save lives by promoting these simple local design strategies. Failure to do so would require Cairo’s public health authorities to plan to rely on the mass deployment of mechanical air conditioners, along with a centralized energy cost subsidy, to make lifesaving conditioning affordable to all those living and working in Cairo.

4.1 Study Limitations

Although the monitoring within all three building typologies was done in living rooms, the orientation of the rooms was not analysed in our results. Thus, south or west oriented rooms could have been exposed to the sun more intensely than the north and east facing rooms. Our study design also only captured data from a single location within each typology, making it difficult to draw wide-reaching conclusions regarding the observations collected. A larger monitoring sample set in a future study could evaluate more generalizable heat stress trends in different urban typologies.

In our study design and evaluation criteria, we did not dive more deeply into indirect risks to human health due to constraints faced at the time of the fieldwork. However, these indirect risks pose some of the most disruptive potentialities, and thus must be assessed if we are to mobilize the political will to prevent horrific individual and social impacts of climate change.

5. Future research needs

The use of continuous real-time measurements using simple, low-cost sensors to collect a small dataset enabled us to capture residential heat data unobtrusively for residents within each typology as a continuous long-term data collection. Working in intimate living environments in the future using this method would make it possible to explore exposure profiles and contextual impacts for measured variables such as air temperature and humidity. Beyond sleeping difficulties for those without air conditioning, and other transitory diurnal and seasonal patterns, heat stress poses a serious health risk as a “threat multiplier” that can lead to “many second order effects” including “health insecurity” [8]. Researchers must begin including direct and indirect threats into their study designs.

6. CONCLUSION

Even with the limited number of data points collected in this study, we observed signs of heat induced health risk in Cairo. As always is the case with small data sets, we caution against making sweeping generalizations based on our findings. Furthermore, any generalizations drawn from case studies such as this one requires conscious reflection on the similarities and differences between contextual features, urban development and historical factors. Even in this small sampling, we can already see a potential tendency towards a higher level of heat stress that can be mitigated by modifying design elements, rather than by more expensive mechanical air conditioning. In contrast with historical Cairene courtyard houses that featured cooling architectural features, indoor heat stress is not easily mitigated. We found that indoor temperatures
were slightly cooler in the low-density typology in which UGSs, pointing to the importance of incorporating more UGSs and other low-cost urban design measures in order to leverage green infrastructure for reducing urban heat stress.

Finally, we urge researchers to address both direct and indirect risks to human health in future studies.

ACKNOWLEDGEMENTS

The authors are grateful to Professor Tord Kjellström at the Health and Environment International Trust, Mapua, New Zealand, for providing data loggers for our study. We also thank all residents and the park management staff for granting access to our study sites.

AUTHORS CONTRIBUTION

Marwa Dabaieh 30%, Karin Lundgren Kownacki 25%, Siri Kjellberg, 25% and Aditi Bunker 20%.

REFERENCES


ABSTRACT: The impacts of climate change and extreme weather events can be seen all around us, causing record-breaking damage. Such events, coupled with wars and social unrest, are resulting in people losing their homes at an unprecedented and growing rate, forcing them to rely on semi-permanent structures. To explore the design of these structures in extreme cold, a prototype tent made of innovative materials, capable of resisting the extreme weather in Antarctica, was made, and tested, on a site at King George Island, in 2019. The shelter was left on-site there for twelve months, during which some damage was recorded, resulting in high levels of humidity in the structure, and wind damage on the outermost fabric layer. This paper attempts to reverse-design the tent comparing theoretical, and field data. Using an algorithmic design tool, the shelter was modelled within the site contours, and comfort and airflow simulations were made to assess the thermal properties of the used materials. Durability and comfort performance are discussed and compared with permanent standard structures, as are their implications on the design of similar projects in extreme weather conditions in future unpredictable climates.


1. INTRODUCTION

Over the past decades, disaster-related events have been responsible for the displacement of millions of people around the world, and roughly 90% of those are weather-related [1]. Buildings are increasingly failing because of the escalating impacts of climate trends and weather events [2]. Moreover, it is estimated that by 2050 there will be an increase from 55% to 68% of the world population living in urban areas, and most of this urbanization will have to be prepared for a very different climate and environment [3]. A recent study on coastal flooding indicates that up to one billion people now occupy land which is less than 10 meters above current high tide lines, including 230 million below 1 meter, and these numbers will increase as people flock to coastal cities [4]. With the consequent explosion in health emergencies and social, economic, and climate issues, people will require huge numbers of adaptable temporary structures. With that in mind, a multidisciplinary team was assembled to develop and experiment with a yurt-like tent in Antarctica, to take lessons from the extreme weather, to improve and adapt temporary shelters in the field, and to prepare them against future weather conditions.

Four expeditions to King George Island resulted in the development of a high-performance shelter at Collins glacier (Fig. 1), which can be easily built in a day and house up to four field workers comfortably while resisting extreme winds and cold temperatures throughout the year. A prototype inspired on a traditional Yurt was mounted in Antarctica in 2016 (PL1) [5], but it proved to have some shortcomings in terms of thermal performance, and its structure collapsed during a storm with wind gusts of over 170kmh.

The design was then improved, after exploring new solutions to increase structural resilience, make it more wind resistant, and using innovative materials to improve thermal performance and water tightness. A novel skin envelope was finally chosen, composed of two skins of a new lightweight, eight-layer material called ORV8, one in each side of the timber structure, surmounted by an outer layer of Dyneema made of recycled racing yacht sails. ORV8 underwent preliminary testing in a cold facility in the UK and proved very effective as a thermal insulator [6]. The second tent (PL2) was constructed in England, incorporating these materials, and then transported for testing on-site at Collins Bay, Antarctica, in 2019, where it was easily erected, tested, and reported on, for its siting [7] and its structural [8] and thermal [9] performance. A key finding of that experiment was that the inclusion of theoretical assumptions should be backed up by liaising with experts, bench and field testing, and simulation to validate performance analyses and optimize the design [10].

What proved difficult in testing the new materials was their property characterization. Dynenea is one of the strongest materials, given its weight and strong resistance to wind and rain, making it ideal for high-performance racing sails [11]. The two multi-purpose...
layers of ORV8 had not been tested before the PL2 team’s experiment, which was conducted in a cold room with one person occupying the tent for 15 minutes. The indoor heat gains were of 1.1ºC per minute, ranging from -15 to -5 ºC, and tripled when a small gas heater was deployed. Even though these tests lacked more robust information on the materials’ thermal properties, it was decided that the final tent would be built for field testing.

In February 2020, a third field trip to Collins Bay was undertaken to see how the tent withstood the extreme weather conditions in the twelve previous months. Upon arrival at the site, the tent looked intact. The structure resisted the 2019 Antarctica Winter without any damage. In terms of its envelope, a detailed damage report showed that it had suffered slight deterioration, including small rips on the external Dyneema layer, damp accumulated between the lower and upper groundsheets, and moisture damage on some of the tent wall trellis members and rafters. The location and intensity of the damage were mapped and recorded in a full condition report for the tent after its first year.

After reviewing the gathered data, several questions emerged regarding the causes of envelope damage, and the thermal properties of the innovative materials. These are important to understand the long-term potential of this shelter as a semi-permanent structure rather than as a temporary, seasonal one. This was particularly relevant for the head of the Chilean Base, who was interested in using the tent as temporary housing for workers during the summer season. To answer these questions, this research aims to use simulation, informed by readings taken on-site, to reverse-engineer the shelter to better understand its future usefulness as a shelter in the local climatic conditions and geomorphological context.

The adopted methodology integrates Algorithmic Design (AD) and Building Performance Simulation (BPS) after the design and construction process, as opposed to traditional applications of AD and BPS which are made, respectively, during early and final design stages. The goal is to (1) provide a better understanding of the damages reported in the envelope material properties, (2) correlate the comfort metrics gathered in the field with the simulation results, and (3) compare the shelter’s performance against a permanent heavyweight structure within the same climatic conditions.

2. WORKFLOW

To achieve the proposed goals, the workflow presented in Fig. 2 starts by analyzing the data collected from an expedition to Antarctica, particularly, regarding the damage suffered by the envelope shelter, and moves on to the use of an algorithmic design and analysis tool to model the shelter and simulate its behaviour [12]. One of the advantages of this tool is its ability to coordinate different analyses, as well as integrate them with optimization algorithms within the same platform [13].

The design is parametric, to facilitate the rapid adjustment of design parameters during the analysis and comparison stage. Executed analyses in this research comprise CFD (Computer Fluid dynamics) and comfort simulations, which will respectively provide metrics such as wind velocity, and direction, around the structure, and indoor comfort metrics.

2.1. Damage, weather, and indoor comfort metrics

Weather data was retrieved from the local Airport Operations Center and contains a CSV file with wind speed (kt), and direction from March 2019 to February 2020, thus allowing the simulation of extreme scenarios to which the shelter was exposed during the Antarctic winter.

The initial visit to the shelter’s site on the third field trip there was made to assess its condition and...
damage, which showed that the outdoor window was partially open over winter, and there were some shreds in the Dyneema layer (Fig.3). These were mapped and incorporated in a model for further correlation with wind speed data. The hypothesis is that the wind speed was sufficient to create the Von Kármán Vortex Street pattern responsible for generating fabric vibrations, which ripped in its seams [14]. Through the CFD simulation, it is possible to check if high speeds are occurring in the shredded areas, indicating the creation of these patterns and the necessity of applying a different method to attach the envelope layer. Following the damage survey, data loggers were implemented outdoors and indoors during the whole mission period, collecting temperature, relative humidity, and illuminance.

Fig. 3 - Temporary mend of the envelope shreds with tape and safety pins

2.2 Algorithmic design and analyses

The parametric model was created with an AD tool, using a simple BIM space syntax. Parameters used that may vary are the trellis bottom and top radius, number of beams, trellis and roof height, width and length of the beam section, and the interval in which the beams connected each other from bottom to top. In this case, the height of the trellis was 1.5m and 1.2m for the beam length (Fig.4). Furthermore, the model is automatically exported in the required geometric format for each simulation.

OpenFoam© was used to simulate outdoor airflow using, as input parameters, wind speed and direction, test geometry, and the simulation area. We tested the most extreme case in each month since last year’s expedition. August, for example, brought winds over 30 knots that came mostly from East and Southeast, and the highest recorded speed was 70 knots from the East. The output of the simulation is the wind speed and direction in all tested points within the test area.

The inputs of the comfort analysis encompass (1) the shelter geometry; (2) the material properties, namely thermal conductivity, density, specific heat, thickness, and absorptance; (3) weather file, namely relative humidity, dry bulb temperature, and dew point temperature values gathered in the site during the expedition period; and (4) schedules describing occupancy, equipment, lighting, cooling, and heating. The equipment was switched off during the unoccupied periods and were used only during the two nights spent in the shelter for repairs, surveys, and field testing.

Material properties were developed from largely referenced values, except the ORV8, which is composed of orve+wrap©, with an additional internal lining of fleece and polyurethane on the outer layer. Laboratory test results were available for orve+wrap© that revealed its thermal resistance, emissivity, dimensions of sample, heat flux, and temperature difference for both cold and hot surfaces. This is enough to deduce the conductivity, density, specific heat, and material absorptance. The final values applied in the simulation can be seen in table 1.

Simulation outputs were compared with the data loggers regarding indoor operative temperature and relative humidity. Subsequently, a correlation was

Table 1 – Material properties used for the simulations

<table>
<thead>
<tr>
<th></th>
<th>OrveWrap</th>
<th>Fleece</th>
<th>PU</th>
<th>Wood</th>
<th>Dyneema</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (m)</td>
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<td>0.001</td>
<td>0.001</td>
<td>0.01</td>
<td>0.001</td>
</tr>
<tr>
<td>Conductivity (W/m-K)</td>
<td>0.033</td>
<td>0.15</td>
<td>0.03</td>
<td>0.11</td>
<td>20</td>
</tr>
<tr>
<td>Density (kg/m3)</td>
<td>0.5776</td>
<td>23</td>
<td>32</td>
<td>510</td>
<td>980</td>
</tr>
<tr>
<td>Specific heat (J/kg-K)</td>
<td>2800</td>
<td>1350</td>
<td>1800</td>
<td>2301</td>
<td>1850</td>
</tr>
<tr>
<td>Absorptance</td>
<td>0.48</td>
<td>0.9</td>
<td>0.95</td>
<td>0.9</td>
<td>0.9</td>
</tr>
</tbody>
</table>
made and used to quantify maximum and minimum temperature deviation values between field and simulation results and compared with the elaborated damage report.

3. RESULTS AND DISCUSSION

From the proposed workflow, the following sections follow a categorized approach in which results and discussion are divided into two stages that consider the proposed objectives, which are:

- Damage assessment and prevention.
- The relevance of AD and BPS for the design for extreme conditions.

In the first stage, a damage report is compared with simulated wind tunnel tests, and from observed air circulation, it might be possible to check if any correlation exists between the simulations and the shredded fabric. The second stage will show the operative temperature in the simulated parametric model and its comparison with the recorded indoor values during the field expedition period. Additionally, the Lodge’s performance will be tested against one of a permanent standard structure for the same weather.

3.1 Damage report and airflow simulation

The Venturi effect is well-known in fluid dynamics: when a fluid flows through a constricted section, its velocity increases and its pressure diminishes [18]. This also occurs on a macro scale, throughout urban and natural areas due to topography and the built environment. The lodge was deployed in Collins bay between the refuge base and a rocky slope, which creates constricted sections and makes it prone to higher wind speeds in these areas. Dyneema rips were numbered and mapped through their position and height to include them in a model of the shelter at Collins bay area. These were found on the structure’s eastern, western and northern sides, with heights varying from 5 to 80 cm (Fig.5). Additionally, predominant winds were recorded coming from East, West, and North, and respective highest speeds were 70, 44, and 40 knots respectively.

![Fig. 5 – Mapped envelope shreds within the site contours.](image)

Three simulated wind tunnel tests with a 45-second duration were made using the three identified predominant directions and a wind speed of 70 knots, hitting the terrain, the shelter, and a recently erected adjacent rock wall. Results from northern and eastern wind analysis showed higher values (= 20 knots) in the damaged areas due to the constrictions created by the shelter’s cylindrical geometry, the terrain near the eastern side, and the permanent refuge in Collins bay, on the western side. Moreover, the western wind analysis showed high speeds hitting the rock wall area, which prevented vortexes creation. The speed heat and vector maps (Fig.6) show a clear relation of high speeds and constricted areas with damaged zones in the structure. Furthermore, the above-described Venturi effect is observed, and it might arguably indicate the probability of Von Kármán vortex street patterns appearing where the wind speed is higher, which might be responsible for Dyneema fabric rips.

The observed results might explain the appearance and location of the damage and help prevent and protect high-risk structure areas that might suffer damage in the future. Furthermore, it shows the usefulness of these simulations in creating comfortable urban spaces.

![Fig. 6 – Northern, Western and Eastern wind speeds (left to right), and respective velocities visible in a heatmap.](image)
### 3.2 Comfort simulations

Upon arrival at Collins glacier, loggers were set from February 2nd to 9th, and the team occupied it for repairs and surveys from the 5th in the afternoon to the 8th in the morning, which meant that the door had to be open for most of the repairs, and the gas heater was used in the early night. During this period, simulation results for the shelter’s operative indoor temperatures show the biggest discrepancies, since occupancy schedules were turned off. While considering this period, it is visible an average deviation between logged temperatures in the field and those simulated of ±3 degrees °C, and with maximum values reaching a standard deviation of 10 °C. However, if we exclude the occupied period, this lowers considerably to an average of ±1 °C and a standard of 5.5 °C (Fig.7).

![Fig. 7 – Indoor and outdoor operative temperatures logged in the field and simulated indoor temperature](image)

Results show good thermal heat storage during the day regarding the tent performance, with values reaching over 25 °C with a small gas heater turned on, and 15 °C while unoccupied. Nevertheless, minimum temperatures of ≈0 °C, similar to outdoor temperatures, were registered during unoccupied nights around 1:00 AM (Fig.8). Additionally, the high humidity values and the damage registered are an indication that the shelter is not doing well regarding infiltrations, suggesting that additional steps are needed to address this issue. Finally, these results indicate an accurate simulation that allows estimating the tent performance throughout the year, with an acceptable level of confidence.

![Fig. 8 – logger results for indoors and outdoors relative humidity (left y-axis) and temperature (right y-axis)](image)

When comparing the shelter’s annual indoor temperatures with that of a permanent structure with standard grade materials, the latter shows less thermal amplitude. From the heatmap presented (Fig.9), the shelter’s temperature reaches averages of 4 °C during the night and 14 °C during the afternoon. However, during hard winter it shows an inability to sustain human life without extra support, with temperatures reaching -14 °C. This is where the standard structure proves itself to be more efficient since it is visible a smaller thermal amplitude with minimum values of -2 °C and maximums of 5 °C during winter. These results confirm that despite the shelter adequacy for summer expeditions, it is still a long way from being able to support life during winter when compared to a heavyweight structure.

![Fig. 9 – Annual Indoor temperatures: Shelter on top and standard structure below. X-axis – months of the year; Y-axis: day period.](image)

### 4. CONCLUSIONS AND FUTURE WORK

This article started by identifying emerging topics of global development such has home displacement due to weather events, over-urbanization, and future climatic environments. These were addressed through the design, construction, and deployment of a shelter capable of resisting extreme weather, namely, cyclonic winds, and cold temperatures, near Collins Glacier in King George Island, Antarctica. After a year in-situ, a field excursion was organized to survey the condition and repair damages the shelter might have suffered, as well as gather data about the tent performance. The observations raised many questions regarding the reasons behind the envelope damage suffered by the shelter, the properties of the used innovative materials, the reliability of simulation tools in early design stages, and the shelter’s performance when compared to structures such as the ones seen in classic Antarctic bases.

Through the integration of Algorithmic Design (AD) and Building Performance Simulation (BPS), a 3D model was created and tested with airflow and energy.
simulations. A simulated wind tunnel test was compared with the damage location in the outermost layer of the design and gave insights regarding the importance of the geomorphological context of the site and of the deployment and positioning area of the shelter to avoid further damage. Energy simulations returned indoor temperature values similar to the gathered field data with an average error of ±1 °C for unoccupied periods, proving the reliability of the used simulation tools. Finally, the shelter’s annual performance was compared with that of a standard heavyweight structure regarding indoor operative temperature, uncovering issues that need to be addressed, such as the humidity permeability of the shelter, which may be affecting the tent performance during winter. Accordingly, the permanent structure showed better results during this period, indicating that there is still work to be done regarding the design optimization of this shelter for winter use.

This research also identified errors that might be the result of mishandling data loggers, of the occupancy schedules during the expedition, of the material properties and construction layers used for the simulation, and even the simulation tool itself, which cannot be fully validated unless data loggers are deployed in the shelter for the whole year. All these might be affecting readings on-site and yearly simulation values, although results from the short period data sample appear to be compatible with theoretical values, which confirms the usefulness of AD and BPS.

Future work on this topic is going to be conducted around the exploration of design parameters and its integration with structural analysis and optimization, to minimize weight while maximizing portability and performance. This can be done through CFD analysis of wind loads based on the registered wind speed. With the results, it is possible to apply a multi-objective optimization approach to minimize the shelter deformation and minimize its cost according to the material and the respective amount required to withstand such extreme climates. We are convinced that integration of this optimization process can prove helpful in the creation of adaptive solutions capable of responding to the rising challenges from this decade.

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Integrating algorithmic processes in informal urban and architectural planning
A case study of a Maputo’s neighborhood

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²Instituto Superior Técnico, Lisbon, Portugal

ABSTRACT: Urbanization growth in developing countries is an undeniable reality and translates into concerns regarding these countries’ ability to include slums, underdeveloped communities, and neighborhoods in economic, health, and climatic goals. This research focuses on the development of algorithmic design and analysis strategies to compose a methodology to study, define, and measure key parameters that affect the design and rehabilitation of these areas. Wall and roof construction scenarios are tested for improvements, and design dimensions such as height and surface area are analyzed to establish design and comfort thresholds. Results show improvements in thermal comfort with several different construction scenarios from which a two-staged rehabilitation plan is defined. The first stage comprises the identification of buildings that significantly improve with rehabilitation, and the second defines the most suitable construction scenarios considering the cost of application and comfort improvement.

KEYWORDS: Informal Housing, Sustainable Development, Algorithmic Design, Software & Simulations

1. INTRODUCTION

As urban development is steadily increasing, it is estimated that, by 2050, 66% of the world population will live in urban areas, 90% of which is predicted to be concentrated in Africa and Asia [1]. This suggests an urbanization growth in many underdeveloped countries, highlighting the concern over the way informal housing and settlements fit in the economic, health, and climatic goals of these countries [2]. Most of this expansion has no effective planning and, therefore, populations are living in slums that often show poor living conditions, with no clean water, insufficient infrastructures, and poor construction quality [3]. The research here presented proposes strategies to address the fast urban transition of rural and underdeveloped communities, bridging a less explored frontier of architectural and urban design, towards the era of post-carbon cities.

An example of enabling strategies in slums is the case of Mozambique, which approved a regulation and the corresponding manual of procedures regarding land use and appropriation rights: DUAT (Direito ao uso e aproveitamento de Terra) [4]. The country is currently applying this housing regulation strategy with the two specific goals of having instruments for adequate soil management and neighborhood improvement. The manual of procedures describes 11 stages towards correct land management and is being applied in a case-study known as the HABITAT Project: Maputo’s neighborhood of Chamanculo C. Some of the stages of the manual of procedures are related to street regulation and assessment of land parcels to each owner. However, throughout the manual, no consideration is given to architectural decisions and housing rehabilitation. Nevertheless, it is appropriate to improve users’ thermal comfort by including passive design and sustainable modular rehabilitation processes that follow the urban program applied in each land parcel [5][6].

House upgrading programs comprise rehabilitation strategies that enhance building performance at reduced costs. An example is shown by Bonaccurso, Martins, and Carrilho da Graça [7]. The authors applied three bioclimatic strategies in a full-scale prototype model and validated their thermal impact during summer through real-time measurements and simulations. The model was updated with a solar chimney, radiant insulation, and albedo. Results show different levels of impact on indoor temperature by these strategies. While the use of albedo did not show significant changes, the solar chimney and radiant insulation solutions successfully improved indoor comfort.

Passive design, along with similar approaches, can be modeled and analyzed on a larger scale through Algorithmic Design (AD) and Building Performance Simulation (BPS). AD facilitates the creation of fluid shapes through mathematical and logical concepts represented in algorithms [8], while BPS helps to predict building performance when there is no possibility to test it empirically.

AD and BPS tools can be combined into a method known as performance-based design, which guides the design by focusing on building performance for goals like comfort, energy consumption, and structural performance [9].
In this context, Taleb and Musleh [10] seek to develop an urban parametric design and optimize design solutions dependent on environmental factors like wind speed, solar radiation, and energy consumption. The case study in UAE, composed of several simple houses, is optimized regarding height and volume, providing independent optimal solutions for each simulation. Results show improvements of 8% in cooling loads and 30% in wind speed.

In line with the related work described above, this research explores the combination potential of AD and BPS in improving urban expansion. This is achieved by implementing algorithmic approaches while establishing a preliminary study of informal housing typologies and urban expansion trends in the area. Moreover, design metrics and rehabilitation scenarios were tested regarding the impact they have on indoor comfort, through an analysis of the design parameters. To address limitations pointed out by previous research [11] regarding parameter exclusion, time spent setting up the simulation environment, and lack of harmony between processes, we will use an AD tool that integrates CAD, BIM, and analysis tools, allowing a seamless flow between design and analysis [12].

2. WORKFLOW

We propose a three-phased workflow to structure data gathering, algorithmic processes, and sensitivity analysis (Fig.1). The first phase comprises the definition of the case study’s urban fabric and its respective building typology.

Phase two includes model generation and performance simulations. By algorithmically modelling the studied urban fabric from OpenStreetMap (OSM) data, it is possible to measure the impact on people’s comfort of different (a) material scenarios and (b) design dimensions (height, area). The latter is easily applied and regulated in the field for future constructions while the former is suitable for modular rehabilitation processes.

Finally, phase three analyzes the thermal autonomy at different scales to understand how each scenario and design parameters impact indoor comfort.

2.1 Case study – Chamanculo C urban fabric and building typology.

Chamanculo C is a neighborhood in the city of Maputo, district of Nhlanamku, characterized as an old suburb type A. These are mainly described as basic infrastructures composed of zinc cladding and/or cement bricks, densely distributed in non-delimited areas, and showing high population density with very narrow public spaces [10]. To represent the urban fabric, we used OSM data to generate 3D models of the corresponding houses that match the urban landscape, covering a total of 334 building units. This allows an urban-scale analysis of different construction solutions and the identification of critical areas for rehabilitation, mitigating construction and rehabilitation costs (Fig.2).

One of the most common self-made houses seen in the area is the “Ventoinha” house. Landowners add units incrementally according to the family needs and their financial availability (Fig.3). These units usually have the same dimensions and are rotated so that the roof angles create a fan-like shape, hence the house’s name. Most of these houses comprise rooms with areas ranging from 9 to 12 m² with exterior washrooms [13].
2.2 Algorithmic design description and parameters

When planning incremental informal housing in developing nations facing challenges related to housing provision, it is useful to design these building typologies parametrically. To this end, we started from one cuboid unit with variable length ($l$), width ($w$), and height ($h$), and a triangular prism with the same length and width, but with relative height related to the roof angle. To form a complete house, this starting unit is rotated four times around the center corner (Fig. 4).

![Fig. 4 – Unit parameters (left) and $n = 4$ units (right).](image)

### Table 1 – Construction scenarios to be tested in the neighborhood. Numbered layers go from the innermost to the outermost coating.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Layer</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>1</td>
<td>Zinc</td>
</tr>
<tr>
<td>W2</td>
<td>1</td>
<td>Cement brick</td>
</tr>
<tr>
<td>W3</td>
<td>1</td>
<td>Zinc</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Air gap</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Zinc</td>
</tr>
<tr>
<td>W4</td>
<td>1</td>
<td>Cement brick</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Air gap</td>
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<tr>
<td></td>
<td>3</td>
<td>Cement brick</td>
</tr>
<tr>
<td>W5</td>
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<td></td>
<td>2</td>
<td>Air gap</td>
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<td></td>
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<table>
<thead>
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<td></td>
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<td>XPS</td>
</tr>
<tr>
<td>R2</td>
<td>4</td>
<td>Zinc</td>
</tr>
</tbody>
</table>

The material properties were obtained from EnergyPlus' library for wall-air resistance. However, cement bricks and extruded polystyrene show differences in their properties according to the manufacturing processes and their type. In this case, material thermal properties were retrieved from tables for common construction materials (Table 2).

Simulation outputs include an adaptive chart indicating indoor and outdoor temperature distribution for the respective analysis period, and the percentage of time in which each house is in the comfort zone of the ASHRAE adaptive chart, a metric known as Thermal Autonomy (TA) [13]. This analysis was made for the summer period, from 10 am to 8 pm, as it comprises the warmest hours of the year. Furthermore, results were compared with the worst-performing scenario (W1+R1 - zinc cladding), to quantify and visualize the impact of each upgrade and evaluate the suitability of each scenario for each building.

### Table 2 – Materials thermal properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (m)</th>
<th>Conductivity (W/m-K)</th>
<th>Density (kg/m³)</th>
<th>Specific heat (J/kg-K)</th>
<th>Absorptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc</td>
<td>0.002</td>
<td>0.06</td>
<td>122</td>
<td>380</td>
<td>0.25</td>
</tr>
<tr>
<td>Xps</td>
<td>0.034</td>
<td>2.085</td>
<td>14.42</td>
<td>1131</td>
<td>0.7</td>
</tr>
<tr>
<td>Cement Brick</td>
<td>0.12</td>
<td>1</td>
<td>2085</td>
<td>900</td>
<td>0.9</td>
</tr>
</tbody>
</table>

After the material analysis, we investigated the impact of design parameters on the thermal performance. To this end, we implemented an iterative simulation with different values for the height and surface area. This quantifies the TA variation towards the establishment of design thresholds to regulate informal construction.
3. RESULTS AND DISCUSSION

The urban analysis results are presented through 3D model heatmaps for the TA of each building (Fig. 5), allowing the identification of areas that might benefit from modular upgrades, as well as line charts with the TA range of each construction (Fig. 6), providing a more detailed view of the performance of each construction scenario.

3.1 Urban model analysis

The results illustrated in Fig. 5 show that walls W1, W2, and W3 have similar performance, and W4 and W5 have better performance. The same wall scenarios with roof R2 show greater improvements in every construction. Consequently, regardless of the wall construction, a roof upgrade emerges as the most viable option of slum upgrade. Moreover, houses in different areas of the neighborhood vary their TA according to both their surface area and their context and surroundings. Thus, it is possible to define different rehabilitation plans for neighborhood areas that require more urgent upgrades.

Regarding the overall comfort spectrum (Fig. 6), the best-performing scenario is W4+R2, a double pane of cement brick with a wall air gap and a roof composed of double zinc cladding with air space and XPS as insulation. Scenario W5+R2, composed of one layer of zinc cladding, wall air space, and one cement brick pane, also shows promising results and has the added advantage of being a better rehabilitation solution due to its adaptability to the identified building typologies in the area.

A larger performance discrepancy between walls is visible when roof R2 is applied. Buildings with W4+R1 have roughly the same performance as zinc walls with roof R2, showing a minimum TA of 30% and 33%, respectively, a maximum of 69% and 67%, and an average of 45% and 46%. Furthermore, W5, which had similar performance to scenarios W1 and W3 when the first roof scenario R1 was used, shows a bigger improvement when the second roof scenario R2 is applied. Consequently, roofs behave differently with each wall construction and show different levels of improvement in the buildings' TA.

These improvements can be quantified by TA variation between buildings with scenario W1 and all the others with and without roof improvement. Table 3 shows the TA variation of each house with all the scenarios compared to the original one. Results show that some houses worsen their thermal comfort up to -40% but, on average, the variation ranges from -10% up to 114%, with a maximum increase in thermal performance reaching 218%. While scenarios W4 and W5 show the biggest improvements, some buildings show a neutral or negative impact from these and other upgrades, either because of sun exposure, building density, or surface area, which motivates a spatially contextualized analysis.

Fig. 6 – Thermal Autonomy from worse to best performing house for each construction scenario (comfort spectrum).

Fig. 7 shows the results of the TA variation on a scale from 0% or below (in red) to 100% and above (in green). The performance of the wall scenarios is highly sensible to the roof construction, which acts as a catalyst for comfort improvement. This is illustrated by scenarios W4 and W5, which provide little to no improvements with roof R1, and the best-performing solutions with roof R2. However, many buildings have significant TA increases with less costly walls and/or
roof rehabilitation scenarios. The wide range of viable design solutions and corresponding impact factors can be difficult and time-consuming to analyze and control, highlighting the need for optimization processes regarding the cost and TA improvements of the whole urban model.

If the levels of TA improvement for each scenario are compared with their respective cost per building (Fig. 8), it is possible to grasp that the original with only a roof upgrade would cost as much as rehabilitating with any better wall scenario, while yielding similar and, in some cases, even better results. Additionally, this comparison reflects the conflicting nature of TA and costs. However, with the integration of these optimization processes, it might be possible to determine a good solution, with lower costs, by applying higher cost materials only in critical buildings according to the comfort results.

### 3.2 Housing typology dimensions

The next analysis focuses on the impact of surface area and building height on TA. The simulated model comprises a single house with scenario W5+R2, a height between 2.25m to 3.5m, a unit surface area from 6.25 m² to 16 m², and a natural ventilation schedule from an outdoor temperature of 16°C to 28°C. Results show a decrease of up to 4% as the height increases and an improvement of 4% to 7% as the area increases (Fig. 8).

At a single-house scale, variations in height and area do not have as much significance in TA as construction scenarios, and the comfort decrease might result from air stratification or sensor positioning in the analysis tool. Nevertheless, we did further experiments to assess the performance variation of each wall scenario as the unit area increases. In these experiments, the roof scenario used was R2 due to its better performance.

Fig. 9 shows that TA increases in larger proportional areas and scenario W2 proves to perform better than W1 and W3 in areas up to 100 m². However, the TA of scenario W3 is similar to the one of scenario W2. Additionally, scenarios W1, W2, W3, W4, and W5 show maximum increases of 44%, 21%, 34%, 13%, and 8%, respectively. Two scenarios (W4 and W5) easily stand out as better construction solutions regarding the impact of surface area.
CONCLUSIONS AND FUTURE WORK

Around the world, projects, such as Africa HABITAT, target the improvement of people’s living conditions, particularly in slums. In Mozambique, DUAT (Land use and appropriation rights) is positively improving land use but fails to address important topics such as architectural decisions and housing rehabilitation materials regarding comfort and well-being. Additionally, these projects can act as vessels for the practical application of architectural research, contributing to a more affordable and climate-friendly approach towards a comfortable and healthy environment.

This research highlights the integration of algorithmic processes in informal architectural and urban practices, to identify how different construction scenarios and design parameters affect the buildings’ thermal autonomy (TA) within the neighborhood. Results show that the impact of different wall solutions can be increased through the application of alternative roof solutions. However, while some construction scenarios return little to no improvements in the building’s thermal performance, others might show significant improvements. To help make this distinction, we use a heat map comparing the TA variation between the studied neighborhood and rehabilitation scenarios, facilitating the recognition of critical areas.

To phase the slum rehabilitation and reduce its cost, it is necessary to define strategies that address the most important cases first and identify the least costly upgrades that obtain acceptable levels of comfort for each building. In the presented case study, height and surface area were analyzed in detail for selected scenarios, and the area thresholds with maximum TA were documented. We also conducted a sensitivity analysis to understand the impact of different design parameters in a specific climatic context. Although weather data and other input sources may be a cause for model uncertainty, the integration of building-performance simulation in an algorithmic design workflow helps architects perceive the impact of the developed project solutions.

Future work will comprise cost analysis of the identified upgrades so that their costs-efficiency in the urban neighborhood can be evaluated as a whole. We also plan to develop new algorithmic methods to integrate multi-objective optimization in rehabilitation. Finally, it would be worthwhile to do an on-site validation of the simulation results.

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Analysis of outdoor thermal conditions in different neighbourhood typologies of Ha Tinh city, Vietnam

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2 National University of Civil Engineering, Ha Noi, Viet Nam

ABSTRACT: The city of Ha Tinh city is becoming more vulnerable to urban heat island effect due to urban development. As a measure with design approaches at neighbourhood scale, the concept of neighbourhood typology was introduced for the study the effect of neighbourhood on thermal comfort in Ha Tinh, and five typologies were recognized within the city. Thermal conditions in the three most typical typologies were examined by field measurements from August to October 2019. The two thermal indices of Wet-bulb globe temperature (WBGT) and Thom’s Discomfort index (TDI) were employed in the evaluation of outdoor comfort in the studied areas. The results showed a high correlation between physical aspects of a neighbourhood typology (density, openness, positions, greenery and street designs) and thermal environment while non-physical factors that form the typology of a neighbourhood were not analysed and explained in this paper. There were certain disagreement between WBGT and TDI when it came into the analysis of comfort level in tropical climate of Ha Tinh. Future studies are needed for further assessment of physical and non-physical factors and their impacts on thermal condition of a neighbourhood. This would be an important basis for the development of climatic-resilient neighbourhoods in Ha Tinh.

KEYWORDS: Neighbourhood typology, Outdoor thermal condition and comfort, Heat stress, Mobile and stationary measurement

1. INTRODUCTION

The today city of Ha Tinh is a medium-size Vietnamese city of over 200,000 inhabitants where urban population represents 74% out of it [1]. Recent urbanization in the city has and will cause significant changes to land use distribution in most of its peri-urban areas where major parts are currently agricultural land and rural neighbourhoods. In addition to severely hot weather in summer [2], the city is vulnerable to global warming as negative effect of climate change due to more built-up areas, worsening urban thermal environment by causing more heat stress. As a response to increasing potential of urban heat island effect, a significantly greater share of green spaces and water bodies was proposed in the city master plan to 2030 as a measure for better cooling effect [3].

The urban micro-climate is also driven by the design at neighbourhood scale which normally takes into a wide range of physical, social and demographical factors [4] into account and forms a typology of each neighbourhood. Therefore, further studies into neighbourhood development are required for making a better thermal environment in the city of Ha Tinh, and the starting point should be an investigation of how the neighbourhood typology shapes its thermal condition.

This paper introduces typical neighbourhood typologies in Ha Tinh city and analyses the thermal conditions in these neighbourhoods by monitoring.

2. METHODS

2.1 Neighbourhood typology identification

At first, all the neighbourhoods of the city were examined based on their morphology and socio-economic conditions. The aim is to form a classification scheme of typology for the selected neighbourhoods, which is important to the evaluation of actual situation of climatic adaptation and future development of climatic resilient neighbourhood typologies. The typology of a neighbourhood is defined by physical (built) and non-physical (social and demographical) factors and may vary when interference happens. For a number of studies on urban outdoor thermal condition, the neighbourhood morphologies characterized by density [5], aspect ratio [6], materials [7] and streets pattern [8] were detected. Besides factors that are merely associated with buildings and materials, effects of green and blue spaces were considered in various studies on urban heat island (UHI) [9] and urban heat stress [10].

However, the formation of a neighbourhood is also related to its non-physical properties including functionality, demographical, socio-economic and historical conditions. As the result, for the detection of neighbourhood typologies in Ha Tinh, major criteria of a neighbourhood were taken into account and grouped in physical and non-physical aspects. The schematic list of neighbourhood typology classification is shown in table 1, and used for the identification of existing typologies in Ha Tinh. From the identification of the current typologies, most
typical neighbourhoods were chosen for the assessment of outdoor thermal comfort. 

Table 1: Criteria for neighbourhood typology classification [4, 5, 6, 7, 8]

<table>
<thead>
<tr>
<th>Physical</th>
<th>Non-physical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position-urban, suburban, or rural</td>
<td>Functionality</td>
</tr>
<tr>
<td>Terrain</td>
<td>Historical and cultural context</td>
</tr>
<tr>
<td>Street layout, street pattern</td>
<td>Population size and density</td>
</tr>
<tr>
<td>Built density</td>
<td>Occupation</td>
</tr>
<tr>
<td>Building height and distribution</td>
<td>Economic condition</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>Daily routine and customs</td>
</tr>
<tr>
<td>Permeability</td>
<td>Religion</td>
</tr>
<tr>
<td>Land use distribution</td>
<td>Local business and handicraft</td>
</tr>
<tr>
<td>Green space configuration</td>
<td>Strategy of development</td>
</tr>
</tbody>
</table>

2.2 Mobile measurement

In order to evaluate the variation of outdoor thermal comfort influenced by street design and landscapes over a wide range of neighbourhood typologies, mobile measurement was conducted to collect data on various thermal variables including dry-bulb temperature, humidity, black globe temperature and Wet-bulb Globe Temperature (WBGT) [11]. The mobile measurement allows a flexible and quick monitoring at various locations characterized by different streets and landscape elements, and therefore enables visualization of thermal condition at typical time of days on a large-scale which is not possible with only a system of static sensors. A transverse measurement campaign was designed in order that trajectories covered typical street patterns and urban morphologies as parts of neighbourhood typologies of the city. Particularly, monitoring route 1 representing typologies 1 and 2 (see table 4 and figure 1) connected most urbanized parts of the city that are formed by urban streets, alleys and several city parks and small lakes, while the route 2 and 3 were planned for monitoring thermal condition in new developed and rural neighbourhoods as of typologies 3 and 4. Table 2 gives details of the three measurement routes with their corresponding trajectory maps. The selection of routes also allowed the whole measuring period not to exceed 1 hour, in order to limit the impact of temporal variation of ambient temperature and humidity in a day on the gathered data.

The routes were simultaneously conducted with three heat stress meters Lutron 2010 SD for dry-bulb air temperature (±0.8°C), relative humidity (±3%), and WBGT (±1.5°C). Each sensor for one particular measurement track was front mounted on a motorbike that drove at 20 km/h along each route, and all thermal parameters were recorded at time interval of 5 seconds. During the mobile measurement, each trajectory was recorded with a GPS tracker which helped in generation of position file with full coordinate values. The collected data on thermal parameters and position were then combined and converted into shape-based files before they were imported to ArcMap 10.5.1 [12] for visualization of thermal distribution maps.

The mobile measurements were conducted on several days in August, September and October 2019 with two daily measurement campaigns. Campaign 1 started daily at 13:15 when air temperature and solar radiation intensity were at the highest values, while the starting time for campaign 2 was 20:15, which was suitable for a study of nocturnal urban heat. The observed values of WBGT were compared to reference limits defined by the standard ISO 7243:2017 [11] to evaluate actual level of outdoor comfort in the studied areas.

Table 2: Description of three transverse routes for mobile measurement

2.3 Stationary measurement

A number of fixed sensors were installed for long-term observation of outdoor temperature and relative humidity at representative locations inside neighbourhood typologies from August to October 2019. This monitoring is intended for a psychrometric analysis which provides more insight into the impacts of neighbourhood typology on outdoor microclimate. Sensor type and accuracy can be found in Table 3.

Table 3: Specification of sensors used for stationary measurement

All these sensors were located at private outdoor places in the selected neighbourhoods for safety reasons, and they were protected with house-developed passively-ventilated shields to avoid overheating by intense solar radiation. From August to October 2019, there were two observation period
which respectively lasted from 28 August to 12 September at 7 locations, and from 4 to 22 October 2019 at 11 locations (see figure 2 and table 5).

The gathered individual parameters of dry-bulb temperature and relative humidity were used for the approximation of comfort index Thom’s DI [13] explained by the following equation (1):

\[
DI = 0.5T_w + 0.5T_a
\]

where \( DI \) – Discomfort Index (°C); 
\( T_w \) – wet-bulb air temperature (°C); 
\( T_a \) – dry-bulb air temperature (°C).

To assess comfort level, calculated DI values at measurement locations were interpreted to comfort classes by Epstein & Moran [14] which were employed in a number of heat stress studies in different climates [15, 16].

### 3. RESULTS

#### 3.1 Neighbourhood typologies in Ha Tinh city and selection of measurement locations

With the introduced classification scheme of neighbourhood typologies, all neighbourhoods in the city were grouped into five corresponding typologies based on the physical and social-demographical conditions. General description of introduced typologies for the neighbourhoods in Ha Tinh is explained in table 4, and the distribution of the detected typologies is illustrated in a descriptive map shown in figure 1.

![Figure 1: Distribution of five neighbourhood typologies in Ha Tinh city](image)

Although a scheme of five typologies was recognized, this research focuses only on the three most typical typologies 1, 3, and 4 which respectively characterize most urbanized (1), new urbanized neighbourhoods (typology 3) and rural communes (typology 4) where properties were characterized by built density, urban morphology, openness and effects of green/blue bodies. Due to different availability of sensors, seven sensors were installed in August at locations 1, 2, 4, 6, 7, 9 and 11 and four more sensors were added in October for locations 3, 5, 8 and 12.

To evaluate the differentiation in thermal condition and comfort level by typologies, eleven loggers for temperature and relative humidity were installed sparsely in the typical places of city center (typology 1), new urbanized neighbourhoods (typology 3) and rural communes (typology 4) where properties were characterized by built density, urban morphology, openness and effects of green/blue bodies. Due to different availability of sensors, seven sensors were installed in August at locations 1, 2, 4, 6, 7, 9 and 11 and four more sensors were added in October for locations 3, 5, 8 and 12.

### Table 4: Neighbourhood typologies in Ha Tinh city

<table>
<thead>
<tr>
<th>Group</th>
<th>Typology</th>
<th>Brief description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban old neighbourhood</td>
<td>1</td>
<td>Mixed rise (~4 – 40m) – High density (Compact) (~70 – 80%) – Low perviousness (Asphalt, concrete and cement pavement) – High &amp; medium income – Busy business activities</td>
</tr>
<tr>
<td>Urban new developed</td>
<td>2</td>
<td>Mixed rise (~4 – 40m) – High and medium density (~40 – 80%) (Partly compact) – Low and medium perviousness – High and medium income - Moderate business activities</td>
</tr>
<tr>
<td>Urban new developed</td>
<td>3</td>
<td>Mixed rise (~4 – 100m) – High and medium density (~30 – 80%) – Average and high perviousness – High and medium income - Moderate business activities</td>
</tr>
<tr>
<td>Rural neighbourhood</td>
<td>4</td>
<td>Low rise (~3 – 10m) – Low density (~10 – 30%) – Only rural residential block - Medium and low income - Few business activities</td>
</tr>
<tr>
<td>Rural neighbourhood</td>
<td>5</td>
<td>Low rise (~3 – 40m) – Low and medium density (~10 – 50%) – Mixed rural and new urbanized block – Medium and low income – Few business activities</td>
</tr>
</tbody>
</table>

#### Table 5: Measurement locations

<table>
<thead>
<tr>
<th>Location</th>
<th>Typology</th>
<th>Characteristics</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>City – Alley – Unshaded</td>
<td>C-AL-US</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>City – Near park – Attached – Partly unshaded</td>
<td>C-NP</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>City park</td>
<td>C-P</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>City – Attached houses – Tree shaded</td>
<td>C-TS</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>New urbanized neighbourhood – Villas – Unshaded</td>
<td>O-V-US</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>Open neighbourhood – Detached houses – Partly tree shaded</td>
<td>O-D-US</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>Open neighbourhood – Attached houses – Partly unshaded</td>
<td>O-A-US</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>Open neighbourhood – Alley – Unshaded</td>
<td>O-A-US</td>
</tr>
<tr>
<td>9</td>
<td>4</td>
<td>Rural neighbourhood – Alley – Tree shaded</td>
<td>R-A-TS</td>
</tr>
<tr>
<td>10</td>
<td>4</td>
<td>Rural neighbourhood – Tree shaded – Water body</td>
<td>R-TS-W</td>
</tr>
<tr>
<td>11</td>
<td>4</td>
<td>Rural neighbourhood – Detached houses – Unshaded</td>
<td>R-D-US</td>
</tr>
</tbody>
</table>

![Figure 2: Locations of stationary measurement](image)
3.2 Effects of neighbourhood typologies on outdoor thermal condition

To evaluate the thermal comfort level of selected areas, observed data of temperature and relative humidity were used for the determination of daily cycle median temperature and the histogram of comfort levels.

The daily cycle of measured temperature in Aug-Sept is shown in figure 3. The cycle showed the significant deviation of UHI intensity by locations characterized by typologies. Nocturnal median temperature in rural open area without shades (RO-US) was of lowest value, almost 2°C lower than official weather station in city centre, and lower than a private balcony of an attached house close to the city park (C-NP). The phenomena could be explained by long-wave radiative cooling of grass lands, rice fields and soil in rural areas. However, temperature in this rural open space (RO-US) rose up at very high rate, becoming higher than observed value at city weather station (difference at 1°C), and by far higher than urban locations where tree shades were available (difference at 2°C). During the day, cooling effects of trees or pergola were more evident since both locations in city (C-TS) and suburb (RA-TS) had lower temperature values compared to sun-exposed positions.

Figure 3: Daily cycle of median value of measured temperature with an hourly time resolution, from 28 August to 12 September 2019, at selected locations

The effects of neighbourhood typologies were also made clear with median temperature daily cycle for the second monitoring in October 2019 (see figure 4). The observation showed a clear gap between shade and unshaded locations. Under well-shaded condition, a place in city where built density was high (C-BSS) could obtain lower temperature during day than unshaded open space in rural part (R-D-US). At night, temperature in rural low density area fell quickly and became almost equal to the value obtained in another rural location (R-TS-W) at which trees, grass lands and a small water bodies were present. From figure 4, a slight deviation in diurnal temperature by city, open and rural neighbourhood can be figured out, where maximum temperature observed in city where tree shade (under pergola) was available (C-TS) was 0.5°C higher than other locations in open (O-V-US) and rural (R-D-US) areas. The impact of openness and density as parts of neighbourhood typologies were most evident at night, where temperature difference of 0.5 to 1°C was recognized between rural, open and urban areas. The results are similar to what could be concluded from mobile measurement.

Figure 4: Daily cycle of median value of measured temperature with an hourly time resolution, from 4 to 22 October 2019, at selected locations

To gain insight into thermal comfort level, the discomfort index Thom’s DI were calculated for all measured locations. The value of 28°C considered a threshold of severe heat stress, and 22°C is a value at which mild perception could be obtained. Figure 5 shows the statistical variation of DI at measured places, and revealed a large amount of time when actual DI by far exceeded severe limit value. The frequency of DI values at each location was approximated and presented in figure 6 for a further assessment of comfort level. It was shown that the amount of time when DI was equal or below 22°C (satisfaction) was in relation to neighbourhoods, and much affected by shading, either by trees or buildings. The tree shades and water bodies was the main reason for the highest level of comfort in the rural area (R-W-TS) where amount of minutes with DI value falling below 22°C was approximately 1.5 times larger than that obtained in an unshaded location in city centre (C-US).

Figure 5: Temporal variation of DI at different measurement locations from 4 to 14 October

Another link between built density and thermal comfort can be seen from the statistic with duration...
when DI was above 28°C. The open and rural neighbourhoods had more time of comfort (DI ≤ 22°C) and less severe occurrence than urbanized and compact areas. The exception was observed with the location in an alley which was shaded by low-rise building (C-BS) which hold much lower amount of severe DI value than other city locations, but less mild values than places nearby the park and in the centre. The most common DI values obtained in all neighbourhoods were in range from 22 to 28, which are sorted to heavy category.

Figure 6: Statistical comparison of DI index for studied neighbourhoods from 28 September to 22 October

3.3 Outdoor thermal comfort and streets design

Measured data on WBGT along the studied streets in the afternoon of 22 October and in the evening of 23 October were visualized in figures 7 and 8 respectively where all the observed values were sorted in reference to the classification by ISO 7243:2017 [2]. The daytime transverse measurement on figure 7 showed a slightly lower value WBGT (28 to 30°C) on shaded Northwest – Southeast oriented streets in the city centre than those where shades by either city plants or buildings were absent (from 30 to 33°C). The observed outdoor comfort on routes by the city park was in relatively wide range of 28 to 33°C, and showed not a big diurnal cooling effect though there was a large amount of grass and bushes planted along. The measurement revealed a lower intensity of heat stress in the more urbanized part of the city when compared to new urbanized and open neighbourhoods as of typology 3, where value of difference were recorded at 2 to 3°C. The deviation can be explained by the higher presence of city trees, shades by high- and medium-rise buildings in urban old streets than new developed neighbourhoods where plants were in early growing period and low-rise buildings made up a large part.

The nocturnal mobile monitoring in figure 8 revealed a better comfort level during night time in new developed areas where built density and building height were generally lower than the city centre. A high percentage of WBGT values under and equal 25°C were observed in the measurement loop 2 passing by opened and relatively sparsely-built areas, showing a high daily cooling rate of this region compared to a more densely-built areas in the most urbanized parts of the city. However, the difference was not significant since maximum values captured in city centre with measurement track 1 were not higher than 26°C. The results of transverse measurement along the park showed more cooling benefits at night of city park with large amount of water body than during the day.

Figure 7: Observed WBGT values along measurement tracks during daytime from 13.00 to 14.00 on 23 October 2019

Figure 8: Observed WBGT values along measurement tracks during night time from 20.00 to 21.00 on 22 October 2019

It is worth noting that all the monitored WBGT along measurement tracks did not exceed maximum reference value of 33°C by ISO 7243:2017 [2]. It can be seen a light heat stress situation were prevalent in late summer in Ha Tinh. This comparison was not in line with the evaluation of outdoor comfort with DI. Reason for this difference could be the DI and limit values was originally designated for people who get acclimatized with cold and moderate climate, and uptake for tropic may lead to over-estimation of heat stress risks. Meanwhile, the WBGT is better designated for hot environment and is used to evaluate heat stress level since it takes more the effect of radiation into account. However, the values of WBGT were collected with motor-biking at the average speed of 15 – 20 km/h, so the perceived value of WBGT for pedestrian may be higher and
therefore may cause more discomfort. Another measurement campaign has been planned in the summer of 2020 for further analysis of correlation between street parameters and outdoor comfort.

4. DISCUSSION AND CONCLUSION

The introduction of neighbourhood typology gives a complete approach to the study of thermal condition in different urban areas thanks to the consideration of physical aspects and non-physical factors. The uptake of neighbourhood typology scheme provides a comprehensive understanding of actual context within a neighbourhood and consequently facilitates answers for how urban micro-climate takes shape. For the case of Ha Tinh city, the introduction of five neighbourhood typologies is important to gain first insights into the effect of neighbourhood design on urban thermal condition. Through this research and further studies, correlation between individual parameters forming a typology and outdoor comfort can be captured and contribute to better development of future neighbourhoods in Ha Tinh.

The monitoring results indicated the differences in outdoor thermal comfort level between different parts of Ha Tinh city. It brought more insight into the effect of the mentioned physical aspects of neighbourhood typologies on outdoor thermal condition in the city. The data collected from the stationary measurement with installed loggers at different locations showed clear evidences on the effects of density, openness, positions and greenery on the outdoor thermal condition. However, further measurement campaigns should be combined with a transverse monitoring along various longitudinal sections of representative neighbourhoods so that the impact of land use distribution and green/blue configuration and typologies on thermal profile could be better evaluated.

From the mobile measurement of thermal comfort and individual thermal parameters (air temperature and globe temperature) on the selected streets, big impact of street shading on comfort level was observed but the correlation between aspect ratio (H/W) and the index of WBGT was not strong. The link between street orientation and WBGT was recognized, but not strongly evident. It could be explained by the disregard of different shading effects on measured WBGT on common streets which resulted in widely varied and incomparable observed values. For the further studies, measurement on both street sides which are differed by sun exposure and comparison made within a purely similar exposure condition would be more feasible for the conclusion of the impact of street designs on comfort level.

In this study, the two indices of WBGT and Thom’s DI were used for the evaluation of outdoor comfort in the city of Ha Tinh but they showed a not high agreement when employed to the elaboration of outdoor comfort on measured streets of the mobile trajectories. The difference can be blamed for the different principle employed to the calculation of these indices and defined thresholds for the classification of comfort levels which were not introduced for a typical humid tropical climate. Moreover, the evaluation of outdoor comfort through Thom’s DI index is limited due to the fact that only temperature and humidity were considered. Thus, for the more comprehensive analysis, further measurement campaign should be designed with sensors that allow measurement of more variables of local weather condition i.e temperature, humidity, global solar radiation, wind speed and direction. Moreover, studies on reference value limits of thermal comfort indices are necessary for research on outdoor comfort in Vietnamese cities as of tropical humid region.

ACKNOWLEDGEMENTS

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Energy Optimization of Climate Adapted Buildings in an Urban Context
The Case of Subtropical Climate

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ABSTRACT: Improving the building sector so that buildings have better energy performance depends on several factors. Two of the important factors are the form of each building and the urban morphology. These factors impact the amount of solar radiation which has a role on the energy demand; thus, reducing insulation (incident solar radiation) is critical for energy-efficient buildings. This paper addresses the relationship between the complex urban environment and the design of energy-efficient buildings. The methodology aims at designing energy-efficient buildings in an urban context through combining two methods: (1) making use of urbanization by exploiting the advantage of the overshadowing that reduces the amount of insolation from surrounding existing buildings and (2) optimizing the building form so that it is harmonious with its environment because it receives reduced direct solar radiation. Through a case study in the subtropical region, the optimization tool shows up to 42% less insolation depending on the latitude.

KEYWORDS: Insolation, Building form, Optimization, Energy efficiency, Urban context

1. INTRODUCTION

Rapid urbanization is shaping our future and affecting many socio-economic disciplines at a fundamental level [1]. Climate responsive and environmentally sensitive urbanization that adheres to the Sustainable Development Goals (SDGs) is a necessity, especially in the subtropical region given the expected increase of urban population [2]. Researchers have investigated the impacts of urban morphology on cooling load [3]. The countries in the subtropical region have extended hot summer days, the fact that causes a higher energy demand to cool indoors [4]. Climate change increases the cooling demand even further; thus, urbanization and climate change have increased the energy consumption in the subtropical cities. In addition, the building form affects the amount of insolation [5]. One key factor in increasing the cooling demand is the amount of incident solar radiation (insolation) which strikes the buildings’ facades and gets stored in these surfaces, thus increasing the surface temperature [6].

1.1 Objective

Urban population in most subtropical regions is increasing. This rapid urbanization has significantly increased the needed energy to cool buildings in these urban areas. For better living conditions in the building sector, several actions should be taken towards the design and construction of energy-efficient buildings. In this regard, this paper focuses on two objectives:

• To make use of urbanization by exploiting the advantage of the overshadowing that reduces the amount of insolation due to the existing surrounding buildings.
• To optimize the building form in an urban context so that it is harmonious with its environment because it receives reduced direct insolation.

To address these objectives, a software system is created including a back-end optimization engine with a front-end graphical user interface enabling a design team to experiment with different settings.

1.2 Significance

Researchers have been exploring the design of energy-efficient buildings [7]. However, existing studies remain limited in that they address particular aspects such as materials, window wall ratios, renewable energy, etc. This work considers design variables in an urban-related environment and presents a computationally efficient method to be implemented by a design team consisting of architects, engineers and other specialists. This paper intends to show that, at the early building design stage, it is crucial to take into consideration the urban environment as well as apply the appropriate optimization algorithms to reduce insolation and thus minimize the energy demands to cool down indoor spaces. The aim is to optimize energy through reducing solar gains in buildings and therefore, decreasing the need for space cooling.

This research is significant and practical during early urban planning and design phases especially in the high-density subtropical areas.
2. METHODOLOGY

The proposed methodology is subdivided into the following parts: i) building’s form optimization with respect to the incident solar radiation (insolation), ii) building’s insolation when placed in an urban morphology, and iii) building’s form optimization to minimize the insolation while making use of the urban morphology to shade parts of the building. The methodology used is simulated on a real case study which is explained in Section 3.

2.1 Graphical User Interface

An interactive Graphical User Interface (GUI) has been developed for inputting the required data such as the dimensions and height of the initial building, the built-up area, the dimensions and heights of surrounding buildings, the latitude and longitude of the site, the study timeframe, and other optimization parameters. This interface makes the proposed solution easily used by architectural design teams. The user inputs different requested information about the target building as well as some information about the surrounding buildings in the neighbourhood which might have an overshadowing effect on the proposed building. The methodology used is based on an optimization algorithm which run in the back end of this interface.

Figure 1 shows the GUI that we developed using MATLAB. This interface allows the user to experiment and change the different design parameters which are related to the building under study as well as the neighbouring surrounding buildings in the urban morphology from all eight cardinal and intercardinal directions. The reduction in insolation varies significantly from site to site, depending on the latitudes, heights of the buildings and the distance between these buildings.

2.2 Reducing Insolation on the Baseline Building Form

The aim of this part is to show the impact of the building form on the amount of incident solar radiation absorbed by the façade of the building without considering the urban morphology in which the studied building exists. It is a stand-alone building. The conventional rectangular building requires high energy to cool down the indoors in the subtropical region because it receives increased insolation. The optimized building form receives reduced insolation; therefore, it decreases the cooling energy demands.

To determine the optimized building form, the following information must be defined: the coordinates of the specific plot of land, and the built-up area. In addition, the total built-up area is predefined based on the terrain area, setbacks and the building code of the country. From the solar azimuth and elevation coordinates, the sun’s direction vector can be computed based on three cartesian coordinates and the intensity of the solar radiation is estimated using an empirical expression from [8, 9].

Given the inputs by the user, the problem is formulated as a constrained optimization problem where the objective function is to minimize the total insolation received by the building. The optimization problem considers the rectangular mesh building as its starting point.

To define the total insolation of a stand-alone building, the following equation is used:

$$ E_{\text{total}} = \sum_{i=1}^{n} e_{ir} $$

where $E_{\text{total}}$ – total solar radiation impacting the building (Watts-hour Wh);

$e_{ir}$ – solar energy per triangle and ray (Wh);

$t$ – triangle in the building mesh;

$r$ – solar radiation during a particular timeframe.

The proposed solution aims at reducing the total amount of insolation presented in Equation (1). However, there are other architectural and construction constraints that should be taken into consideration as well. For instance, floor height should be fixed to avoid tilted roofs or uninhabitable shapes.

The solution is based on Penalty Successive Linear Programming (PSP) [10]. The PSP approach solves
the optimization problem in a computationally efficient manner. More details on how to formulate the different constraints and make use of PSLP to solve this problem can be found in [9].

2.3 Impact of Urban Morphology and Overshadowing
There are several parameters to be considered when modelling an urban morphology such as the urban form, street width, street orientation and the dimensions and height of the surrounding buildings [11]. In this section, we will consider the impact of the urban morphology on the amount of incident solar radiation. The surrounding neighbouring buildings can affect the final optimal form of the building that has reduced incident solar radiation. Therefore, the urban configurations especially during the warm months of the year in the subtropical region impact the shaded parts of the target building to be constructed.

To account for the effect of the surrounding buildings, we update the formulation so that it considers only the solar radiation \( r \) which reaches the target building without being interrupted by any neighbouring object in the urban area. The updated equation of the total insolation, as shown in the following equation:

\[
E_{\text{total}} = \sum_r \sum_{\text{sir}} e_{r,sir} \quad \text{such that: } r \cap SO = \emptyset \quad (2)
\]

where \( r \) – solar radiation during a particular timeframe;

\( \cap \) – intersection; \( \emptyset \) – empty set;

\( SO \) – surrounding object in urban environment.

The proposed approach aims to optimize the form of a building in an urban context while taking into consideration and benefiting from the shadows cast on the target building. Mathematically, this optimization equation aims at minimizing the total insolation represented in Equation (2) subject to the same constraints as presented in Section 2.2.

3. APPLICATION – CASE STUDY
A case study in the subtropical region is presented here. In this region, the warming during summer is exceeding the natural variability by at least two standard deviations [12]. This increase in temperature is causing an undesirable effect in electricity consumption.

3.1 Site
The site of the building to be built is defined by first importing the surrounding urban environment from AutoCAD files that allow 3D workspace. This urban morphology exists in a Mediterranean city and is commonly found in urban areas in the subtropical region [5]. The chosen site has an old building which will be demolished. The surrounding buildings are then modelled to account for their shading effect on the amount of incident solar radiation received on the site being studied. An example of the AutoCAD project site is shown in Figure 2.

![Figure 2: An example of using AutoCAD to visualize and identify an urban context of project site.](image)

3.2 Parameters
To define the sun path and the radiation data, the formula proposed by Duffie et al. [8] is used to generate different solar rays. For each solar ray, the angle and the intensity are computed at hour intervals during the day. As for the timeframe, the parametric analysis is conducted using dynamic solar radiation simulations on the date of August 5. The location is defined at latitude 24 degrees N to 40 degrees N with more focus on the Mediterranean area (33.5 degrees N location within the Mediterranean) [13].

3.3 Software Used
MATLAB is used as an interface program running on a PC with Intel Core i7-6850K CPU and 32 GB of RAM. To solve this PSLP optimization problem, a commercial optimization tool CPLEX is for solving the linear programs [14].

3.4 Method and Calculation
The optimization process always starts from the conventional rectangular building as the initial form of the building. For the case of urban context, in the parametric analysis, we take into consideration self-shading and overshadowing from four adjacent buildings. More detailed analyses are conducted to estimate the amount of insolation during hot days as well as during cold days where the aim is to maintain or increase the solar access.

4. RESULTS AND DISCUSSION
In order to assess the performance of the proposed approach, several experiments are done. The experiments are chosen so that several scenarios are considered from real-life cases in a subtropical region.

The objective is to optimize the form of the building to minimize insolation while maintaining the same built-up area. Both the initial and optimized forms have the same built-up area which in this case is 1728 m² (12 meters × 12 meters × 12 floors in the conventional building form).
4.1 The Stand-Alone Form Before Overshadowing

The aim is to show how the form of the building changes after reducing the effects of insolation without overshadowing. Figure 3 shows the initial and the optimized shapes at 33.5 latitude during the fifth day of August. The initial stand-alone building (Figure 3, left) has a square footprint. The optimized shape is elongated along the east-west axis and tilted towards the south to shade itself.

![Figure 3: Form change with optimization without urban environment.](image)

In this scenario, analysis is conducted to compare the initial form with the optimized form. Table 1 summarizes the results. The percentage is the decrease in insolation with respect to the initial building.

<table>
<thead>
<tr>
<th>Building</th>
<th>Insolation (KW)</th>
<th>Average (KW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>496.7</td>
<td>0.265</td>
</tr>
<tr>
<td>Optimized</td>
<td>293.1</td>
<td>0.146</td>
</tr>
<tr>
<td>Improvement</td>
<td>40.9 %</td>
<td>45 %</td>
</tr>
</tbody>
</table>

4.2 Influence of Urban Morphology

The design of new optimized buildings in an urban environment allows urban planners to create environmentally friendly urban designs [15]. This part illustrates that having the constructed building in an urban neighbourhood with surrounding buildings can reduce the amounts of insolation and thus support the creation of a more shaded building. Figure 4 shows the optimized building in an urban environment surrounded by four buildings. The figure also shows how the proposed approach outputs the optimized building with built up area that is equal to the initial un-optimized shape in an urban context.

![Figure 4: Isometric view of optimized building (red) in urban context.](image)

4.3 Insolation Measurements

Different scenarios have been analysed and compared: the urban initial scenario without any optimization, the intermediate scenario where the stand-alone optimized form is inserted into existing urban environment, and the optimized design scenario where the target building is optimized given the urban environment in which it exists. The urban environment is in this case similar to Figure 2 where eight neighbouring buildings are considered.

![Table 2: The percentage improvement in insolation (KW) for urban context scenarios.](image)

4.4 Influence of Latitude Variation within Subtropical Region

One of the critical aspects to analyse is the latitude within the Subtropical Region. Figure 5 shows how the percentage improvement, defined as the reduction in insolation compared to the initial conventional building, changes with respect to the latitude during the fifth day of August. The figure shows that as the latitude increases, the percentage improvement slightly increases as well. Although the initial and the optimized amounts of solar radiation increase with the latitude [16], the difference between the initial and final values is maintained. Therefore, the proposed approach is generic.

4.5 Influence of Day Variation

The amount of solar radiation reaching Earth peaks at the summer solstice on June 21 in the Northern Hemisphere [17]; therefore, to estimate the reduction in the insolation on this special day, we run the optimization on June 21. Figure 6 shows the average insolation per external envelope surface area (KW/m²) for both summer dates: August 5 and June 21. The results show that in June 21, the optimized building is less tilted towards the south since it follows the solar altitude. In addition, the percentage reduction in the insolation per envelope surface area is higher in
August than in June compared to the initial conventional rectangular building.

![Graph showing improvement in insolation](image)

**Figure 5:** The optimum building forms and their specifications at different latitudes of 24 degrees (Cairo, Egypt), 32 degrees (Beirut, Lebanon) and 40 degrees (Istanbul, Turkey).

![Graph showing average insolation](image)

**Figure 6:** The effect of changing the dates of study.

### 4.6 Implications During a Cold Day on December 12

The last simulation shows the implication of the proposed optimization approach on the insolation of the building during a day in December. Figure 7 shows the insolation amounts for initial and optimized buildings in both stand-alone and urban scenarios for two days of the year. These two days represent a hot summer day (August 5) and a cold winter day (December 12). The figure shows that the same building which is optimized to receive less incident solar radiation on August 5, receives more insolation on December 12 as compared to the initial rectangular building. Hence, the proposed methodology results in more efficient building during the hot day as well as on the cold day. Therefore, our approach is beneficial for residential buildings in particular where solar gains may be required in winter and part of mid-season.

For the stand-alone scenario (illustrated in Figure 3), the figure shows that the optimized form has 41% decrease in insolation during August 5 while it has 7% increase in insolation during December 12 compared to the initial rectangular building. As for the urban environment (illustrated in Figure 4), the figure shows 42% less insolation during hot day with 9% more insolation during cold day. This is explained by the fact that, on December 12, the solar altitude is lower than that on August 5; hence, our proposed optimized building benefits from this low solar altitude angle and the building feels warmer during a cold day than the conventional rectangular form.

![Graph showing behavior of optimized form](image)

**Figure 7:** The behaviour of the optimized form on December 12 and on August 5.

### 5. Application in the Architecture Design Process

Integrating the information provided by the proposed method allows the definition of performant architectural form. A brief illustration of the process starts by the following allowable development inputs. A site is 24 m x 18 m; the allowable area for each floor is 156 m² and the allowable number of floors is 12. Figure 8 shows an early concept design sketch of the output that the design team sees after 3 minutes; it receives 42% less incident solar radiation. This shape can be developed by enhancing its architectural shape, balcony articulation, its window to wall ratios, etc. (Figure 9). If this form is not suitable, or if the design team would like to investigate a different option, then the input could include a different number of floors and an associated modification of floor plan area (to maintain an overall built up area that is equal and comparable to allowable exploitation).

This study focuses on the transformation of the form; therefore, we assume that the envelope is made of a uniform material. The aim of this methodology is to invite design teams to start with our optimized form and then define construction materials to further enhance the sustainable dimension.

### 6. Conclusion

This paper presents the study of the impact of urban morphology on the amount of insolation while considering all building design variables to minimize the amounts of incident solar radiation. In addition,
this paper proposes an optimization approach to optimize both i) a stand-alone building without considering the surrounding urban context and ii) a building to be constructed in an urban context thus benefiting from the shadow cast by surrounding buildings. Moreover, this paper proposes a novel optimization tool that can exploit the advantages of having surrounding buildings to overshadow the optimized building.

The optimization approach is illustrated through a case study where an urban neighbourhood in a subtropical region is simulated. Results show that for this case study, a reduction of 42% in insolation can be obtained by optimizing the building form while making use of the urban context due to shadow cast on the target building.

Future works will evaluate urban daylighting and the solar access of public streets and other spaces to optimize both the insolation of buildings and streets during an extended summer period.

![Figure 8: An early concept design sketch of the optimized building.](image)

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Towards Passive Working Environments: Free-running office in Guadalajara, Mexico

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ABSTRACT: Unlike vernacular architecture, most of the newly built office buildings in Mexico are poorly adapted to the climate. The main reason is a lack of normative to limit and regulate the environmental performance of office buildings, since the existing one, is focused on active methods, disregarding the possibility of free-running buildings. This research focuses on the interaction between architecture and the climate to design comfortable environments for office workers in the region of Guadalajara, Mexico. The investigation starts with a climate analysis to reveal the climate’s challenges and opportunities as well as the potential for passive design strategies. Fieldwork was conducted in an office tower originally designed following the results of a predesign analysis. With the outcome from the case study, a building module was developed, and the initial parameters were set for further parametric analysis. The results were measured considering the percentage of time in comfort of each different case, as well as the percentage of time overheated. The study identified solar protection as the most effective passive strategy for the location, for the cases where is not possible, a high resistance building envelope is recommended with the inclusion of thermal mass, and insulation.

KEYWORDS: Office buildings, Free-running buildings, Natural Ventilation, Mexico, Design guidelines

1. INTRODUCTION

As part of the global efforts to reduce energy consumption, energy efficiency programmes have been implemented around the world. The possibility of success of these programmes is directly related to the normative on which they are based, whereas their outcomes can be measured according to the trends and consumption numbers during the periods after their implementation.

During the last decade, a peak of economic investment in happened in Mexico. This growth was directly reflected in the construction industry, therefore, the automatic appearance of numerous high-rise office buildings in all the major cities. One of the main concerns of this growth has been the extra loads to the state’s infrastructure, together with the unplanned energy expend these buildings have brought [1], this is mainly the outcome of the absence a normative specifically focused in regulating the energy performance of office buildings, the closest to it, is the Mexican official standard for energy efficiency in non-residential buildings [2], which is a set of regulations oriented to a broad spectrum of non-residential buildings. As an attempt to fill this gap, the Leadership in Energy and Environmental Design (LEED) building standard was introduced into the context, disregarding the fact that it is a building energy standard developed for different climates, user’s expectation and building regulations [3], hence the proliferation of fully-glazed air-conditioned buildings, relying on the most inefficient methods for thermal comfort. In accordance with this, the failure of the application of the LEED standard and the national normative is reflected in the constantly growing energy demand for the purpose of space cooling [1], as if was forgotten that historically speaking, in a pre-carbon era, all of the buildings in Mexico were free-running and passive strategies were an essential part of the implicit architectural criteria.

The climates across the Mexican territory are within the classification of tropical and subtropical. These climates provide by definition the necessary conditions for the application of passive strategies [4], hence naturally ventilated free-running buildings seem to be a more logical response, rather than the typical non-climate responsive architecture that seeks to isolate the interior from the exterior. Free-running buildings are not only better in terms of energy saving, they are healthier buildings since they maintain a closer relationship between the occupants and the exterior, their whole operation is based in utilizing the climate features as means to create and maintain comfortable interior conditions [3].

This research is focused on exploring the climate potential for the application of passive strategies in free-running office buildings in a humid tropical climate. The objective is to analyse the climate and investigate the effectiveness of different passive strategies as means to create comfortable workspaces, the research is developed in the city of Guadalajara, Mexico.
2. CLIMATIC CONTEXT

The city of Guadalajara, Mexico is located in the Mexican tropic at the coordinates 20°40′36″N 103°20′51″W. In a climate classified as temperate Cwa climate, which is defined as dry winter humid subtropical climate according to Köppen’s climate classification, theoretically speaking, the main characteristics of this climate are the diurnal and seasonal temperature fluctuations, wet summers with copious precipitation, and cold seasons with an average temperature above 0°C. These features are well reflected at the location, the average yearly temperature is 18°C, with a maximum monthly average temperature of 30.7°C and an absolute peak of 34.3°C, together with a minimum monthly average temperature of 6.5°C, with an absolute peak of -1.04°C. The highest monthly average temperature fluctuation is during the month of April with 17.5°C, while the lowest is during August with 8.5°C. Due to the high altitude of over 1,500 meters above sea level, solar radiation is also intense all year long and the presence of wind is also continuous with an average yearly speed of 1.8 m/s. Figures 1.

The main challenge for a building in a climate like this is to prevent overheating. During the cold season, overcooling should not be a problem since solar radiation is constant, and temperatures rise often above 20°C. According to a theoretical analysis based on the temperature, radiation and the airspeed of the location [6], the most efficient passive strategies are passive solar heating, thermal mass, natural ventilation and night cooling, Figure 2.

3. THERMAL COMFORT AND OVERHEATING

There is not an official comfort criterion established for the location. Although, the Mexican normative does not suggest or imposes any specific method to estimate comfort, the use of the LEED standard has implied the utilization of the ASHRAE’s Standard 55 [6]. Nevertheless, use of this standard or the European CEN Standard EN 15251 (recently renamed to EN 16798) could be arguable since they were conceived considering meteorological and user’s data from different geographic and cultural contexts, located at higher latitudes, therefore, differences in the user’s satisfaction and comfort boundaries could be expected [3].

The utilized comfort algorithm in this research was the CEN Standard EN 15251 for naturally ventilated buildings. The European CEN standard was chosen given that it considers the exponentially weighted running mean of the daily mean outdoor air temperature ($T_{rm}$) rather than the mean monthly temperature or ($T_{om}$) considered by the ASHRAE standard 55, the use of the $T_{rm}$ implies the inclusion of the thermal history of the subject giving more influence to the recent experiences (i.e. the constant high temperatures during a heatwave), for this reason, it is possible to say that the EN-15251 is better suited to predict the thermal stress induced by overheating since it considers the subject’s ability to adapt and acclimatize. [3] Following this, it was also considered, a comfort bandwidth of ±4K, implying an 80% of acceptability limits as it specified in the application of adaptive theory for naturally ventilated buildings.

Since there is not a broadly accepted method to measure overheating in naturally ventilated buildings located in tropical tempered locations. An overheating assessment was elaborated considering the strength and frequency of operative temperatures above the upper comfort limit, with the interest of acquiring quantitative and qualitative data regarding the overheating hours. The method [7], [8] classifies and enumerates the number of hours in five different categories, number of hours above 0.1°K, 1°K, 2°K, 3°K and 4°K.

4. CASE STUDY

The building taken as case study was the Cube Tower I (Figure 3). It was designed by the Spanish firm Estudio Carmen Pinos, It was finished during the year 2009, and it has been fully occupied ever since, the building is located in one of the financial districts of the city. Although it does not possess a building energy standard, it was designed considering the application of passive strategies following the self-imposed objective of becoming a naturally ventilated free-running comfortable office building, [9].
The application of environmental criteria through passive strategies can be noticed at plain sight. The building is mainly composed of concrete, it possesses a double façade with a first layer of solar protection and a second layer of glazing, and is divided into three volumes attached to a vertical hollow structure, implying with these features, plenty of thermal mass, the reduction of solar gains, and the enhancement of surface exposure area, the vertical hollow nucleus maximizes the airflow through buoyance and stack effect. Figure 4 shows what could be called the typical floor plan of the building, considering that it is not followed completely because of the removed spaces for the airflow optimization, this is possible to appreciate in figure 5, where a cross-section of the building is shown. The identified passive strategies were thermal mass, solar protection, orientation massing, passive solar heating and the possibility of crossed ventilation and night cooling.

A digital model of the building was prepared, and the first set of thermal simulations were elaborated. The architectural plans and the constructive specification (Table 1) were provided by the administration and the designing studio, a fieldwork campaign was carried out with the purpose of a better understanding of the energy balance of the composing elements in the building, it included the placement of dataloggers, thermal imaging and general occupation statistics. With the gathered information, the interior conditions were modelled Figure 6, successively, the first set of simulations was performed, during this sets, it was found that the measured performance could be improved, but the occupant decided to remain like that, theoretically speaking during the warmest hours of the day, temperatures were above the upper comfort limit, for less than 2°C during periods of approximately 2 hours, but the analysis showed that it was the occupant’s choice, since they had access to the window operation and air-flow could be improved together with the thermal sensation and operative temperature. With this in consideration, a window operation algorithm was programmed, the algorithm considered the upper and lower comfort band temperatures as limits for the maximum and minimum outdoor temperature for natural ventilation, as well as slight openings of 1% overnight for night cooling.

The second set of simulations were performed using the programmed natural ventilation algorithm, followed by the overheating assessment. The comfort hours and percentage of time in comfort were calculated considering an occupancy time from 9:00 to 19:00 hrs, the optimized model was capable to reach a total of 95.17% of the time in comfort equivalent to 3821 hours out of 4015, the 4.83% or 194 hours of occupancy time above the upper
comfort limit, was composed by 118 hours or 2.94% of occupancy time above 0.1°K but below 1°K, 63 hours or 1.57% above 1°K but below 2°K, 11 hours or 2.94% above 2°K but below 3°K, 2 hours or 0.05% above 3°K but below 4°K, and no hours above 4°K. In figure 7 is possible to appreciate a chronological distribution of these hours. Following this results, the energy balance of the office suite was calculated (Figure 8) where is possible to appreciate the heat balance of the office suite, the major source of heat gains correspond to the solar gains, followed by the equipment gains in second place, and the lighting gains in third, the heat gains from the occupants are considered but it is not possible to appreciate them due to the scale of the graphic, in the side of the heat losses, the elements with the mayor discharge of energy are the natural ventilation and the glazing depending on the season, followed by the infiltration, the heat losses through the opaque conductions are also considered but not visible at the scale of the graph.

The simulation results together with the overheating analysis show the possibility of creating and maintaining comfortable conditions. Even when most of the overheating is concentrated during the 3 hottest months of the year, the actual recurrent overheating is in between 0.1°K and 2°K completely manageable with the proper application of adaptive strategies, the percentage of time above 3°K indicate that strong overheating is rare and high levels of thermal stress are also uncommon, but still within the effective spectrum of adaptive opportunities. The main feature of the building and therefore, the office module, is the combinations of strategies rather than the single application of them, the first layer of the façade, the solar protection, blocks around half of the incoming solar radiation, the other half, is absorbed by the building elements, and stored inside the thermal mass, thereafter, slowly release as longwave radiation from where it is flushed by the infiltration, natural ventilation and night cooling, the lack of insulation and high resistance materials, also help with the discharge of the heat gains during the non-occupancy time, the proportion of the office modules of the building provide enough thermal storage as well as exposure area for the storage and release of heat, with additional effect to the mean radiant temperature perceived by the occupants.

4. ANALYTIC WORK

The physical proportions and constructive specifications found in the building and the office suite were interpolated to a building module (table 2), subsequently, two sets of additional simulation runs were performed. The simulations were performed with a modelled rectangular office module

### Table 1: Constructive materials, densities, and U-values

<table>
<thead>
<tr>
<th>Elements</th>
<th>Materials</th>
<th>U-Value</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior Walls</td>
<td>Concrete</td>
<td>2.8 W/m²K</td>
<td>300 mm</td>
</tr>
<tr>
<td>Interior Walls</td>
<td>Gypsum</td>
<td>2.5 W/m²K</td>
<td>150 mm</td>
</tr>
<tr>
<td>Exterior Windows</td>
<td>Single Glazing</td>
<td>5.2 W/m²K</td>
<td>12 mm</td>
</tr>
<tr>
<td>Shading</td>
<td>Wood</td>
<td>5.9 W/m²K</td>
<td>25 mm</td>
</tr>
<tr>
<td>Slab</td>
<td>Concrete &amp; Flooring</td>
<td>0.33 W/m²K</td>
<td>4500 mm</td>
</tr>
</tbody>
</table>

### Table 2: Physical dimensions and proportions of the office module

| Interior Surface | 105.7 m² |
| Interior Volume  | 370 m³   |
| WFR            | 0.69     |
| WWR            | 0.77     |
| Infiltration   | 1 ACH    |
| Interior Height| 3.00 m   |
of 105m² with windows oriented towards the north and south, the roof and floor slabs were adiabatically considered since it was assumed that the module was part of a vertical development.

The first set of additional simulations was performed only changing the solar protection, maintaining all the other features as they were found in the case study. The unmodified features were internal conditions, infiltration rate, building materials, internal height, and glazing ratio (tables 1 and 2). A parametric shading device was modelled as an overhang and it varied in each simulation run, a total of five runs were executed, the placement of the overhang started perpendicular to the walls, in the first cases it only covered the incoming radiation from the highest point of the sun’s altitude, the protection only covered the north and south facades, the model was programmed to increase progressively from 0 to 2.70 meters, until the overhand was capable of blocking all the incident direct solar radiation.

The results of these simulations are shown in Figure 9, where the percentage of overheating hours are shown in the Y-axis, while the different overhang lengths are shown in the X-axis. In the figure it is possible to appreciate a decrease from 20.2 to 3.1 of percentage overheating hours, the first 1.2 meters of the shading device are the most effective since they decrease the percentage of time overheated in less than half, subtracting the 12% of overheating hours, from 20.2% to 8.0%, the following additional 0.90 meters from 1.2 to 2.1m of overhang length, only decrease the 4.2% of time overheated, the following 0.60 meters only 0.7% of overheating hours.

The second set of additional simulation runs was performed completely suppressing the solar protection, varying the wall types, window types, internal height, and glazing ratio. On a first subset, different resistance values for the building envelope elements were tested, maintaining the internal height and glazing ratio as they were found in the base case. The tested combination included the original single glazing windows with a U-value of 5.2 W/m²K, as well as double glazing windows of 2.7 W/m²K mixed with the original concrete wall of 300mm with a U-values of 2.8 W/m²K, a thinner concrete wall of 150mm depth and 4.7 W/m²K, and a wider double layer wall of 300mm of concrete plus 160mm of insulation with a U-value of 0.33W/m²K. On a second subset, different internal heights of 2.7m, the original 3.0m and 3.3m were tested, versus to different glazing ratios of 0.2, 0.4, 0.6 and the original 0.8, maintaining the original resistance values of the envelope.
radiation, but it also permits a heat exchange during the night-time allowing the captured heat gains to escape.

Table 3: Relationship between internal height and glazing ratio versus overheating hours.

<table>
<thead>
<tr>
<th>Internal Height</th>
<th>Glazing ratio</th>
<th>Glazing type</th>
<th>% of time in Comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.7</td>
<td>0.8</td>
<td>Single</td>
<td>79.5</td>
</tr>
<tr>
<td>3</td>
<td>0.8</td>
<td>Single</td>
<td>79.8</td>
</tr>
<tr>
<td>3.3</td>
<td>0.8</td>
<td>Single</td>
<td>82.0</td>
</tr>
<tr>
<td>2.7</td>
<td>0.6</td>
<td>Single</td>
<td>83.1</td>
</tr>
<tr>
<td>3</td>
<td>0.6</td>
<td>Single</td>
<td>83.2</td>
</tr>
<tr>
<td>3.3</td>
<td>0.6</td>
<td>Single</td>
<td>85.5</td>
</tr>
<tr>
<td>2.7</td>
<td>0.4</td>
<td>Single</td>
<td>87.8</td>
</tr>
<tr>
<td>3</td>
<td>0.4</td>
<td>Single</td>
<td>88.0</td>
</tr>
<tr>
<td>3.3</td>
<td>0.4</td>
<td>Single</td>
<td>90.8</td>
</tr>
<tr>
<td>2.7</td>
<td>0.2</td>
<td>Single</td>
<td>93.7</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>Single</td>
<td>93.9</td>
</tr>
<tr>
<td>3.3</td>
<td>0.2</td>
<td>Single</td>
<td>95.7</td>
</tr>
</tbody>
</table>

The results of the second subset of simulations are presented in Table 3, where it is possible to perceive the minimal effect of the interior height among the cases with the same glazing ratio, as well as the significative effect of the glazing ratio in all of the cases. The internal height showed a general average increase of performance of 1.2% across the 4 different tested glazing ratios, as it escalates from 2.7m to 3.3m, while the reduction of glazing ratio showed an average increase of performance of 4.6% when comparing only the cases with heights of 3.3 meters, the highest percentage of time in comfort was obtained by the case with an interior height of 3.3m with a 95.7%, corresponding to the 0.2 glazing ratio, while the percentage of time in comfort for the same height but with a glazing ratio of 0.8, as it is in the case study, is 82%, with a difference of 13.8% among them. The obtained results, highlight the importance of the glazing ratio when there is no solar protection considered, a decrease in the glazed area, implies a decrease of solar gains as well, an increase of the thermal mass, thus less solar gains for the interior and a lower operative temperature, even though all of the tested models in this second subset, had a lower resistance value than the better performing models in the first subset, it was possible to increase the percentage of time in comfort by reducing the glazing ratio.

5. CONCLUSION

This paper focuses on exploring the extent and application of passive strategies for free running office buildings in temperate tropical climates. As a starting point, the research starts with a climate analysis and a building precedent was analysed as well as the effectiveness of the passive strategies detected, moreover, further analysis is elaborated in a module where the previous findings were applied. The results were measured considering the percentage of time in comfort of each different case.

This study identified solar protection as the most efficient and effective passive strategy for naturally ventilated office buildings at the location. The application of a shading device allows the possibility of increasing the glazing ratio until desired daylight levels are reached, but it is important to keep in mind the risk of glare due to the brightness of the tropical sky. Another advantage of the consideration of solar protection is the possibility of more window opening areas for natural ventilation. When the solar protection is omitted, the best performance is achieved with a high resistance envelope with a combination of thermal mass and insulation, combined with a low glazing ratio, the main issue with this configuration is the reduction of daylight and natural ventilation area. Similar results can be expected as long as the not tested features such as proportion and orientation are kept similar to values kept during the work.

ACKNOWLEDGEMENTS

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REFERENCES

1. INTRODUCTION

The majority of the European building stock was built before the establishment of building energy codes, mostly presenting a lower energy efficiency [1]. Its conversion into Nearly Zero-Energy Buildings (NZEB), in the frame of the Energy Performance of Buildings Directive (EPBD), is being done pursuing the airtightness and the heavily insulated envelope model [2].

However, this static envelope solution has recently been related to the overheating risk [3], in the context of current global warming. As an opportunity to reduce building energy use and CO₂ emissions, without compromising comfort, the concept of adaptive envelope is emerging. With the aim of improving the overall building performance, these envelopes are able to change their functions, features or behaviour over time in response to transient performance requirements and boundary conditions [4].

Having in mind that up to 110 million European buildings need renovation [5], the opportunity to introduce climate adaptivity into building envelopes must be seized.

Auto-responsive technologies (ARTs) operate on intrinsic mode, enabling the usage of their reactions to environmental stimuli in a positive way, without processors or external power [6]. They represent a huge potential to implement thermal adaptive strategies (TAS) into building envelopes.

Within the scope of this communication, we intend to discuss criteria for ARTs use on opaque facades thermal renovation. In this analysis thirteen ARTs were considered which are triggered by variations of temperature, humidity and/or solar radiation, that can contribute to nine different thermal adaptive strategies (TAS) with the intent to control the temperatures of the outer and inner cladding and the corresponding indoor environment (Fig. 1) [7]. The selection method is established by applying the criteria to the TAS in which the ARTs can be useful.

2. CRITERIA

The criteria of climate suitability, thermal behaviour compatibility, constructive and urban constraints will be studied for the ARTs applicability into pre-existing opaque facades. Only climate suitability is discussed in more depth. The remaining criteria still need further study.

2.1 Climate suitability

The qualitative allocation of each TAS into zones of a building bioclimatic chart (BBC), indirectly allows to establish the climate adequacy of each ART. The BBC is a psychometric chart permitting the graphical representation of the relationship between air temperature and humidity conditions of a given geographic location. Furthermore, it identifies different zones that correspond to conditions of occupants’ comfort or to conditions in which comfort can be achieved if a specific building passive design strategy is implemented [8]. For this purpose, the climate consultant tool 6.0 [9], that graphically analyses climate data, is used. The correspondence between each TAS and some of the design strategies listed in the BBC (from 1 to 14) is possible considering the adequacy of weather conditions for each strategy (Table 1).
thermochromic (TC) technology, allows the change of its reflection coefficient, controlling its solar radiation absorption. To prevent overheating, high reflection values are desired, but the opposite is advisable to enhance solar gains [7]. This strategy is suitable when BBC 10 and/or 11 - Passive solar Direct gain low and high mass and BBC 2 - Sun shading of windows are both recommended to a given location by Climate consultant [9]. Although BBC 10 and 11 refer to passive solar direct gain, which implies collecting solar energy through the transparent envelope directly indoors, such as SRA, they work when solar radiation is available and we intended to take advantage of it. BBC 2 is recommended when available solar radiation is not desirable.

Table 1: Thermal Adaptive and BBC listed strategies correspondence

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Cooling + Heating (H)</th>
<th>Cooling (H)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Adaptive Strategies (TAS)</td>
<td>Cooling + Heating (H)</td>
<td>Cooling (H)</td>
</tr>
<tr>
<td>Solar Reflectance Adaptation (SRA)</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>Storage control (SC)</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>Convective / Conductive Heat Transfer Control (CCHTC)</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>Self-ventilation control (SVC)</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>Self-shading control (SSC)</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>Integrated hygrothermal control - indoor (HIC-I)</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>Integrated hygrothermal control - outdoor (HIC-O)</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>Conduction Heat Transfer Control by dynamic thermal behaviour (CHTC-DTB)</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>Conduction Heat Transfer Control by kinetic behaviour (CHTC-KTB)</td>
<td>C</td>
<td>C</td>
</tr>
</tbody>
</table>

Through the Storage Control (SC) strategy it is possible to balance the indoor temperature by passively storing thermal energy when high temperatures occur and release it when indoor temperatures drop. It can be achievable through phase change materials (PCM), which have the ability to store and release thermal energy [7]. This strategy is adequate when BBC 4 and/or BBC 3 – High thermal mass with or without night flushed and BBC 10 and/or BBC 11 – Passive solar Direct gain low or high mass are recommended by Climate consultant [9]. BBC 4 and/or BBC 3 are useful when it is necessary to store thermal energy to avoid overheating. BBC 10 and/or BBC 11 is suitable when
solar radiation is available and its energy will be useful in a later moment.

The Conduction / Convection Heat Transfer Control (CCHTC) strategy allows to prevent or enhance thermal losses, through the closing or opening of an air cavity between two opaque facade layers by means of a mechanical actuator, i.e. components that change their shape in order to trigger a mechanism that can be made of shape memory alloys (SMA), shape memory polymers (SMP), light responsive polymers (LRP), hygromorph bio-composites (HBC), heat sensitive plastics (HSP) and thermobimetals (TB) (Fig. 1). Inside the cavity, the convective movements generated by wind pressure or by a temperature gradient due to solar gains, promote thermal dissipation. To provide thermal insulation by the still air, the air cavity closes, when low temperatures occur [7]. This strategy is suitable when BBC 2 - Sun shading of windows and/or BBC - 4 High thermal mass night flushed are recommended because it means that there is solar radiation and/or wind pressure available to generate a convective movement inside the wall cavity to promote thermal dissipation (cooling mode). For heating mode, it is suitable when BBC 9 - internal heat gains is recommended because increasing the thermal resistance of the facades allows the imprisonment of the internal heat gains.

The Self-Ventilation Control (SVC) strategy allows the prevention or enhancement of thermal losses through the adaptive configuration of the outer skin, blocking or permitting the air flow [7]. This strategy can be used when both BBC 4 - High thermal mass night flushed and BBC 12 - Wind protection of outdoor space are recommended. The BBC 4 works with high thermal amplitude and/or wind pressure to promote air flow in order to dissipate heat (promote losses) and BBC 12 is necessary when the goal is to restrict losses caused by air flow.

The Self-Shading Control (SSC) strategy of the opaque envelope adjusts the gap between the building’s skin and the surface reached by solar radiation [7]. Although this strategy refers to the opaque area of facades and BBC 2 to windows, both will restrict gains through shading. Elements on the opaque facade contiguous to a window can also have a shading effect on those windows. Therefore, this strategy can be applied when BBC 2 is identified as suitable by Climate consultant [9].

Several ARTs enable cladding configuration changes necessary to SVC and SSC strategies, such as thermobimetals, natural hygromorph (NH), bio-based bilayer components (BBBC) and vertical greener systems (VGS) [7].

The Integrated Hygrothermal Control – Indoor (IHC-I) strategy promotes the surface and/or indoor temperature decrease by evaporation, or moisture removal from a humid environment, enabling human cooling through perspiration. It can be attainable through materials which have the capacity of harvesting and storing moisture by its inherent increase in volume, such as hydrogel (HG) [7]. This strategy can be applied when BBC 5 - Direct evaporative cooling or BBC 6 – Two-stage evaporative Cooling and/or BBC 14 - Dehumidification are recommended.

Also using hydrogel, the Integrated Hydrothermal Control – Outdoor (IHC-O) strategy allows exterior cladding temperature reductions by evaporation [7], and can be applied when BBC 5 is recommended.

The Conduction Heat Transfer Control (CHTC) strategy permits to reversibly modify the thermal conductivity of the facade either through its kinetic or dynamic thermal behaviour. The cladding shape change can allow the formation of an almost airtight pocket of still air, contributing to the increase of the facade thermal resistance. In order to dissipate heat, a reversible alteration in the thermal conductivity can be accomplished with carbon nanotube suspensions in liquid (CNSL) that can modulate its thermal conductivity by a change in the temperature of the material or in the velocity of the fluid [7].

The Conduction Heat Transfer control by dynamic thermal behaviour (CHTC-DTB) can promote losses if the indoor temperature is higher than the outside temperature, such as in the BBC 4 - High thermal mass night flushed and BBC 7 - Adaptive comfort ventilation.

The Conduction Heat Transfer control by kinetic behaviour (CHTC-KB), achievable with ARTs that enable cladding configuration change, can be applied when the BBC 9 - internal heat gains is recommended. In fact, if that strategy is adequate, that means that increasing the thermal resistance of the facades, that allows heat imprisonment, will be favourable.

2.1.2 Climate cases study

Hourly climate data from nine cities (six Portuguese) were analysed in the BBC, through climate consult tool 6.0 [9] (Fig. 2), corresponding to climate types: Csb, Csa, Bwh, Dfb and Aw (Koppen Geiger classification) (Table 2).

Considering the correspondence of the BBC strategies with TAS (Table 1), the percentage yearly period that each TAS is suitable to each climate is established (Table 3) by summing up the period of their related BBC, which is indicated by climate consultant tool 6.0 [9]. It is also possible to observe the time spent on cooling or heating mode for each TAS.

2.1.2.1 TAS adequacy to different climates

The SRA strategy is used in both modes (cooling and heating) in all the studied climates. Climates with higher temperature range and lower sky cover take more advantage of SRA strategy, as in the case of Alice Spring AUS. This climate has a higher percentage of use time (34%) and cumulatively a more balanced use mode between heating and cooling time. Porto
climate is the one that uses SRA strategy in a more unbalanced way, with only 3% in cooling mode, easily explained by the 30 to 60% of sky cover in summertime (Fig. 3). Comparing sky cover in Faro and Évora PT climates, both with CsA Koppen Geiger classification, it is possible to justify the higher percentage of heating mode of SRA strategy in Faro. Even in the wintertime, Faro has sky cover under 60% most of the time (Fig. 3).

Table 2: Weather data summary

<table>
<thead>
<tr>
<th>Koppen-Geiger Climate Classification</th>
<th>Ccb</th>
<th>Csa</th>
<th>Bah</th>
<th>Dfb</th>
<th>Aw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>SWC</td>
<td>INETI</td>
<td>WSC</td>
<td>INETI</td>
<td>RMY</td>
</tr>
<tr>
<td>Lisbon, PT</td>
<td>21</td>
<td>22</td>
<td>23</td>
<td>29</td>
<td>20</td>
</tr>
<tr>
<td>Porto, PT</td>
<td>4</td>
<td>9</td>
<td>10</td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td>Évora, PT</td>
<td>67</td>
<td>83</td>
<td>83</td>
<td>81</td>
<td>81</td>
</tr>
<tr>
<td>Faro, PT</td>
<td>52</td>
<td>75</td>
<td>68</td>
<td>64</td>
<td>55</td>
</tr>
<tr>
<td>Alice Springs, AUS</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Brasilia, BRA</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

In soft Brasilia BR climate, the SC strategy is used in a more balanced way between cooling and heating mode. Although, as in the other study locations, the heating mode is predominant.

The CCHTC strategy has the highest suitability percentage of time for the studied climates compared to all other strategies described. In all the climates, this strategy is predominantly in heating mode, working in a more balanced way in Alice Spring AUS with 20% and 28% of the time in cooling and heating mode, respectively.

Table 3: Yearly percentage in which weathering conditions make each thermal adaptive strategy adequate/functional for nine specific locations.

<table>
<thead>
<tr>
<th>Thermal Adaptive Strategies</th>
<th>Singapore, PT</th>
<th>Porto, PT</th>
<th>Coimbra, PT</th>
<th>Lisbon, PT</th>
<th>Évora, PT</th>
<th>Faro, PT</th>
<th>Alice Springs, AUS</th>
<th>Brasilia, BRA</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRA</td>
<td>20</td>
<td>22</td>
<td>20</td>
<td>25</td>
<td>22</td>
<td>27</td>
<td>34</td>
<td>35</td>
</tr>
<tr>
<td>Cooling mode</td>
<td>5.9</td>
<td>7.0</td>
<td>9.3</td>
<td>8.5</td>
<td>10.2</td>
<td>20.1</td>
<td>4.3</td>
<td>18.3</td>
</tr>
<tr>
<td>Heating mode</td>
<td>13.7</td>
<td>19.2</td>
<td>12.9</td>
<td>15.3</td>
<td>13.2</td>
<td>13.2</td>
<td>16.7</td>
<td>14.2</td>
</tr>
<tr>
<td>SC</td>
<td>14</td>
<td>20</td>
<td>15</td>
<td>19</td>
<td>13</td>
<td>19</td>
<td>14</td>
<td>11</td>
</tr>
<tr>
<td>Cooling mode</td>
<td>0.0</td>
<td>0.6</td>
<td>2.2</td>
<td>3.3</td>
<td>0.0</td>
<td>1.6</td>
<td>0.8</td>
<td>5.4</td>
</tr>
<tr>
<td>Heating mode</td>
<td>13.7</td>
<td>19.2</td>
<td>12.9</td>
<td>15.3</td>
<td>13.2</td>
<td>13.2</td>
<td>16.7</td>
<td>14.2</td>
</tr>
<tr>
<td>CCHTC</td>
<td>33</td>
<td>55</td>
<td>55</td>
<td>57</td>
<td>47</td>
<td>57</td>
<td>48</td>
<td>26</td>
</tr>
<tr>
<td>Cooling mode</td>
<td>5.9</td>
<td>3.0</td>
<td>9.2</td>
<td>13.0</td>
<td>8.5</td>
<td>12.5</td>
<td>20.1</td>
<td>4.3</td>
</tr>
<tr>
<td>Heating mode</td>
<td>27.3</td>
<td>51.7</td>
<td>45.3</td>
<td>43.5</td>
<td>38.2</td>
<td>44.2</td>
<td>27.7</td>
<td>21.5</td>
</tr>
<tr>
<td>SVC</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Cooling mode</td>
<td>0.0</td>
<td>0.0</td>
<td>2.2</td>
<td>3.5</td>
<td>0.0</td>
<td>3.0</td>
<td>0.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Heating mode</td>
<td>1.3</td>
<td>0.0</td>
<td>0.3</td>
<td>0.2</td>
<td>0.0</td>
<td>0.3</td>
<td>0.0</td>
<td>7.0</td>
</tr>
<tr>
<td>SSC</td>
<td>6</td>
<td>3</td>
<td>7</td>
<td>10</td>
<td>9</td>
<td>10</td>
<td>20</td>
<td>4</td>
</tr>
<tr>
<td>Heating mode</td>
<td>4.3</td>
<td>3.3</td>
<td>4</td>
<td>8</td>
<td>16</td>
<td>28</td>
<td>5</td>
<td>16</td>
</tr>
<tr>
<td>IHC-I</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>IHC-O</td>
<td>8</td>
<td>7</td>
<td>14</td>
<td>15</td>
<td>11</td>
<td>22</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td>CHTC DBT</td>
<td>2</td>
<td>7</td>
<td>14</td>
<td>15</td>
<td>11</td>
<td>22</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td>CHTC KB</td>
<td>27</td>
<td>52</td>
<td>45</td>
<td>44</td>
<td>38</td>
<td>44</td>
<td>28</td>
<td>21</td>
</tr>
</tbody>
</table>

In the analysed climates, the SVC strategy is considered poorly adequate. The higher percentage of time occurs in Toronto CAN (7%) but only working in heating mode in order to protect building skin from wind that occurs, in 47% of the time, with a speed between 5 and 9 m/s. In cooling mode, promoting losses next to the building skin occurs only in 5% of the time in Brasilia BRA where annual mean wind speed is under 3 m/s and the temperature range is small, not allowing to take advantage of that strategy. In Alice Springs AUS, with even lower annual mean wind speed, this strategy is not considered worthy to use in any mode.

The SSC strategy is adequate for longer in Alice Spring (20%) with a higher monthly diurnal average global radiation, mainly constituted by direct radiation, than in the other studied locations.

In hot dry summers, such as in Alice Spring AUS, Évora PT, and Bragança PT, the IHC-I strategy will be useful in humid indoor environments, such as kitchen and showers. It has the greatest potential in Alice...
Spring (28%) with dry bulb temperatures monthly average above 24°C in 39% of the time. With higher relative humidity, in other climates, the humidity harvesting in Summer is useful for enabling cool down through human perspiration. Brasilia BR, with relative humidity monthly average of 67 to 79 % in summer, take advantage of IHC-I strategy in 16% of year time.

For Alice Spring AUS, with a dry bulb temperature monthly average between 24-38°C in 39% of the time and a relative humidity monthly average under 40% most of the time (54%), the IHC-O is considered suitable in 25% of the time. For this climate, a solution, such as the investigated by Irie et al. [10], which with a small amount of water continuously poured forms a very thin water film on a highly hydrophilic surface and, through its evaporation, decreases the surface temperature, could be adequate. The only Portuguese cities where IHC-O is considered useful are Évora (CsA) and Bragança (Csb). Both cities have a high relative humidity daily variation from under 40% to around 80% in summer days, with dry bulb temperature higher than 24 °C in the afternoon when RH is under 40% (Fig. 4). With IHC-O strategy it is possible to collect humidity during the night through hydralog cladding, and to drop the surface temperature by its evaporation during the afternoon.

![Image: Dry bulb temperature and humidity in July and August in Évora PT](image_url)

Figure 4- Dry bulb temperature and humidity in July and August in Évora PT [9].

Although CHTC-KB having the purpose of responding to heating needs, it is suitable in a higher % of the time in a soft weather such as in Brasilia (40%) than in a cold climate, such as Toronto CAN (22%). It should be noted that active heating must be used in 58.4% of the time in Toronto, which can justify that.

2.2 Further criteria

Although still in need of further study, the criteria of thermal behaviour compatibility and urban and constructive constraints are presented.

Concerning thermal behaviour compatibility, it should be noted that the high thermal resistance of the existing facade limits the potential of strategies that are highly dependent on facades' heat flow, such as SRA, SVC, SSC, IHC-O, and CHTC-DTB. Therefore, it is recommended to use those strategies in existing facades with low thermal resistance.

For ARTs applicability, three constructive aspects are considered: the geometric irregularity of facades (architecture features), the existence of a wall cavity, and ARTs easiness of implementation. The first restrains the application of modular cladding elements, compromising the implementation of strategies that imply facade configuration changes, such as SVC, SSC, and CHTC-KB. The second is mandatory to implement the CCHTC strategy. The last is related to the ARTs’ connection type with the existing facades, and can be classified on a scale from A (the simplest one, like painting) to D (the most difficult, implying several mechanical connections).

Urban constraints are related to space availability and facade shading. For the implementation of SVC, SSC, IHC-O and CHTC-KB strategies, outdoor space is necessary. Indoor space availability is required for SC, IHC-I and CHTC-DTB strategies. The implementation of SSC strategy does not make sense on facades that are continuously shaded. It is also possible to take more advantage from SRA and IHC-O strategies when implemented on unshaded facades.

3. RESULTS

Table 4 summarizes the conditions for the application of strategies and respective technologies that allow their implementation.

3.1. Case study

A typical Portuguese facade system of apartment blocks of the seventies, in Lisbon PT city, is considered in order to test and describe the steps of ART’s selection method. This facade, with low thermal resistance (U-value of 1.07 W/(m²K)), is composed of two leaves, made of hollow fired-clay brick walls of 0.11 m each, with an air cavity (approx. 0.04 m).

First, hourly climate data (epw format) are introduced in climate consultant tool 6.0 [9] in order to generate the BBC (Fig. 2), in which the % of time adequate to each BBC strategy is indicated. The time that each TAS is adequate to the Lisbon climate (Table 3) is obtained by summing up the time of each BBC adequacy considering their correspondences with the strategies, synthesized in Table 1. For instance, the time of CCHTC adequacy corresponds to the sum of the time that BBC2, 4, and 9 are recommended. In the case of Lisbon, adding BBC2 9.5%, BBC4 3.5%, and BBC9 43.5% (Fig. 2) corresponds to 57% of CCHTC adequacy time. This corresponds to the longest adequacy period of a TAS, although in an unbalanced way with only 13% in cooling mode (Table 3), since BBC 2 and 4 have cooling purposes.

In the next step, Table 4, where the criteria are synthesized and ARTs suitability for each TRAS is indicated, is observed. For the implementation of this strategy, it is mandatory to have a wall cavity. Therefore, this wall system is suitable. With SMA, SMP, LRP, HBC, HSP, and TB ARTs, a mechanical actuator can control the opening and closing of the wall cavity. For this purpose, several openings must be created in the facade. This translates to a C classification in the easiness
of implementation, not encouraging the choice of the CCHTC strategy.

For the second most adequate strategy (44%), CHTC KB, outdoor space availability is mandatory. Frequently, in apartment blocks the building and property limits match, making it impossible to implement this strategy and also SSC (10%), and SVC (4%) ones.

The third recommended strategy is SRA, with 25% of adequacy time (10% and 15% in cooling and heating mode, respectively). To take advantage of this strategy, beyond the recommendation of implementation on unshaded facades, it is also recommended that facades have low thermal resistance in order to be easily crossed by heat fluxes. For SRA strategy implementation, thermochromic ARTs can be easily applied incorporated in paints (implementation classification of easiness A).

If indoor space is available, SC strategy will be useful in 19% of the time but contributing only 4% of the time to the summer comfort. For it to be accomplished, PCM should be used. Even less interesting will be the hydrogel application solution in the interior (IHC-I strategy), only with a cooling purpose (4%).

Table 4: Criteria synthesis for ARTs application on existing facades.

<table>
<thead>
<tr>
<th>Thermal Adaptive Strategies (TAS)</th>
<th>SRA</th>
<th>SC</th>
<th>CCHTC</th>
<th>SVC</th>
<th>SSC</th>
<th>IHC-I</th>
<th>IHC-Q</th>
<th>CHTC DTB</th>
<th>CHTC KB</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Auto-Responsive Technologies (ARTs)</strong></td>
<td>TC</td>
<td>PCM</td>
<td>SMA, SMP, LRP, HBC, ICP-2D</td>
<td>TB, NH, BBVC, VSS</td>
<td>HG</td>
<td>VSS, HG</td>
<td>C0SL</td>
<td>TB, NH, BBVC</td>
<td></td>
</tr>
<tr>
<td><strong>CLIMATE SUITABILITY</strong></td>
<td>1. Generate the BCC for a specific location through the climate consultant tool.</td>
<td>2. Consider the correspondence between strategies (BCC / TAS) in table 1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>THERMAL BEHAVIOUR COMPATIBILITY</strong></td>
<td>facade low thermal resistance</td>
<td>recommended</td>
<td>recommended</td>
<td>recommended</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CONSTRUCTIVE CONSTRAINT</strong></td>
<td>facade geometric regularity</td>
<td>mandatory</td>
<td>recommended</td>
<td>recommended</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>wall cavity implementation ease</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>B</td>
<td>D</td>
<td>B</td>
<td>D</td>
</tr>
<tr>
<td><strong>URBAN CONSTRAINT</strong></td>
<td>outdoor space availability</td>
<td>mandatory</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>indoor space availability</td>
<td>mandatory</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>unshading facade</td>
<td>mandatory</td>
<td></td>
<td></td>
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</tbody>
</table>

4. CONCLUSION

A method for the selection of ARTs for thermal renovation of opaque facades was proposed through the application of climatic, constructive, urban and thermal behaviour criteria to the TAS that depend on those technologies.

To test the implementation of the climatic criterion, nine climates were analysed, and the full method was checked and described through a brief case study.

The use of this method may later contribute to understanding the potential and scope of application of specific ARTs, leading to the promotion of research in materials science in order to overcome some of their current limitations, such as durability.

ACKNOWLEDGEMENTS

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REFERENCES

Scalable Design Framework for Sustainable Urban Housing: The Case for Lagos, Nigeria

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Architectural Association, London, United Kingdom

ABSTRACT: Rapidly growing cities of Africa, Asia and Latin America will absorb more than 2 billion new urban population in the next 30 years. Providing new city-dwellers with adequate housing in an environmentally sustainable manner will be instrumental in mitigating climate change and eradicating poverty, thus addressing virtually all Sustainable Development Goals. This paper is based on a research which used Lagos, Nigeria, as a ‘laboratory’ for fieldwork and subsequent analysis. The research aimed at developing a scalable design framework for affordable, liveable, and environmentally sustainable urban housing. The resulting methodology is thought to be adaptable to various urban, climatic, and socioeconomic contexts across the developing world and has the potential to effectively address the highlighted global challenges.

KEYWORDS: Developing world, Affordable urban housing, Climate impact, Bioclimatic design, Local materials

1. INTRODUCTION – LOCAL CONTEXT
Lagos is the most populous city of Africa and one of the fastest growing urban agglomerations globally, expected to reach 30 million inhabitants before 2050, and to become the world’s largest city by 2100 [1]. Lagos shares acute systemic problems of rapidly growing developing world cities, which are also adverse drivers of irregular migration, including poor infrastructure, unreliable energy and water supply, housing shortage, rising number of slums, environmental degradation, air pollution, and general poverty [2-3].

Two thirds of Lagos’ population live under the poverty line and the current housing deficit exceeds 2.5 million units, yet there is virtually no framework in place for low-income housing provision. Affordable housing projects of the past have been failing to deliver the promised number of units by significant margins. Informal settlements remain illegal in the eyes of the local government, which frequently results in forceful demolition of buildings and displacement of people without the provision of functioning alternatives [2].

Lagos is situated in southwest Nigeria, bordering the Gulf of Guinea, and surrounding the Lagos Lagoon. The city is close to the equator (6.5°N) and features a hot-humid climate with small annual variation in temperature (Figure 1). The occurrence of approx. 1500 mm annual rainfall defines dry (Nov-Mar) and rainy (Apr-Oct) seasons. Due to high solar angles, roofs receive far more solar radiation than façades. Wind velocity and direction are stable throughout the year.

Fieldwork findings and observations of local people and their ways of staying comfortable correspond with literature on the subject [4]: shading and constant air movement are instrumental in achieving thermal comfort both indoors and outdoors.

2. FIELDWORK AND FORWARD ANALYSIS
2.1. Fieldwork in Lagos
Two weeks of fieldwork was carried out in Lagos in June 2018 where numerous housing estates were visited, occupants and local professionals were interviewed, and thermal comfort measurement data was collected. Several housing-related problems were identified that negatively impact daily life, which are addressed in subsequent chapters. Arguably the most important one is the unreliable power supply and the need to maintain liquid fuel generators at high cost and discomfort. Secondly, the unpredictable water supply and poor water quality force people to create
their own supply network via boreholes, pumps, and water tanks, yet pay for bottled drinking water. As a third factor, the forceful demolition of structures built by residents to accommodate their income-generating activities not only deteriorates the environment, and increases crime rates, but also takes away people’s livelihood. Finally, occupant comfort is compromised by the lack of consideration for climate responsive design, inadequate spatial arrangements, and poor construction quality.

2.2. Forward Analysis - Refurbishing Dolphin Estate

Fieldwork measurement data of a studied apartment in Dolphin Estate was used to create and calibrate a dynamic thermal model in EnergyPlus. Several refurbishment-type interventions were simulated with the aim of improving indoor thermal comfort.

The analysis of the calibrated base case model confirmed the hypothesis that openings without adequate solar protection and exposed concrete external walls are significant sources of overheating. Additionally, it was found that large exposed thermal mass exacerbates overheating by delaying indoor temperature peaks to higher occupancy hours of the early evening. A solar protection strategy was explored in the form of fixed overhangs, shading screens, and manually operable window shutters. Alternative wall constructions, larger opening sizes, and the effect of the use of ceiling fans were also studied. The combination of these strategies results in 100% thermal comfort throughout the year in both historical and 2050 weather, assuming a severe (A2) climate change scenario (Figure 2).

ANNUAL TIME IN COMFORT

<table>
<thead>
<tr>
<th>BASE CASE</th>
<th>73%</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘REFURBISHED’</td>
<td>100%</td>
</tr>
</tbody>
</table>

Figure 2. Annual time in comfort for ‘Base Case’ and ‘Refurbished’ scenario – simulations used historical weather data of Lagos/Ijeka weather station, obtained from the Meteonorm database (Rhino, GH, Honeybee, EnergyPlus).

3. PROJECT-SPECIFIC DESIGN OBJECTIVES

Based on literature review, fieldwork outcomes, precedent studies and analytic work, fifteen project-specific design objectives were established and grouped into three categories: Affordability, Liveability, and Environmental Sustainability (Table 1). These objectives were used as the evaluation criteria for the prototype design proposals, discussed in Section 5.

Table 1. Project-specific Design Objectives.

<table>
<thead>
<tr>
<th>AFFORDABILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. WORKING FINANCIAL MODEL: Financially viable option for low-income individuals, families, and communities.</td>
</tr>
<tr>
<td>III. SIMPLE ASSEMBLY: Easy to build for supervised non-skilled locals via simple detailing &amp; low-tech components.</td>
</tr>
<tr>
<td>IV. NO LIFTS: No lifts to reduce capital costs, but space provision for possible future installation.</td>
</tr>
<tr>
<td>V. NO GLAZING: Openings are not glazed unless indoor visual, thermal, or acoustic comfort requires so.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LIVEABILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>VI. DENSE BUT LOW-RISE: Adequate built density for a large developing city; achieved by maximum four storeys.</td>
</tr>
<tr>
<td>VII. CELEBRATE TRADITION + CULTURE: Embrace traditional lifestyle and space use, strengthen identity.</td>
</tr>
<tr>
<td>VIII. ROOM FOR EXPANSION: Space planning to allow for extra rooms or apartments to be added later.</td>
</tr>
<tr>
<td>IX. MIXED-USE: Dedicated space for productive and commercial activities within the proposed scheme.</td>
</tr>
<tr>
<td>X. COMFORT WITHOUT A/C: Thermal comfort achieved by natural means and adaptive features, without A/C.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ENVIRONMENTAL SUSTAINABILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>XI. LOCAL MATERIALS: Locally sourced natural materials to minimize carbon footprint and benefit local industry.</td>
</tr>
<tr>
<td>XII. LOW RESOURCES DEMAND: Demand minimized via design optimisation and education of occupants.</td>
</tr>
<tr>
<td>XIII. NO LIQUID FUEL GENERATORS: Eliminate noise, heat, air pollution &amp; emissions of liquid fuel generators.</td>
</tr>
<tr>
<td>XIV. RENEWABLE ENERGY SUPPLY: Electricity generated by PV, stored via batteries &amp; distributed via microgrid.</td>
</tr>
<tr>
<td>XV. RAINWATER USE: Meet clean drinking water demand by collection, purification, and re-use of rainwater.</td>
</tr>
</tbody>
</table>

4. SYNTHESIS – PROTOTYPE DESIGN DEVELOPMENT

4.1. Design Process

A model design process was followed, exploring design solutions for a new affordable, liveable, and environmentally sustainable urban housing prototype. The process addresses important early stage design decisions and involves comparative analyses at different scales, offering practical and realistic guidelines. Given the length limitations to this paper, only part of the design process is discussed in more detail in the following subsections.

4.2. Built Form and Orientation

In the context of Lagos, ideal built form minimises unwanted solar exposure via self-shading properties. Solar exposure of five typical four-storey building forms (O, I, H, L, U) were studied at different orientations, altogether 28 instances, some of which are shown in Figure 3.

Analysis results indicate a substantial 20% exposure difference between the worst-case instance (I-shape, 90°) and the best case instance (O and H-shape, 0°) (Figure 3). The O-shape at 0° (true N-S
orientation) was brought forward, not only because it had the best self-shading properties among the studied instances (0.86x), but also the built form corresponds to the traditional Yoruba compound (Figure 4). In addition, this spatial organisation is thought to facilitate social interaction and security control via occupants overlooking communal areas.

Figure 3. Comparative solar exposure analysis of selected built forms and orientations. Numbers at each instance (i.e. 0.84x) indicate total annual direct solar radiation on façades (kWh/m²) relative to the unobstructed reference object (•).

4.3. Spatial Planning

Traditional Yoruba1 compounds served as a precedent to space planning. These mixed-use compounds were built around semi-private courtyards where everyday activities, domestic work, crafts, and commerce took place. Such buildings were inhabited by extended families and it was common to attach additional rooms as families grew [5].

As discussed in Section 2.1, contemporary low-income housing estates fail to provide space for income-generating activities of occupants, which leads to informal building activity and forceful demolitions. The four-storey prototype design attempts to address this by re-introducing the mixed-use component and dedicating the ground level to productive, commercial, and service activities. Levels 1-3 are only residential floors, while the rooftop hosts community facilities and building services, such as the accessories of the PV and rainwater system (Figure 5).

Figure 4. Traditional Yoruba compound [6]. Yoruba people are the dominant ethnic group of southwest Nigeria.

Shaded transitional spaces are created around the floor perimeter, which serve as circulation and balconies. Room for lifts is provided but they are not installed at the beginning. Each residential floor includes four one-bedroom apartments at the outset, with space provision on the same floor plate for future expansion, should families need additional rooms.

Figure 5. Functional diagram of the prototype.

4.4. Roof Design

Roofs are arguably the most important single building element in the tropics, serving as a shading device, potentially accommodating PV installation, providing the primary rainwater harvesting surface and influencing airflow patterns around the building.

A double roof construction was proposed for the prototype, where the roof not only protects living space from high temperature and solar radiation, but also creates useful space for social interaction and activities underneath. Three typical roof geometry options were evaluated: inward sloping roof (A), outward sloping roof (B) and gable roof (C) (Figure 6). These were compared along five parameters:
construction simplicity, solar protection, PV potential, rainwater harvesting, and influence on airflow.

Figure 6. Annual solar irradiation on top slab, % reduction indicated, compared to unobstructed roof (Ladybug).

Option B was selected to be brought forward as it prevailed in three of the five criteria: achieved 84% reduction in solar exposure on the top slab compared to the unobstructed base case; it is the simplest to construct, owing to its relatively uncomplicated hip details compared to the extensive valleys and ridges of A and C; the roof’s influence on airflow in typical wind conditions featured the least compromised leeward zone and most even flow pattern under the roof surface (Figure 7).

Figure 7. Airflow pattern as a function of roof geometry in typical wind conditions (3m/s SSW direction) (Autodesk CFD).

The chosen outward sloping roof configuration can host up to approximately 55.5 kWp PV capacity, assuming typical polycrystalline PV panels at 330 Wp each. The annual PV yield, calculated using the Ladybug Photovoltaic Surface component, is well above 60,000 kWh, which potentially makes the building a net electricity producer, subject to the type of business activities on ground level.

The double roof already reduced the direct annual solar radiation falling on the top floor slab by 84%. Unprotected façades would still receive 464-689 kWh/m² solar radiation annually, which underlines the need for solar protection (refer to Figure 1).

The proposed façade design consists of three key components: structural overhangs, louvred shading screens and louvred window shutters. Firstly, 1.25m deep uniform overhangs were applied to all façades, which reduced annual solar irradiation by 60%, compared to the unprotected case. To protect the façade from both low angle direct and diffuse radiation, louvred shading screens were introduced with 40% screen opacity. Simulation data indicates that solar exposure is further reduced by 44%, to

4.5. Façade Design

Apart from being a centrepiece of a building’s architectural character, façades in the tropics offer great opportunity to eliminate the need for air conditioning by providing shading and enhancing natural cross-ventilation.

Early analytic work was carried out to study optimal device configuration in relation to the solar geometry (Figure 8). For south and north, fixed horizontal (H) and vertical (V) shading device depths are provided, to completely block out direct radiation. East and west orientations are more complicated as both receive direct solar radiation at very low angles too. Horizontal overhang depths (H) are provided, blocking direct radiation between 11am and 3pm. Further protection is necessary before 11am and after 3pm, which may be provided by adjacent buildings, trees, or shading screens.

Figure 8. Study of shading device configuration for cardinal orientations.
achieve an overall 78% reduction compared to the unprotected state (Figure 9).

Figure 9. Annual irradiation on unobstructed façades (left), with 1.25m overhangs (centre), and overhangs + shading screens (right) (Ladybug).

4.6. Ventilation Concepts

Sensible air movement around the skin is essential for indoor comfort in tropical climates as it has a cooling effect and can extend the comfort band considerably. The prototype residential units are double aspect and feature full height openings with operable louvres to allow for occupant controlled natural cross ventilation.

CFD analysis was undertaken to confirm assumptions on permeability and cross ventilation with the proposed design. The analysis setup reflects typical wind characteristics in Lagos (SSW, 3m/s) and confirms that wind-driven cross ventilation is achieved in these conditions (Figure 10).

Figure 10. Block-scale CFD analysis showing wind-driven cross ventilation in Level 1 apartment (Autodesk CFD).

Four typical ventilation modes have been defined to address prevailing weather conditions:

- Wind-driven cross-ventilation: all louvre zones, or all windows, open.
- Buoyancy-driven cross-ventilation (Figure 11).
- Wind-driven cross-ventilation at night: only bottom louvre zones open, to direct air movement across the body.
- Privacy mode with operating ceiling fans: louvres are closed, ceiling fans induce air movement.

Figure 11. Buoyancy-driven cross-ventilation scenario.

4.7. Materials and Construction

A sustainable supply chain of locally sourced natural materials could benefit local economy immensely. Considering this, over 90% of the proposed building’s volume consists of such materials, including timber, bamboo, and laterite (Figure 12).

Figure 12. Material options for various building elements.

The prototype construction fuses prefabrication and self-build methods to achieve speed, safety, and quality, yet support local industry and provide jobs to both skilled and unskilled workers. The ‘base frame’ (including stairs, slabs, roof, electricity, and plumbing) is prefabricated, allowing on-site assembly as quick as a few weeks, and relatively high technical quality. Once the ‘base frame’ is erected, occupants can move in. Remaining building parts are constructed as self-built ‘infill’ (e.g. walls, fenestration, shading screens, finishes, etc.), which can be done at any point in time, even with low skill level and using manpower only.

The building is designed to change during its lifetime; as occupants save money and families grow, they claim provisional areas and attach rooms to their flats, as well as beautify or customise apartments.

4.8. Affordability

Restricted access to mortgages and high interest rates continue to be problems constraining housing supply in Nigeria. However, assuming that low-income households do get access to mortgages, maximum $50 per month mortgage payment could be considered affordable [2]. For housing to be price-competitive in this environment, market price shall not be more than
approx. $15,000 per unit. To achieve this, the following strategies are proposed at this stage:

1. Any ‘unnecessary’ items are excluded from the upfront costs, e.g. lifts, glazing, finishes, built-in furniture, air conditioning, generators, etc.
2. Occupants inhabit buildings in a few months from start of construction, compared to few years for conventional housing estates in Lagos, which saves considerable fees paid for rent elsewhere.
3. Occupants take an active role in constructing and maintaining the self-built parts of their homes, which saves on labour costs, opens doors to growth and creates sense of ownership.
4. Upfront costs of the PV infrastructure are paid externally, occupants get ‘power allowance’ and pay monthly instalments in lieu of electricity bills.

5. EVALUATION

Table 2 summarises the evaluation of the prototype design against the previously defined objectives, on both quantitative and qualitative bases. Each row is colour-coded based on whether the objective has been met (green) or needs further research (yellow).

Table 2. Evaluation of design proposals.

<table>
<thead>
<tr>
<th>AFFORDABILITY</th>
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</thead>
<tbody>
<tr>
<td>I.</td>
</tr>
<tr>
<td>II.</td>
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<tr>
<td>III.</td>
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<tr>
<td>IV.</td>
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<td>V.</td>
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<table>
<thead>
<tr>
<th>LIVEABILITY</th>
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<tbody>
<tr>
<td>VI.</td>
</tr>
<tr>
<td>VII.</td>
</tr>
<tr>
<td>VIII.</td>
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<tr>
<td>IX.</td>
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<td>X.</td>
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<table>
<thead>
<tr>
<th>ENVIRONMENTAL SUSTAINABILITY</th>
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<tbody>
<tr>
<td>XI.</td>
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<tr>
<td>XII.</td>
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<tr>
<td>XIII.</td>
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<tr>
<td>XIV.</td>
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<td>XV.</td>
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</tbody>
</table>

5. CONCLUSIONS & OUTLOOK

The research demonstrated that most of the design objectives could be met, while a few others require further studies. Results of dynamic thermal simulations indicate that thermal comfort can be achieved by passive means, while CFD analysis shows the occurrence of cross-ventilation in typical conditions. Electricity demand and clean potable water demand can be met via roof-mounted solar PV and rainwater harvesting. Outcomes indicate that the design proposals can greatly contribute to a scalable framework for affordable, liveable, and environmentally sustainable urban housing in Lagos. Additionally, the design method is replicable and adaptable to different urban, climatic, and socioeconomic contexts across the developing world. This scalability makes it possible to achieve positive global impact in climate change mitigation and poverty eradication. Additional work is necessary to deliver a detailed financial model by which the framework can be made accessible for the low-income social group. Further constructive design is required to develop detailed design solutions that enable prefabrication and partially self-built construction methods. More research on locally available materials, especially timber, bamboo, and earth, is required to understand how these can be sourced sustainably and manufactured in suitable quality for urban scale residential construction.

6. ACKNOWLEDGMENTS

The authors would like to express their gratitude to everyone who assisted the fieldwork in Lagos, including Lookman Oshodi, David Adio-Moses, Tosin Oshinowo, Taibat Lawanson, Tony Iweka, Mike Adebamowo, Akerere W. Ademola, Mokolade B. Johnson, local academics, professionals, civil servants, and families.

7. REFERENCES


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Effect of Façade Design on Visual and Thermal Comfort in a Passivhaus Laboratory Building
A Case Study of the RAD building in Nottingham, UK

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1 Faculty of Engineering, University of Nottingham, Nottingham, United Kingdom
2 Faculty of Engineering, British University in Egypt, Cairo, Egypt

ABSTRACT: Window and façade design plays a vital role in controlling the admission of natural light into a building. The provision of a direct link to daylight has been shown to help create a visually stimulating and productive indoor environment for building occupants. Additionally, design for daylight can lead to energy savings resulting from reduced dependence on supplementary artificial lighting. Whereas daylighting is an important strategy in controlling occupant visual comfort, it can impact on occupant thermal comfort and result in greater energy consumption for thermal controls. The uptake of Passivhaus has increased in recent years, with its main principle being energy efficiency. In this paper, the authors examine the effect of façade design on the visual and thermal comfort in the RAD research building which was designed to meet Passivhaus standards. As part of this post-occupancy evaluation, on-site measurements of illuminance, temperature and relative humidity were taken to analyse the existing indoor conditions, and a questionnaire administered to evaluate occupants’ perception of visual and thermal comfort. The study shows that window design, window orientation and glazing-to-wall ratios can significantly impact on occupant visual and thermal comfort; and that key suggestions for improvements are strongly linked to the initial design stages.


1. INTRODUCTION
Building fenestrations such as windows are regarded as one of the most significant elements of a building which if properly designed can have a positive impact on the well-being and health of occupants. Windows also play a great part in controlling the overall building’s energy demand [1]. A significant amount of research has found that there is preference for daylighting over artificial lighting in office spaces by users. This preference has been linked to findings that show that daylight helps us in regulating and stimulating our circadian rhythm, and this in turn positively affects our mood and alertness [2]. On the other hand, if windows are not designed appropriately, they can propagate heat gain in the summer and lead to a significant increase in the building cooling load. Around the world, buildings account for around 40% of the energy consumption, with up to 30% of this being apportioned to supplementary lighting requirements. The provision of daylighting does not only impact on visual comfort but can also negatively affect the thermal comfort of users [3]. This risk has been exacerbated by the established trend of buildings with highly glazed facades and insignificant solar control measures. The subsequent solar gain in such buildings has been found to lead to several issues such as overheating [4].

In this paper, the authors examine the effect of facade design on the visual and thermal comfort of a research building designed using Passivhaus tenets and located in the UK. Developed to reduce energy consumption and provide zero carbon and ultra-low energy buildings, the Passivhaus standard aims to provide a well-insulated airtight building which is useful in controlling heat loss in the winter [5]. However, in the summer, a high level of insulation can lead to higher risk of overheating. As the world continues to face climate change and rising temperatures, Passivhaus buildings could be at great risk of overheating due to their high insulation standards [6]. According to previous research, several overheating issues have been found in Passivhaus buildings; additionally, there is a performance gap in the construction output [7]. This being the case, the execution of post-occupancy evaluations (POEs) is essential to providing feedback on existing and future Passivhaus buildings. To contribute to this important and valid discourse, the authors undertook a POE of a Passivhaus non-domestic building in the UK to review its Indoor Environmental Quality (IEQ). Focussing on the buildings visual and thermal performance, data was collected using an occupant survey and on-site data spot and long-term measurements.

2. CASE STUDY
Located in the University of Nottingham, United Kingdom (UK), the Research Acceleration and Demonstration (RAD) building was opened in mid-2018. The building was designed to house a cross-
disciplinary energy hub that was developed as part of the Energy Research Accelerator initiative (ERA). As is shown in Figure 1, the building is orientated with its longitudinal axis north to south. It is divided into two main parts - the southern zone houses laboratory spaces and the northern zone consists of office spaces for the research and administrative staff. Both parts are connected by a central atrium (see Figure 1). The RAD building was designed to be one of the first research centres in the UK to achieve both the Passivhaus and BREEAM sustainability standards. Mainly made up of a steel frame, concrete intermediate floors, triple glazed windows (openable only in the office spaces) and curtain walling which consists of structural insulated panels (SIPs) and zinc cladding [8], the building was designed to have a very high level of airtightness and insulation.

![Figure 1: RAD building orientation and zoning.](image)

The RAD building is mainly ventilated using an MVHR (Mechanical Ventilation with Heat Recovery) system that has three air handling units (AHUs) which supply fresh air to the different zones of the building. The office spaces also have local wet radiators for any supplementary heating. This system aims to supply fresh air throughout the building with temperatures ranging between 18°C and 22°C. The ventilation supply is controlled by a Variable Air Volume (VAV) box which is controlled using passive infrared sensors (PIRs) located in all the rooms [9]. The central atrium, with a large fixed glazing facing the west, also works to provide stack ventilation that assists the active system by collecting passive solar and occupant gains that are extracted via the plant at the roof top of the atrium. As the RAD building had been occupied for just over a year at the time of this study, it presented a valid choice for the POE study. A large fixed skylight is located above the atrium to the west of the building.

3. METHODOLOGY

To evaluate the IEQ of the RAD building, the authors collected a combination of data via an occupant survey and on-site measurements. This process was undertaken during a three-week period, from the end of winter to the start of springtime (March-April) - a period when signs of overheating might potentially be identified. On-site data was collected from four rooms (see Figures 3 and 4). These rooms were selected based on their glazing orientation/exposure and by virtue of housing of key building uses. The selected rooms consisted of 2 labs, 1 open plan office and a meeting room as seen in Figures 3 & 4 showing the glazing orientation. The building’s main façade is mainly oriented towards the west - putting rooms located along it at higher risk of overheating in the warmer months.

As the building was not fully occupied during the study period, only rooms that were occupied (A08, B18, B20) or in regular use (B05) were selected for this evaluation. A questionnaire was administered to establish occupants’ perception of visual and thermal comfort. In addition, spot measurements of illuminance, temperature and relative humidity were taken in the aforementioned rooms. Further, to obtain longer-term data, both temperature and relative humidity data was collected using data loggers during the set three-week period.

![Figure 2: RAD building showing the irregular design of the windows on the North and West facing facades.](image)

![Figure 3: Ground Floor plan showing room A08.](image)

![Figure 4: First Floor plan showing rooms B05, B18, B20.](image)

3. RESULTS AND DISCUSSION

3.1 Occupant survey

The questionnaire was filled out by 18 occupants. Findings on occupant perception of thermal and visual comfort and their level of satisfaction with the thermal and visual experience within their workplace are presented in Figure 5. Overall, most of the
respondents indicated that they were satisfied with the quality of their workspace. This majority did not directly translate to their satisfaction with thermal or daylighting conditions. This could be explained by the fact that most respondents were dissatisfied with the lack of opportunities offered to occupants in adjusting indoor environmental conditions to enhance their thermal (78%) or visual comfort (55%). For example, the respondents expressed dissatisfaction with the small openable window area which did little to help control thermal comfort. On a more positive note, most respondents were satisfied with their views to the outside (66%) and the impact of artificial light improving lighting conditions (78%).

<table>
<thead>
<tr>
<th>Overall quality of your room</th>
<th>22%</th>
<th>67%</th>
<th>11%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Satisfied</td>
<td>Neutral</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Overall satisfaction of thermal condition in the workspace</th>
<th>56%</th>
<th>0%</th>
<th>11%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Satisfied</td>
<td>Neutral</td>
<td>0%</td>
<td>11%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ability to alter temperature to meet your needs (opening windows, turning heater on/off, etc.)</th>
<th>0%</th>
<th>22%</th>
<th>56%</th>
<th>22%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Satisfied</td>
<td>Neutral</td>
<td>0%</td>
<td>11%</td>
<td>11%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Overall quality of light in your workplace (artificial and natural combined)</th>
<th>11%</th>
<th>33%</th>
<th>6%</th>
<th>17%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Satisfied</td>
<td>Neutral</td>
<td>11%</td>
<td>11%</td>
<td>6%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Amount of natural light in your workspace</th>
<th>11%</th>
<th>0%</th>
<th>44%</th>
<th>11%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Satisfied</td>
<td>Neutral</td>
<td>0%</td>
<td>33%</td>
<td>11%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Amount of artificial light in your workplace</th>
<th>11%</th>
<th>56%</th>
<th>0%</th>
<th>6%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Satisfied</td>
<td>Neutral</td>
<td>11%</td>
<td>0%</td>
<td>6%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Views to outside from your workspace</th>
<th>11%</th>
<th>33%</th>
<th>22%</th>
<th>11%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Satisfied</td>
<td>Neutral</td>
<td>11%</td>
<td>22%</td>
<td>11%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ability to adjust artificial light levels to meet your needs</th>
<th>11%</th>
<th>33%</th>
<th>22%</th>
<th>11%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Satisfied</td>
<td>Neutral</td>
<td>11%</td>
<td>22%</td>
<td>11%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ability to adjust natural light levels to meet your needs</th>
<th>11%</th>
<th>33%</th>
<th>22%</th>
<th>11%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Satisfied</td>
<td>Neutral</td>
<td>11%</td>
<td>22%</td>
<td>11%</td>
</tr>
</tbody>
</table>

| Very Satisfied                                                                             | Neutral | 11% | 22% | 11% |

3.2 Visual Comfort

Firstly, an evaluation of the building was undertaken to establish if it met CIBSE and Passivhaus standards for daylighting. Two of the selected rooms, rooms B05 and B20 (Table 1), were found to have more than the recommended glazing area of 15-20% and daylight factor of 2% [10]. Lab B20 also has a south facing glazing area of 34%, which is more than the maximum of 25% advised by Passivhaus [11]. Also, the high window to floor ratios in B05 and B20 were found to put the rooms at higher risk of overheating as a result of solar gain (Table 2).

Secondly, spot measurements were collected on both overcast and clear sky days to assess the illuminance levels in the different rooms of different orientations. This data was collected at three key times to represent key solar times (9am, 12pm and 3pm) and which are relevant to occupancy patterns. According to CIBSE [10], office and laboratory spaces should have an illuminance levels ranging from 300-500 lux and 300 lux, respectively. The illuminance levels in the all the selected rooms were found to be mainly above the acceptable range, this often caused discomfort such as glare to some of the respondents that were located next to a window.

### Table 1: Window to floor ratio of the four selected rooms

<table>
<thead>
<tr>
<th>ROOM</th>
<th>WINDOW AREA</th>
<th>FLOOR AREA</th>
<th>WINDOW TO FLOOR RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>A08-OFFICE</td>
<td>18.6m²</td>
<td>95.7m²</td>
<td>19.4%</td>
</tr>
<tr>
<td>B05-MEETING</td>
<td>14.7m²</td>
<td>24.7m²</td>
<td>59.4%</td>
</tr>
<tr>
<td>B18-LAB</td>
<td>20.2m²</td>
<td>101.7m²</td>
<td>19.9%</td>
</tr>
<tr>
<td>B20-LAB</td>
<td>43.7m²</td>
<td>101.8m²</td>
<td>43%</td>
</tr>
</tbody>
</table>

### Table 2: Daylight factor of the four selected rooms

<table>
<thead>
<tr>
<th>ROOM</th>
<th>W (NET WINDOW AREA)</th>
<th>A (AREA OF ALL SURFACES)</th>
<th>DAYLIGHT FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>A08-OFFICE</td>
<td>18.6m²*0.9=</td>
<td>371.9m²</td>
<td>2.7%</td>
</tr>
<tr>
<td>B05-MEETING</td>
<td>14.7m²*0.9=</td>
<td>125m²</td>
<td>6.3%</td>
</tr>
<tr>
<td>B18-LAB</td>
<td>20.2m²*0.9=</td>
<td>476m²</td>
<td>2.3%</td>
</tr>
<tr>
<td>B20-LAB</td>
<td>43.7m²*0.9=</td>
<td>466.5m²</td>
<td>5%</td>
</tr>
</tbody>
</table>

![Figure 6: Direct sunlight entering A08 open plan room on a sunny afternoon at 3:00pm](image)

![Figure 7(a): Window distribution, room A08. (b)Illuminance distribution, room A08 at 9 am on a sunny day.](image)

![Figure 8: (a) Illuminance distribution in room A08 at 3 pm on a sunny day. (b) Illuminance distribution in room A08 at 12 pm on an overcast day.](image)
In room A08, an open plan office, the illuminance level fluctuated greatly during the 3 key times of measurement. As seen in figures 7 & 8, the lux levels are higher the acceptable range. In addition, in the afternoon of a selected sunny day, direct sunlight is seen to fall on the workspace surface and cause glare. Also, recorded spot measurement of the temperature at that time was quite high reaching up to 27°C which is significantly higher than the maximum indoor temperature prescribed by Passivhaus [11]. Considering that this data was collected during a relatively cooler period of the year (March - April), it was concerning to note what might happen at warmer and full building occupancy times.

Room B05, a meeting room, was found to have a large window to floor ratio (59.4%) and a high daylight factor too. As revealed in the lux mapping shown in Figure 9 and 10, there was a significant amount of direct sunlight entering the room on the sunny afternoon day. As with room A08, the spot temperatures recorded in B05 were significantly high reaching up to 28°C. These high temperatures were recorded when the room was empty therefore discounting the impact of internal gains brought on by occupants and equipment.

![Figure 9: Window distribution of room B05. (b) Illuminance distribution in room B05 at 9 am on a sunny day](image)

![Figure 10: (a) Illuminance distribution in room B05 at 3 pm on a sunny day. (b) Illuminance distribution in room B05 at 12 pm on an overcast day](image)

On the work benches and cause glare discomfort at different times of day. Unlike B18, B20 didn't have very high temperatures recorded in it since its oriented towards the south-east and had direct sunlight in the morning.

![Figure 11: (a) Window distribution of room B18. (b) Illuminance distribution in room B18 at 9 am on a sunny day](image)

![Figure 12: (a) Illuminance distribution in room B18 at 3 pm on a sunny day. (b) Illuminance distribution in room B18 at 12 pm on an overcast day](image)

In rooms B18 and B20, laboratory spaces, illuminance levels were also higher than the range specified by CIBSE [10] with lux levels reaching up to 12000 and 18000 lux. The high window to floor ratios, window design (height spanning from the ceiling to the floor slab) and window placement (significant western exposure) were found to enable direct sunlight to fall.

![Figure 13: (a) Distribution of direct sunlight within the B18 laboratory on a sunny afternoon at 3:00pm. (b) Distribution of direct sunlight and daylighting within the B20 laboratory on a sunny morning at 9:00am](image)

![Figure 14: (a) Window distribution of room B20. (b) Illuminance distribution in room B20 at 9 am on a sunny day](image)
3.3 Thermal Comfort

According to CIBSE [10], temperatures should range within 21-23°C (winter) and 22-24°C (summer) in offices and 19-21°C (winter) and 21-23°C (summer) in laboratories. Passivhaus standards stipulate that rooms must not exceed 25°C for more than 10% of the time annually and with or without occupancy) [11]. In 2018, a thermal comfort analysis of the RAD building was conducted to establish if the building would be able to achieve comfort temperature in the summertime. An average for the year was calculated for all the rooms including the rooms chosen for this study and all were found to meet the Passivhaus overheating criteria, with some on the border just at above 10% [9].

During this study, data loggers placed in the 4 rooms recorded temperature and relative humidity values for the 3 weeks period. Analysis of this data shows that the indoor temperatures reach above 25°C, and that this occurred when the outdoor temperature reached a maximum of approximately 18°C. The indoor temperatures reached a maximum of 28.4°C and were above 22°C, and this occurred for 14% of the entire time, and during working hours. These findings matched temperature values recorded during the spot measurement period. In some cases, the temperature recorded was more than 22°C. This occurred in rooms that had West facing windows (A08, B05 & B18) at 3pm on a sunny day - locations where solar gain is expected to have the significant impact on overheating. Given that the MVHR system is set to maintain temperatures within 18-22°C and that this study was conducted during a cooler period (March - April), this raised concern as to how high the indoor temperature could be during the summer period.

![Figure 15: (a) Illuminance distribution in room B20 at 3 pm on a sunny day. (b) Illuminance distribution in room B20 at 12 pm on an overcast day](image)

![Figure 16: Temperatures recorded over the 3-week period in the 4 rooms and externally.](image)

![Figure 17: Overall satisfaction with thermal condition](image)

![Figure 18: Thermal sensation in summer](image)

![Figure 19: Thermal sensation in winter](image)

Furthermore, most respondents indicated that they found it slightly warm or warm during the summer period. It was also noted that occupant satisfaction with thermal comfort was affected by workspace placement (away or next to a window). Those located next to windows were less satisfied with the thermal conditions of their workplace (Figure 17). It is also clear from the questionnaire that the respondents allocated next to a window felt warmer in both summer and winter than others that weren’t next...
to a window (Figure 18 & 19). This might be due to the fact that they were closer to the source of solar gain. Overall, data collected and analysed indicates that the building is at risk of overheating and especially during the warmer months.

4. CONCLUSION

The uptake of Passivhaus buildings has increased in recent years, its main principle is energy efficiency; this requires careful planning to ensure that suitable indoor conditions are not compromised. In this study, feedback from occupants of the RAD building indicates that they experience issues that impact on their thermal (overheating) and visual comfort (glare and poor distribution of daylight). This has been supported by data collected from spot and long-term on-site measurements. A review of this data and the design strategies employed indicates that more, with respect to the window and façade design, could have been done to reduce these issues.

For instance, whereas the building orientation might have been difficult to alter (owing to plot layout), the designer could have chosen to provide alter the glazing ratio to ensure that there is lower risk of solar gain via glazing and that there are fewer instances of glare and better daylight distribution. As some of the glazing did not abide to Passivhaus standards, with higher window to floor ratios than the recommended, this is thought to have contributed to high indoor temperatures (above 25°C) and poor distribution of daylight that led to occupant discomfort. Further, the RAD building was not found to have any form of external shading. If designed appropriately (e.g. free from the main structure to avoid thermal bridging), shading would have been very useful in not only mitigating solar gain, but could also to better distribute daylight indoors, consequently reducing the need for internal shades and artificial lighting.

Whereas the MVHR would have been expected to ensure indoor conditions are maintained at the required level, more considerate design might have been helpful. For instance, the option of a ‘summer bypass’ might be useful to allow the air flows to pass through the system without exchanging heat. Such a case would happen when outdoor temperature is lower than those indoors. In cases where summer temperatures are expected to rise significantly (e.g. the current climate change scenario), active cooling might need to be considered. In addition, as occupants reported not being able to find relief from opening windows, it might have been useful to consider providing larger openable widow areas to assist occupants in not only helping purge heat gain but also to help them thermoregulate.

Overall, this study has shown that whereas Passivhaus strategies can be used to enhance energy efficiency there can be instances of performance gaps. In this case, it has been concluded that more could have been done at the design stage to enhance visual and thermal comfort. This is vital aspect of designing buildings - Passivhaus or not. Given key concerns on climate change and its link to increased energy use it is important that building design solutions work to mitigate risk and provide occupants with the opportunities to maintain visual and thermal comfort.

ACKNOWLEDGEMENTS

My gratitude to the Developing Solutions Masters Scholarship for giving me the opportunity to continue my studies at a great institution such as University of Nottingham. Enabling me to undertake this research, and it wouldn’t have been possible without the great help from the occupants of the RAD building.

REFERENCES
Developing Adaptive Thermal Comfort Models and Evaluation Criteria for Rural Low-income Residents in China

WEI ZHAO¹, DAVID CHOW¹, STEVE SHARPLES¹

¹University of Liverpool, United Kingdom

ABSTRACT: This research intends to develop an adaptive thermal comfort models and evaluation criteria for rural low-income houses in China. Transverse field surveys were conducted in rural districts of Lankao County in the North China Plain in typical winter and summer seasons. Results show that the majority of researched residents lived in excessively cold indoor thermal environments which is lower than 10.0°C in winter. However, a great number of those residents felt comfortable in the environments. The existing adaptive thermal comfort criteria in ASHRAE 55, EN 16798 and GB/T 50785 are not applicable for rural low-income residents in China. In this research, new adaptive thermal comfort models and evaluation criteria were developed for rural low-income residents. The new models and criteria include a reflection of the residents’ needs and their acclimation abilities, and are applicable for extremely low outdoor temperatures conditions where existing standards are incapable.

KEYWORDS: Adaptive thermal comfort model, rural low-income residents.

1. INTRODUCTION

Urban areas benefited a lot in the booming development in the past 30 years in China. However, at the same time, rural areas were left far behind gradually in all aspects. In 2019, the per capita disposable income (PCDI) per year of rural areas was 13432 Yuan (about £1492), which was only 1/3 of the urban PCDI [1]. Indoor temperature reveals great difference in living condition between two areas. Indoor temperatures in rural low-income houses in North China can be as low as 5°C in winter which is far below that in urban dwellings [2]. Increasing reliance on air-conditioning to improve thermal comfort in rural houses results in even higher energy bills, causing financial stress for these vulnerable rural residents, increase in peak electricity demand, as well as higher carbon emissions and other environmental problems [3]. Emphasizing human adaptive abilities, such as the use of adaptive thermal comfort, can reduce this reliance, particularly when combined with improved building thermal performance.

Adaptive thermal comfort has been an important research topic since the 1970s. In 1973, Nicol et al. proposed the “adaptive principle” that if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort [4]. Adaptive thermal comfort is considered a necessary supplement for theoretical thermal comfort research as it values human adaptation ability which is lacking in theoretical models. Adaptive thermal comfort models were included in standards, such as US standard ASHRAE 55 and European standard EN 16798-1 (formerly EN 15251)[5-7]. The standards are based on field surveys in office buildings in urban contexts. Applicability of the adaptive thermal comfort standards among rural low-income residents are not well-defined.

A few previous researches have revealed the differences between urban and rural low-income residents. Zhang et al. indicated that the rural elderly had stronger adaptability to lower temperatures in severe cold climate region of China [8]. Xiong et al. acquired similar conclusion through field surveys in the Hot Summer Cold Winter climate region in China that rural residents tend to be more tolerant of cold conditions in winter and less tolerant of hot conditions in summer, compared to the urban residents [9]. A research in Chile indicated inapplicability of adaptive thermal comfort standards in low-come houses in central-south Chile and developed a novel adaptive model that best fits with thermal conditions and residents in the researched area [10].

This research investigated the indoor environments in rural low-income houses on the North China Plain, as well as the thermal perceptions of rural low-income residents. Then, this research evaluated the applicability of current adaptive thermal comfort standards in rural low-income conditions and developed adaptive models and evaluation criteria for winter and summer seasons respectively.

2. METHODOLOGY

2.1. Research districts

Lankao County is a typical agricultural county located in the centre of the North China Plain, as shown in Figure 1. About 60% of its population is living in rural areas. The Per Capita Disposable Income (PCDI) of the rural population in 2018 is only £1253 per year which is similar to the average value (£1543) of rural China [1, 11]. Lankao is in the “Cold Zone” climate region of China. Field surveys were carried out in rural areas of Lankao County.
2.2. Field survey

Transverse field surveys were adopted. Winter field surveys started from 21st December of 2018 and terminated on 23rd February of 2019. Summer field surveys were conducted between 22nd July and 4th September of 2019. Overall, 610 valid questionnaires were collected from field surveys.

Each interview included a questionnaire survey and a simultaneous environment measurement in the researched room. The questionnaire survey acquired basic information (for example age, sex and clothing information) and thermal perceptions (thermal sensation vote, thermal acceptance vote, thermal preference vote) of the participants. The environment measurement measured environmental parameters, such as indoor air temperature ($T_{ia}$), indoor globe temperature ($T_{g}$), indoor relative humidity (RH) and indoor air velocity ($V_{a}$). Outdoor environmental information was acquired from the closest weather station which is available on the NOAA website [12].

3. RESULTS

3.1. Outdoor temperature

Figure 2 shows daily outdoor air temperature between 1st October 2018 and 30th September 2019. Durations of winter and summer field surveys are highlighted separately. During the winter field survey, daily outdoor temperature varied from -7.3°C to 8.1°C with mean temperature of 0.7°C. During the summer field survey, daily outdoor temperature varied from 22.6°C to 32.1°C with mean temperature of 26.8°C.

3.2. Indoor thermal environment

Recorded indoor operative temperature during interviews were sorted into temperature bins of an interval of 1.0°C. Results were plotted in Figure 3 and Figure 4.

In winter, the majority of rural low-income houses hold excessively cold indoor thermal environments. More than 90% of recorded indoor operative temperatures were below 10.0°C. And about 67.5% of recorded indoor operative temperatures assembled in an interval between 2.0°C and 7.0°C. Mean value of recorded indoor operative temperature was only 5.9°C. Indoor operative temperatures also varied greatly among houses as recorded indoor operative temperature distributed in a range between 0.7°C to 16.8°C.

In summer, indoor thermal environments are relatively comfortable. The majority (80.9%) of recorded indoor operative temperatures were below 30.0°C. Mean value of recorded indoor operative temperature was 28.7°C. Similar to the winter result, recorded indoor operative temperature in summer also varied greatly among houses. Recorded indoor operative temperature spread in a range between 24.4°C to 37.8°C.

The wide distributions of indoor operative temperature are mainly results of outdoor temperature changings. As shown in Table 1, high values in Pearson’s correlation and R-square indicate strong linear correlations between indoor operative temperature and outdoor temperature in both winter and summer.
3.3. Thermal perceptions

In spite of the indoor environments, a great number of the researched residents felt comfortable. Distribution of thermal sensation votes and thermal acceptance votes in winter and summer field surveys are plotted in Figure 5 and Figure 6. In winter, 73.8% of the research residents voted between “−1 and 1” on thermal sensation vote (TSV). The proportion in summer was 67.3%. About 61.7% of the researched residents voted “acceptable” on thermal acceptance vote (TAV) during winter field surveys. The proportion in summer field survey was 76.1%.

3.4. Feasibility of existing adaptive thermal comfort standards

At present, two adaptive thermal comfort standards are wildly used all around the world. They are ASHRAE 55 2017 in United States and EN 16798-1 2019 (formerly EN 15251) in Europe [6, 13]. Besides, a Chinese standard (GB/T 50785 2012) is widely used in China [14]. The applicability of three adaptive thermal comfort standards in rural low-income houses are analysed in this section. Three adaptive thermal comfort standards and field survey data are plotted in Figure 7, Figure 8, Figure 9. Titles of horizontal axes in three standards are different. However, the definitions and calculation equations are the same. Running mean outdoor temperature \( T_{rm} \) is used to represent the horizontal axis.

As shown in Figure 7, running mean outdoor temperature of winter data distributed between -4.0°C and 5.0°C. They were far beyond the range of application of ASHRAE 55 \((10°C < T_{rm} < 33.5°C)\).

In Figure 8, winter data were not plotted as adaptive thermal comfort standard in EN 16798 only applies during summer and shoulder seasons.

In Figure 9, the Chinese standard has the widest temperature scope of application. It can be applied in a temperature interval which \( T_{rm} \) is between 3.7°C and 31.3°C. The lower limit of temperature scope of application of the Chinese standard is much than other two standards. About 21.7% of the winter field survey data fell in the scope of application of the Chinese standard. The majority of them are beyond the acceptability range of the Chinese standard. Obviously, this is not in line with the thermal votes above.

A great number of researched residents seemed to be satisfied with their indoor thermal environment although both outdoor
temperature and indoor temperature were beyond the scope of application of these three standards. No current standards are applicable for researched residents in winter conditions. New adaptive thermal comfort criteria is needed.

In summer data, running mean outdoor temperature ($T_{rm}$) varied between 24.0°C and 31.0°C. They were in the application range of ASHRAE 55 and GB/T 50785 in term of running mean outdoor temperature. For the case of EN 16798, 12.4% of summer data fell out of the application range ($10.0°C < T_{rm} < 30.0°C$). All three standards seem accurate in evaluating comfort level of indoor environment when $T_{rm}$ is lower than 30.0°C. These standards are based on field surveys in office building and residential buildings in urban contexts[6, 13, 14]. As found in many previous researches, these standards didn’t consider the needs, dressing habits and acclimation abilities of rural low-income residents who live in excessively cold or hot indoor conditions and under great financial stresses. A novel bespoke summer adaptive model is also necessary for the rural low-income residents in China.

![Figure 7: Plot of adaptive thermal comfort criteria in ASHRAE 55 2017 and field survey data](image1)

![Figure 8: Plot of adaptive thermal comfort criteria in EN16798-1 2019 and field survey data](image2)

### 3.5. Development of adaptive model and evaluation criteria

An adaptive thermal comfort model relates indoor comfort temperature to the outdoor air temperature. Griffiths’ method provide the theoretical basis for this analysis. In this research, linear regressions were conducted on comfort temperature ($T_c$) calculated by Griffiths’ method and 7 days running mean outdoor temperature ($T_{rm}$). Equations of adaptive models are shown in Table 2. The winter model only applies when $T_{rm}$ is higher than -4.0°C and lower than 5.0°C. The summer model only applies when $T_{rm}$ is higher than 24.0°C and lower than 31.0°C.

The next step is to determine the 80% and 90% acceptability ranges. Width of the 80% and 90% acceptability ranges are usually derived from the bell shape curve of regression of thermal acceptance votes on indoor operative temperature. However, in this research, winter and summer conditions are researched separately, and no mid-season data are available. Therefore, two half bell shape curves were acquired from field survey data, as shown in Figure 10. There is no possibility to calculate the width of the acceptability ranges with this method. But we are able to get the lower extremum temperatures for winter acceptability ranges, and upper extremum temperatures for summer acceptability ranges. In winter, the lowest temperature of 80% and 90% acceptability ranges are 7.5°C and 8.7°C respectively. In summer, the highest temperature of 80% and 90% acceptability ranges are 29.5°C and 28.7°C respectively.

Another method for acceptability range width calculation is through the weighted linear regression analysis of mean thermal sensation vote (mTSV) on indoor operative temperature ($T_{op}$), as shown in Figure 11 and Figure 12. Slope of the regression equation determines width of the 80% and 90% acceptability ranges.

![Figure 9: Plot of adaptive thermal comfort criteria in GB/T50785 2012 and field survey data](image3)
Generally, -0.85 to 0.85 on ASHRAE thermal sensation scale corresponds to the 80% acceptability range, and -0.5 to 0.5 corresponds to the 90% acceptability range [13]. Deriving from the regression equations, width of the 80% and 90% acceptability ranges are 16.4°C and 10.4°C respectively in winter. Width of 80% and 90% acceptability ranges are 6.4°C and 4.0°C respectively in summer.

Upper and lower boundaries for the 80% and 90% acceptability ranges in winter and summer are shown in Table 3.

By combining the above results, adaptive thermal comfort models, 80% and 90% acceptability ranges for rural low-income residents can be acquired, as shown in Figure 13 and Figure 14. The 80% acceptability ranges in two graphs are marked yellow, and the 90% acceptability ranges in are marked blue. The two zones can be used to evaluate comfort level of indoor thermal environment. With a given running mean outdoor temperature, if indoor operative temperature fall in yellow zones, indoor thermal environment is acceptable for 90% occupants.
correlated with daily outdoor temperatures.

In such indoor conditions, a great number of researched occupants felt the indoor environment acceptable and physiologically comfortable. 61.7% and 76.1% occupants voted “acceptable” on thermal acceptance scale (TSV) during winter and summer field surveys respectively. 73.8% and 67.3% of researched residents voted “−1, 0 or 1” on thermal sensation scale (TSV).

None of existing adaptive thermal comfort standards are applicable for target residents in winter, and are not accurate in summer. Bespoke adaptive thermal comfort models and evaluation criteria for rural low-income residents are needed in winter and summer seasons. Local and specific adaptive thermal comfort models and criteria for rural low-income residents were proposed in this research. New models and standards reflect rural low-income residents’ needs and acclimation abilities when artificial conditioning systems are rarely used due to financial stresses. New models and standards are applicable in extremely low outdoor temperature where existing standards are incapable. They are supplements for those standards.

There is possibility of the new adaptive model and evaluation criteria being applied in other residents who have similar dressing habits, financial level and live in similar climate and indoor thermal environments. Continuous updates of field survey data will improve the accuracy of new adaptive models and standards.

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Table 2: Adaptive thermal comfort models for winter conditions and summer conditions respectively.

<table>
<thead>
<tr>
<th>Season</th>
<th>Adaptive model</th>
<th>$R^2$</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>$T_c = 0.385 T_{rm} + 7.371$</td>
<td>0.325</td>
<td>0.017</td>
</tr>
<tr>
<td>Summer</td>
<td>$T_c = 0.447 T_{rm} + 14.845$</td>
<td>0.515</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Table 3: Upper and lower boundaries for adaptive standards in winter and summer

<table>
<thead>
<tr>
<th>Season</th>
<th>Boundary</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>80% Upper Boundary</td>
<td>$T_c = 0.385 T_{rm} + 15.571$</td>
</tr>
<tr>
<td></td>
<td>80% Lower Boundary</td>
<td>$T_c = 0.385 T_{rm} - 0.829$</td>
</tr>
<tr>
<td></td>
<td>90% Upper Boundary</td>
<td>$T_c = 0.385 T_{rm} + 12.571$</td>
</tr>
<tr>
<td></td>
<td>90% Lower Boundary</td>
<td>$T_c = 0.385 T_{rm} + 2.171$</td>
</tr>
<tr>
<td>Summer</td>
<td>80% Upper Boundary</td>
<td>$T_c = 0.447 T_{rm} + 18.045$</td>
</tr>
<tr>
<td></td>
<td>80% Lower Boundary</td>
<td>$T_c = 0.447 T_{rm} + 11.645$</td>
</tr>
<tr>
<td></td>
<td>90% Upper Boundary</td>
<td>$T_c = 0.447 T_{rm} + 16.845$</td>
</tr>
<tr>
<td></td>
<td>90% Lower Boundary</td>
<td>$T_c = 0.447 T_{rm} + 12.845$</td>
</tr>
</tbody>
</table>

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Indoor Thermal Comfort Consistency Index
Proposal of a new approach for evaluating thermal quality in residential buildings’ design

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ABSTRACT: Delivering thermal comfort to the inhabitants is one of the main functions of buildings but the application of the standard models to residential buildings presents some challenges: the statistical approach does not work and the users have a great number of adaptive opportunities. The most difficult parameters to simulate during the design phase are the ones linked to the inhabitants’ habits and preferences, which often lead to a bias in the energy performance simulation. In this paper the Indoor Thermal Comfort Consistency Index (ITCCI) for residential buildings is introduced: it measures the consistency in delivering constant indoor thermal conditions regardless the variables depending on the inhabitants. The index is calculated through a series of simulations in which the parameters of natural ventilation, internal gains and blind utilization vary between a lower and an upper limit. A case study is presented to evaluate the use of the index on four buildings of the DHOMO project. This index may be a useful tool for designers and could contribute to bring the industry towards the construction of more resilient buildings that are able to provide comfort conditions to a wider range of inhabitants.

KEYWORDS: Thermal comfort, resilient design, residential buildings.

1. INTRODUCTION

The evaluation of thermal comfort has been a topic of research interest for many years. Many approaches have been proposed to describe the thermal quality of an environment [1] on the basis of several physical parameters: the most used are the PMV index [2] and the adaptive model [3]. These models have been applied to different types of buildings: health centres [4], schools [5], offices [6], commercial buildings [7] and also to dwellings [8]. This last application, however, presents some challenges and there is no agreement on how to evaluate thermal comfort in residential buildings yet [9, 10].

The main challenge is the fact that these models are intended for buildings where many people are present at the same time and a trade-off between the preferences of all of them is necessary: the aim is to statistically minimize the discomfort of the users. In residential buildings the situation is very different: the number of persons living in a single dwelling is limited (and actually decreasing year by year). Even for very large families, it is reasonable to think that the indoor temperature is chosen not merely by averaging the preferences of all the components, but by a decision process that involves many factors (for instance, if there is a weak component, like a baby or an elderly person, more attention is given to his/her needs). Moreover it is important to highlight that residential buildings have a large number of adaptive opportunities and inhabitants in a state of discomfort tend to adapt, i.e. modify the conditions, in order to return to a state of better satisfaction [11]. Finally, thermal environments are much more complex than how we are able to describe them with these models [12] and different studies have been developed on the opportunity to create more rich and variable spaces also under a thermal point of view [13].

So, which is the task of comfort models in residential buildings? Surely it’s not to advise the inhabitants on the set point to fix, since they know it very well and, in modern buildings, they should have the possibility to reach it. UNI EN 16798-1 [14] fosters the use of comfort models for evaluating IEQ and having a benchmark for the calculation of energy consumption during the design phase. This is surely an interesting and powerful approach for comparing different solutions, but it is very hard to foresee the actual consumption of a building. This is usually experienced due to the difficulty in forecasting the preferences and effective behaviour of the inhabitants [15]. In simulations, internal gains, ventilation patterns and other variables are acquired as average values, but this approach doesn’t work for residential buildings: different persons have very different needs and preferences that can change throughout the year. Moreover, in the project phase, the designer often doesn’t know who the inhabitant of the building will be.

In this paper we introduce the Indoor Thermal Comfort Consistency Index (ITCCI) for residential free-running buildings. This index does not measure the
energy consumption nor the indoor thermal quality itself, but the consistency in delivering indoor thermal comfort regardless the habits and the preferences of the inhabitants. This is obtained through a series of simulation where some key parameters are changed in order to evaluate the variation of consumption or discomfort inside the building. This index is designed for temperate, continental or alpine climate with cold winters and not too hot summers.

The current design practice often considers a standard behaviour of the inhabitants in order to reach the target energy efficiency or specific thermal comfort conditions. We suggest a different approach: designing buildings that can provide comfort conditions to a wider range of inhabitants’ types. After the proposal of the index, it is applied to the DHOMO project [16], that involves the construction and monitoring for two years of four houses with different characteristic in an alpine region of Italy.

2. METHODS

The Indoor Thermal Comfort Consistency Index (ITCCI) of a building is calculated through a series of dynamic environmental simulations where the parameters linked to the inhabitants’ use and preferences are parametrically changed. The results are analysed with particular focus on the amplitude of the variation of the output parameters. The simulations may be run with any program as long as it has all the features for modelling buildings and analysing both the indoor environment quality and the energy requirements. The outputs of the simulations are the consumption of the heating system and the operative temperatures of the rooms.

Two main conditions are considered: summer and winter. During summertime the main challenge for buildings is to prevent overheating minimizing or completely avoiding air conditioning. For the evaluation of the summer ITCCI, considering European climatic conditions, the simulation has to be run for the period between June and August and the output parameter is the number of discomfort hours, calculated according to the adaptive comfort model (class 3 and 4 of UNI EN 16798-1 [14]). During the summer period the building is considered as free-running, assuming the absence of an air conditioning system. A different approach is followed for the evaluation of the winter ITCCI, where it is considered that the comfort temperature (set conventionally to 21°C) is reached for the whole period. In this case the simulation is run for the whole heating season (typically the period between October and April) and the output parameter is the heating requirement.

All the parameters linked to the building envelope (infiltration, thermal bridges, materials’ characteristics) are to be set as close to real as possible. The choice of the weather file is also important in order to simulate external conditions representative of the building area. The simulation must consider the most used rooms (as kitchen, living room and bedrooms) and the final output is the average of the outputs of the single environments.

The parameters that are changed in the simulations are the ones linked to the inhabitants’ habits and preferences:

- Natural ventilation (1/h);
- Internal gains (W/m²K);
- Blinds utilization (%).

For each of them, three levels have been set:

- MEDIUM: represents the typical average value, that is generally used for energy performance evaluations;
- LOW: the low limit (half the medium value);
- HIGH: the high limit (double the medium value).

2.1 Natural ventilation (NV)

This parameter simulates the habit of the users to open the windows in order to change the air of the rooms. It coincides with the air change rate and it is measured in h⁻¹. The medium value (NVMED) is taken from UNI 10349-1:2016 [17] as reported in equation (1): the amount of ventilation depends on the outside temperature (Tout) and during very rigid periods, only a minimal ventilation is guaranteed.

\[ NV_{MED} = 0.2 + 0.04 \ T_{out} \quad \text{if } T_{out} \geq 0 \ ^{\circ}C \]
\[ NV_{MED} = 0.2 \quad \text{if } T_{out} < 0 \ ^{\circ}C \] (1)

The low (NVLOW) and high (NVHIGH) values are given by the following equations (2) and (3):

\[ NV_{LOW} = 0.5 \cdot NV_{MED} \] (2)
\[ NV_{HIGH} = 2 \cdot NV_{MED} \] (3)

2.2 Internal gains (IG)

The medium value of the thermal internal gains (IGMED) is set as indicated by the standard UNI TS 11300-1:2014 [18]. The amount of heat produced by inhabitants and equipment varies according to the day of the week, the time and the use of the room. The values are reported in Table 1.

<table>
<thead>
<tr>
<th>Day</th>
<th>Time</th>
<th>Living area (W/m²)</th>
<th>Bedroooms (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weekdays</td>
<td>7:00 – 17:00</td>
<td>8.0</td>
<td>1.0</td>
</tr>
<tr>
<td>(Mon-Fri)</td>
<td>17:00 – 23:00</td>
<td>20.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>23:00 – 7:00</td>
<td>2.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Weekends</td>
<td>7:00 – 17:00</td>
<td>8.0</td>
<td>2.0</td>
</tr>
<tr>
<td>(Sat-Sun)</td>
<td>17:00 – 23:00</td>
<td>20.0</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>23:00 – 7:00</td>
<td>2.0</td>
<td>6.0</td>
</tr>
</tbody>
</table>
The low (IGLOW) and high (IGHIGH) values are given by the following equations (4) and (5):

\[
\begin{align*}
IG_{\text{LOW}} &= 0.5 \cdot IG_{\text{MED}} \quad (4) \\
IG_{\text{HIGH}} &= 2 \cdot IG_{\text{MED}} \quad (5)
\end{align*}
\]

2.3 Blind utilization (BU)

There is no agreement in literature on how to simulate a standard use of the blinds (BUmed). Many different methods are available and implemented in simulation programs based on solar radiation, outside temperature, indoor temperature and more. One of the most robust and utilized method is based on global horizontal irradiance (GHI) and we have implemented equation (6), graphically explained in Figure 1.

\[
\begin{align*}
BU_{\text{MED}} &= \frac{\text{GHI}}{300} \cdot 0.8 \quad \text{if GHI < 300 W/m}^2 \\
BU_{\text{MED}} &= 0.8 \quad \text{if GHI \geq 300 W/m}^2
\end{align*}
\]

**Figure 1: Blind utilization in relation to global horizontal irradiance.**

The value of blind utilization is a percentage that goes from 0 (totally open) to 100 (totally closed). It is linear to the intensity of horizontal solar irradiance until the value of 300 W/m², which is considered the threshold where all the blinds are almost entirely closed. The value of 100 has been avoided because this parameter represents an average of all the windows of the house.

In this case, the calculation of the low (BULOW) and high (BUHIGH) levels is slightly different and follows the following equations (7) and (8):

\[
\begin{align*}
BU_{\text{LOW}} &= \left( \frac{\text{GHI}}{300 \cdot 2} \right) \cdot 0.8 \\
BU_{\text{HIGH}} &= \left( \frac{\text{GHI}}{300 \cdot 0.5} \right) \cdot 0.8
\end{align*}
\]

2.4 Calculation of the ITCCI

Once the parameters have been set, the simulations may be launched, considering all the possible combinations of the variables both for the summer and the winter period. For each season, the amplitude of the difference between the highest and lowest output (Δ) is calculated. In summer the delta is computed on the number of discomfort hours, while in winter on the energy requirements. The ITCCI is then calculated as reported in the following equations (9), (10) and (11):

\[
\begin{align*}
\text{ITCC}_{\text{SUMMER}} &= 1 - \left( \frac{\Delta_{\text{SUMMER}}}{\Delta_{\text{SUMMER}} + 100} \right) \quad (9) \\
\text{ITCC}_{\text{WINTER}} &= 1 - \left( \frac{\Delta_{\text{WINTER}}}{\Delta_{\text{WINTER}} + 100} \right) \quad (10) \\
\text{ITCCI} &= \frac{\text{ITCC}_{\text{SUMMER}} + \text{ITCC}_{\text{WINTER}}}{2} \quad (11)
\end{align*}
\]

The maximum value of the ITCCI is 1, which corresponds to the case where no variations occurs in the output when the three parameters change. This utopian result means that good indoor thermal conditions are maintained no matter which is the behavior of the inhabitants. A building with a high score of ITCCI can be considered more resilient because it can adapt to the different types of inhabitants and it can dampen the effect of the heat produced by their behavior.

3. CASE STUDY

The proposed new method for the evaluation of the building’s consistency in delivering thermal comfort has been tested on four single family houses that are under construction in the municipality of Predaia (Tn) - Italy, in the context of the DHOMO project [16]. Predaia is an alpine village with an alpine-temperate climate.

**Figure 2: Location of the DHOMO project.**

These houses have the same shape, orientation and position but they are built with different materials (both for the structure and the finishing) and building techniques.

**Figure 3: Axonometric diagram of the buildings of the DHOMO project.**
The material used for the structure and the finishing of the four houses are the following:
- A: timber structure + drywall;
- B: concrete and masonry structure + drywall;
- C: timber structure + plaster;
- D: concrete and masonry structure + plaster.

The building envelopes are designed to have a similar thermal transmittance (U) but different values of periodic thermal transmittance (Y_{mn}) and inner areal heat capacity (k).

**Table 2: Characteristics of the buildings’ envelopes.**

<table>
<thead>
<tr>
<th>Building</th>
<th>U (W/m²)</th>
<th>Y_{mn} (W/m²)</th>
<th>k (kJ/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.09</td>
<td>0.003</td>
<td>28.9</td>
</tr>
<tr>
<td>B</td>
<td>0.10</td>
<td>0.015</td>
<td>41.6</td>
</tr>
<tr>
<td>C</td>
<td>0.09</td>
<td>0.006</td>
<td>55.5</td>
</tr>
<tr>
<td>D</td>
<td>0.10</td>
<td>0.018</td>
<td>75.3</td>
</tr>
</tbody>
</table>

The houses are equipped with heating system, mechanical ventilation and also with an air conditioning system. Anyway, given the mild climate condition, it is likely that the building could be used as free running for the most of summer and spring time. The plans of the dwellings are shown in Figure 4: they are arranged on two floors and the main rooms, which are taken in consideration for the evaluation of the index, are the living room, the kitchen and three bedrooms.

*Figure 4: plans of the dwelling*

The weather file has been assembled using the data of a weather station situated in a nearby village relating to the year 2014.

*Figure 5: Dry bulb temperature variation throughout the year in Predaia.*

The buildings were modelled using the software TRNSYS 18 [19] and a routine in R [20] was created for running multiple simulations with all the possible combinations of the parameters. The total number of simulations is 108 (27 for each building). This case study is very interesting because it is possible to analyse the effect of the different materials when all the other parameters remain unchanged.

4. RESULTS AND DISCUSSION

In the following charts, the results of the simulations are reported in detail and discussed.

4.1 Summer simulation

In Figure 6 the results of the summer simulations are plotted, reporting the number of discomfort hours due to overheating for each building. According to the adaptive model described in UNI EN 16798-1 [14], the discomfort is reached when the operative temperature is three degrees above the comfort temperature. The building was considered as free-running disregarding the air conditioning system.

*Figure 6: Results of the summer simulation.*

Each point represents a simulation with a different combination of natural ventilation, internal gains and blind utilization. At first, it is interesting to highlight that, for every building, it is possible to define a specific combination of parameters that leads to the target of 0 hours of discomfort. What we are more interested in, however, is the amplitude of the difference between the best and the worst combination. At first glimpse it is possible to state that building D is less sensitive than others to the type of inhabitant and it can deliver better indoor comfort conditions to a wider range of users.

To better understand the meaning of the results, it is helpful to focus on two specific types of users. The inhabitants α and β have the characteristics reported in Table 3 and their output is highlighted in Figure 7. It is important to highlight that our intention is not to judge the behaviour of the inhabitants; on the contrary, we want to analyse the differences in the performance of the buildings subject to different uses.
Table 3: Characteristics of two specific types of users.

<table>
<thead>
<tr>
<th>Building</th>
<th>Natural ventilation</th>
<th>Internal gains</th>
<th>Blind utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>LOW</td>
<td>LOW</td>
<td>MEDIUM</td>
</tr>
<tr>
<td>β</td>
<td>HIGH</td>
<td>MEDIUM</td>
<td>LOW</td>
</tr>
</tbody>
</table>

Figure 7: Results of the summer simulation related to the user-types α (Δ) and β (X).

For a α-type user the choice of the building is almost irrelevant: surprisingly buildings A and C perform even better than B or D; however the number of discomfort hours is very low in any case. On the other hand, for a β-type person the indoor thermal comfort could vary drastically according to the building characteristics: the same person could suffer 15 hours of discomfort in building D and more than 45 in building A.

4.2 Winter simulation

The following graph in Figure 8 reports the output of the winter simulation: the heating requirement of the four buildings under all the combinations.

Figure 8: Results of the winter simulation.

In this case the difference between the buildings is very low. This is consistent with the fact that the thermal transmittance (the main variable for describing the winter behaviour of a building) is similar between the four houses. The factor that has the biggest influence on the heating requirement is the amount of natural ventilation, which is responsible of the big gaps between the groups of points. As it is shown in Figure 9, the difference between the buildings is marginal for both types of user α and β.

Figure 9: Results of the winter simulation related to the user-types α (Δ) and β (X).

4.3 ITCCI calculation

Finally, it is possible to calculate the ITCCI as it has been previously defined.

Table 4: Calculation of the ITCCI for all the buildings.

<table>
<thead>
<tr>
<th>Building</th>
<th>Summer delta (h)</th>
<th>Summer ITCCI</th>
<th>Winter delta (kWh/m²)</th>
<th>Winter ITCCI</th>
<th>ITCCI</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>48.4</td>
<td>0.67</td>
<td>52.4</td>
<td>0.66</td>
<td>0.66</td>
</tr>
<tr>
<td>B</td>
<td>22.8</td>
<td>0.81</td>
<td>52.1</td>
<td>0.66</td>
<td>0.74</td>
</tr>
<tr>
<td>C</td>
<td>32.4</td>
<td>0.76</td>
<td>52.1</td>
<td>0.66</td>
<td>0.71</td>
</tr>
<tr>
<td>D</td>
<td>17.2</td>
<td>0.85</td>
<td>52.1</td>
<td>0.66</td>
<td>0.76</td>
</tr>
</tbody>
</table>

The fact that all four buildings perform equally during the winter season flatten the results between 0.66 al 0.76. Anyway, the best performing house in terms of indoor thermal comfort consistency is building D with an ITCCI of 0.76 and an ITCCI\text{summer} of 0.85. Building D has the envelope with the higher inner area heat capacity. This parameter is strongly linked to thermal comfort in relation to internal gains,
because it dampens the heat spikes and helps to maintain stable thermal conditions. For this reason, it is not surprising that it is also linked to the ITCCCI. The findings of this study suggest that buildings with a high inner heat capacity are more consistent in delivering good indoor thermal comfort conditions.

5. CONCLUSIONS

In this paper a new index is proposed for the evaluation of consistency of residential buildings in delivering thermal comfort conditions. A case study is utilized for showing the potential of the index in helping the designer during the very first phase of the project. Four single family houses of the DHOMO project are analysed and the ITCCCI index is calculated for each of them. The results show that the house built with a concrete/masonry structure and with a plaster finishing performs better in terms of ITCCCI and could deliver better thermal comfort condition to a wider range of inhabitants. These findings will be questioned during the monitoring phase of the DHOMO project: several tests will be conducted on the real dwellings in order to verify the indoor thermal comfort consistency of the four buildings simulating different behaviours of the users.

The challenge of residential buildings is that they are designed and built with the aim of satisfying every single person and not just one category of people. Moreover, the inhabitants have the possibility to behave as they wish and they have the maximum control over the environment. Their needs and preferences are rapidly changing and so are the performances and the characteristics of the envelope and the installation. This study tries to change the current point of view: the aim is not to suggest to the user how to behave in order to reach the optimum indoor comfort condition. In fact, this is an approach leading to spaces where the inhabitants are limited, must follow certain rules and it is not suitable for residential buildings. On the contrary, we believe that the house “must adapt” to the different pattern of use and preferences maintaining good performances of thermal comfort. This ability is exactly what is measured through the ITCCCI, which may become a powerful tool for designers also considering future environmental changes and severe conditions.

ACKNOWLEDGEMENTS

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Traditional courtyard house of Lahore, Pakistan

The investigation of the role of social, cultural and environmental factors in shaping the spatial formation and enhancing thermal comfort in the courtyards of Haveli Barood Khana, for a semi-arid climate

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ABSTRACT: Lahore, a metropolis city of Pakistan, is facing increasing temperatures. This is due to the densification of urban land, Urban Heat Island effect and the global climate change. The design of the urban environment plays a vital role in mitigating the adverse thermal conditions in densely populated areas. The current design of the city shows inadequate respect to the regional vernacular courtyards architecture. In old Lahore, the inhabitants have continued to use outdoor courtyards for their socio communal gatherings, as an aged long tradition of the city.

This research investigates a traditional multiple courtyard house, “Barood Khana Haveli” in old Lahore, by exploring the characteristics of the courtyards and the significance of their original architectural morphology in contributing to the outdoor thermal comfort in a semi-arid climate. The research methodology adopted for this study includes a comprehensive literature review, fieldwork and digital performative analysis. The result reveals micro climate differences created in the four courtyards. Based on these findings, appropriate orientation, and geometries of the courtyards are proposed for the development of desirable microclimates for Lahore. However, the development of outdoor comfort is site specific but the general findings can guide the designers into collaborating it with local restrictions.

KEYWORDS: Courtyards, Outdoor thermal comfort, semi-arid climate, microclimate

1. INTRODUCTION

A courtyard is an enclosed space which is delaminated by buildings but open to sky. It is applied as a micro climate modifier for its surrounding environment (1). Courtyards attempt to tame the climate, ‘to bring forces of nature under control’. The great Egyptian architect Hasan Fathy writes to the benefits of a courtyard houses as “In the context of sustainability where ecological issues are of prime importance, courtyards can still be perceived as an important design element that functions both as a social space as well as something that reduces the carbon footprint of the building.”

1.1 Courtyards, climate and comfort (Courtyards as micro climate modifiers):

The courtyards develop their significant micro climates with respect to the diurnal and seasonal variations. The courtyard can act as medium for producing a new micro climate as compare to the city urban climate. When the courtyards are provided with necessary elements like vegetation, shade and water, the courtyard behaves as a “cooling well” and provides lower temperatures. (2).

As the courtyard is open to sky, the level of sun penetrating into the courtyard envelop defines or affects the thermal comfort in that space. A common strategy is to restrict the greater sun infiltration. However, to what level this solar access is to be controlled, varies from one location to another. Shading is an important element during the hot sunny days also regarded as the thumb rule for comfort in summers while in winters, the solar penetration is welcomed more. (1). The amount of heat falling on the courtyard surfaces, is either absorbed or reflected. This solar insolation highly depends upon the material properties. The courtyard geometry plays a vital role in its thermal behaviour as mentioned above. Daniel Dunham writes in his article, ‘The courtyard house as a temperature regulator’, ‘Only a small courtyard can be protected by the sun’. But as a small courtyard cannot always fulfil the socio cultural requirements, people generally build one big courtyard, on which Durham further suggests to have two courtyards instead of one large courtyard, as in the latter the shaded area will be diminutive.

Ratti et al. states that large courtyards are suitable for cold climates by offering wind protection and allow sun exposure at the same time considering certain geometrical features. (3)

The aspect ratios and the solar shadow index can be determined by the following formulas, (4)

\[
\text{Aspect ratios: Area of the courtyard floor} \div \left(\text{Average height, surrounding walls}\right)^2
\]
In older cities, due to lack of proper grids in the city planning, many versions of courtyards layout are observed. For the courtyards elongated along the east-west orientation, direct sun cannot enter the longer axis. The shorter sides are the most vulnerable during the summers, while in the winters when the sun is welcomed by the inhabitants, this sun is almost absent (5).

2.2 Introduction to case study:
The traditional courtyard houses (locally known as Haveli) in Pakistan have developed throughout many decades till they reached to a state of general acceptance from its users. The prevailing layouts observed in the traditional dwellings of Lahore suggest open to sky courtyards, enveloped by verandas and rooms (6). Despite having an average temperature of 30˚C, this open morphology of courtyards leads to the question How these wide, open to sky courtyards corresponds to the warm climate in terms of outdoor comfort and serve as a protection against it? And whether the micro climate developed in these areas are enough to counter the problem. 

The city of Lahore is a metropolitan city and capital of the most populous province Punjab in Pakistan. It is located in central east of Pakistan and is characterized by warm summers from May to mid-September and a small winter from November to February. See Table 1

Table 1

<table>
<thead>
<tr>
<th>Geography</th>
<th>Climate</th>
<th>Demography</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location: 31° North and 74° East</td>
<td>Summer: 40°-25°C</td>
<td>Population: 11,126,285</td>
</tr>
<tr>
<td>Altitude: 217 m</td>
<td>Autumn: 23-18°C</td>
<td>Density: 6300/km²</td>
</tr>
<tr>
<td>Area: 1772 km²</td>
<td>Winters: 20°-5°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spring: 28-19°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Average temp. 30°-32°C</td>
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Most cities have an older nucleus from which the city has originated and grown spatially. In Lahore, this nucleus is the eleventh century Walled City surrounded by the areas that developed in the nineteenth and early twentieth century and that today form the inner-city core. The common archetype is courtyard houses in the region. For conducting the research on outdoor comfort, the Barood Khana haveli was selected as case study in this neighbourhood. 

The case haveli was determined by a number of criteria like the usage of space, originality of architecture, multiple courtyards, and organization of space. The selected specimen of construction had the following characteristics,

1- The building has an original layout with very minimal periodic alternation.
2- The occupants were living in the house from more than a century so the history of the building can be easily verified by them.
3- The construction materials were local.
4- The building consist of multiple courtyards so a better study of aspect ratios, canyons and layout can be done.
5- The building utilizes its courtyards for the socio-communal purposes. This lively attribute of the courtyards will help in unfolding the attributes for outdoor micro climate.

Barood khana Haveli is massed around four nearly rectangular courtyards in an irregularly shaped house. The outer courtyards have been laid out with the concept of outside in, bringing the city to the building. The two private courtyards have screens to abbreviate the view. The courtyards are neighboured by an urban fabric comprising of arched balcony and double heighted rooms on first floor which overlook the courtyards and additionally perform the responsibility of minimizing the sun penetration in the areas. The rooms are located mostly in the northern hemisphere of the haveli with the windows opening in the northern orientation to avoid the southern sun. The courtyards are divided here as Inner courtyard 1, Inner courtyard 2, Inner Courtyard 3 and Main Courtyard. See Figure 1.
2.2.1 Morphological Indicators:
The morphological indicators are used in this research to study the outdoor comfort and access the four courtyards on the basis of their individual behaviours. According to section 1.1, these ratios and indices have a close relationship with the sun penetration. See figure 2.

As the aspect ratio becomes higher, the exposure of courtyard surface increases too. This exposure however allows the courtyards to complete its daily life cycle, receiving the warmth during the daytime and releasing the heat at night allowing the surface temperatures to cool down. As Reynold states that ‘a shallow courtyard admits more sun both summer and winter, admits more wind, and radiates more easily to a cold night sky’ (5)

3. Fieldwork Protocol:
The fieldwork was covered with the instantaneous data and long-time recorded data. The fieldwork aimed to explore and to assess the thermal and environment of the selected courtyard buildings. The work’s step progress was:

- Spot measurements were recorded in all four courtyards. For the micro climate study a thermal walk was conducted on 19th April, 2018 from 11:00 Am to 1:00 Pm. For this anemometer, surface temperature recorder, thermal imaging and Illuminance mobile application was used. The Lahore weather, as recorded by the nearest weather station for the time of spot measurement (11:00 Am, 19th April, 2018) was as following,
  Dry Bulb temperature 35 °C Humidity 31%
  Wind 10km/h
  Sky condition cloudy/ light drizzle in morning , clear sky in afternoon

- Monitoring days were selected during the last week of April. The data loggers monitored the temperatures and relative humidity at an interval of 30 minutes for one week (23rd April-28th April 2018). The monitoring period had days from spring, mild summer and extreme hot days. For winters, digital simulations were conducted.

Note: The courtyards were watered in the mornings and the occupancy schedules showed that the courtyards were used for communal meet ups during the evenings.

3.1. Spot measurements
For the micro climate study a thermal walk was conducted on 19th April, 2018 from 11:00 Am to 1:00 Pm. For this anemometer, surface temperature recorder, thermal imaging and Illuminance mobile application was used. The Lahore weather, as recorded by the nearest weather station for the time of spot measurement (11:00 Am, 19th April, 2018) was as following,
  Dry Bulb temperature 35 °C Humidity 31%
  Wind 10km/h
  Sky condition cloudy/ light drizzle in morning , clear sky in afternoon

Figure 3 Spot measurements of DBT, RH and wind speed
3.2 Monitoring through Data loggers:
The four courtyards were segregated into zones. The key locations were main sitting areas in the axes North-south and east west. This data was collected 23rd April-28th April 2018. It was observed that the main courtyard with the highest aspect ratio, showed lower temperatures. To further investigate, two days, 21st April and 26th April with mean maximum and mean minimum temperatures were selected from the observed week to study the effectiveness of different strategies in the courtyards.

The onsite data is compared to get more information regarding the development of microclimate and the impact of surrounding urban canyon and plantation on thermal conditions.

3.3 Result Analysis:
The graphs in figure 5 and 6 show that the main courtyard has low temperatures. Here the natural intrusion from the plants played the key role. As Reynolds also states that without the natural or manmade ‘Interventions’, the shallow courtyards will be harder to cool on a warm summer day (5).

The rest of the shallow courtyards showed results in relations to, the shallower is the courtyard, the more it is exposed to the sun and hence it is more heated.

Inner courtyard 3; the deep courtyard acted as a space with the average temperatures of both maximum and minimum temperatures recorded in the other courtyards for the day. However, during the night hours this courtyard 3 gave high temperatures. This is because of the night vent property of the surrounding thermal mass. As the courtyard has a small area as compared to the remaining three courtyards, it heats up quite rapidly during the night because of the heat release by the thermal mass (5)(7).

4. Digital simulations:
As the fieldwork had a major limitation of time, hence digital simulations were run to further extend this research for the whole year for detailed assessment of the geometric and green features of the courtyards which affect the microclimate. There are number of tools for investigating micro climates and comfort indices but for this study, following software were used.

- Rhino (Grasshopper and ladybug plugin)
- ENVI-MET
- TAS

4.1 Climate Data and Inputs:
The effects of Winter, spring and summer season were taken into account. For obtaining the mean radiant temperatures, the data of all three seasons for their respective months were used as an input.

The Humans and clo values considered are as following,

Height = 1.8m, Weight = 75 kg, Activity = sitting, Exposure = 3 hours, Clo = 0.5 summers & mid season, 0.9 winters.

The Albedo for simulations was taken 0.3-0.5. The vegetation with 4m height and head crown of 2-4m was used.

4.2 TAS and Grasshopper workings:
The weather file generated by Meteonorm was added in grasshopper to obtain the Dry bulb temperature, relative humidity and wind. The wind profile at ten meters was computed by using the component ‘wind speed calculator’.

In order to generate results from TAS, a three dimensional model was created within the software.
The areas under study were divided into zones. These zones were provided with necessary information about the heat gains, occupancy schedules and material construction to perform dynamic simulation. The building simulator calculated the mean radiant temperatures in the courtyards. The resultant mean radiant temperatures are as following.

Furthermore, in order to make sure that the values obtained through the TAS software are precise, their accuracy was checked by 'Ladybug Outdoor Solar Adjustor ' in Grasshopper Plugin.

4.2.1 Outcome:
The preliminary results suggest that the shallow courtyards with high aspect ratio, and more exposure from surrounding urban canyon receives higher solar gains. Here this has to be mentioned that the main courtyard was protected by south sun, while the inner courtyard 1 was exposed from both south and west direction. But, the main courtyard has a more exposed area to sun with Height/Width ratio 0.5, and the inner courtyard 1 with Height to width ratio of 1.6, is more deeper that the main courtyard. Thus this can be deduced that for a warm climate, two main inputs must be considered while shaping the courtyard, Direction of sun penetration and Area exposed to sun. The above exercise states that both of the courtyards had achieved one of the aforementioned considerations of design. However, the morphology of the courtyards with respect to their shallow and deep widths play a more vital role with the urban canyon for protecting the area from sun protection. Note: These simulations were run without vegetation.

5. GEOMETRY AND PLANTATION POTENTIAL:
The geometrical properties of the four courtyards in the Haveli Barood Khana are as following

- H/W ratio of Inner courtyard 1 = 1.6
- H/W ratio of Inner courtyard 2 = 0.8
- H/W ratio of Inner courtyard 3 = 1.2
- H/W ratio of Main Courtyard = 0.5

The deduced conclusions from the theoretical study and precedents were tested in Grasshopper plugin and TAS for Barood Khana Haveli by considering no vegetation.

1. The courtyards placed perpendicular to the sun axis.
   From the fieldwork and simulations, it is derived that placing the courtyards away from the sun axis cannot assist alone in blocking the excessive sun penetration. For example, The two courtyards (Main courtyard and inner courtyard 1) are placed perpendicular to the sun movement and present the maximum and the minimum Mean radiant temperatures. Despite the courtyards are surrounded by the buildings but the afternoon sun can still penetrate into the courtyards from west.

2. The courtyards placed parallel to the sun axis present higher temperatures.
   The inner courtyard 2 and inner courtyard 3 are placed parallel to the sun axis. The inner courtyard 2 is surrounded by buildings in the south, west and north sides. Whereas the inner courtyard 3 is only exposed from the west side and allows the afternoon sun to enter the courtyard. These two courtyards showed intermediate Mean radiant temperatures, which indicate that even if a courtyard is placed parallel to the sun axis, but the longer side has enough urban fibre canopy to protect it from the summer sun, the courtyards will be self-shaded providing a better outdoor climate.
6. THE THERMAL PERFORMANCE OF NATURALLY SHADED COURTYARDS.

The Haveli Barood Khana is heavily shaded by the vegetation. The plants can be incorporated as a solution, if the geometry is not enough to self-shade the ground. The plants not only provide shade, but they clean the air, improve the air temperatures and encourage the wild life. To cover these courtyards fully by some man made assembly will require mechanical aid that would close during the day and open at the night. Such assembly can be incorporated in the more corporate projects but for domestic use, more natural means can suffice. These plants also behave according to the urban climate. They blossom in the summers while shed their leaves in the winter when the sun is welcomed by the inhabitants. The model for Barood Khana Haveli was created in ENVI-met. The software allows to create the geometry using small cubic units. Hence the three dimensional model was created with special consideration to keep the model holistic with respect to the present site. The ENVI-met analysis with and without vegetation showed that a difference of 5-10 degrees in the mean radiant temperatures can be expected. The inputs used for the model was as following,

6. CONCLUSION:

The fieldwork indicated that the courtyards with the maximum vegetation despite exposed perpendicular to the sun path showed lower temperatures. As TAS and grasshopper cannot take into account the effect of vegetation, hence the results obtained were merely based on the physical morphology of the courtyards. In ENVI-met, the effect of mean radiant temperature was studied with plants and without plants. This lead to the fact that the vegetation play an important role in changing the behaviour of the courtyards. The studies conducted on the thermal behaviour of these courtyards in the city of Lahore suggest that it is very crucial to control the amount of incoming sun insolation. The simulations revealed that courtyards protected by the intrusion of west sun show slightly lower temperatures even without the vegetation. Hence, the west sun must be blocked by either the built form or by shading devices. Increasing the height of wall enclosures in the courtyard provide more shaded areas and low mean radiant temperatures. Use of trees can cover the previously unshaded areas and lower the thermal discomfort. The areas covered with vegetation can show a significant surface temperature difference with a fully exposed to sun surface. These findings are site specific but provide a basic outline for design. As the temperature in Lahore can reach to harsh ranges during the summers, hence the outdoor activities during the summers can be limited. However during the spring season, the courtyards can be used in the later afternoon to evening and night. During the winter, these courtyards can be accessed all the times.

REFERENCES


Exploring the Robustness of Building-Integrated Photovoltaics Renovation Scenarios to Climate Change Perspectives: Results for a multi-family building in the Swiss context

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ABSTRACT: Building renovation is one of the main strategies put forth in western countries, where energy regulations are becoming increasingly demanding. Switzerland for example has set the ambitious target aiming at carbon neutrality for 2050. Building-integrated photovoltaic systems, functioning both as envelope material and on-site electricity generator, have the potential to strongly contribute towards these objectives. When designers consider the fulfillment of the 2050 objectives, the question of the robustness of the design decisions to the different climate change (CC) scenarios appears. Designing today, but taking into account climate evolution pathways, is a new challenge that architects must face. Based on publications from the IPCC, we know that CC effects, characterized by global warming, are already visible. In this context, we must learn to design by integrating uncertainty related to CC. One way to take these changes into account is the use of artificial weather files representing different possible scenarios. Focusing on the energy performance of a multi-family building, this article compares the results obtained for a series of BIPV renovation variants based on three IPCC scenarios. Despite the impact on the energy performance, results show no contradiction with respect to the strategies designed using the typical meteorological year scenario.

KEYWORDS: building-integrated photovoltaic, renovation, robustness, climate change, synthetic weather files

1. INTRODUCTION

Energy regulations in western countries are becoming increasingly demanding. Switzerland for example has set the ambitious target for 2050 of reducing its greenhouse gas (GHG) emissions by 76% compared to 2005 [1]. More recently, the government has even announced aiming at carbon neutrality for 2050 [2].

In this context, within the building sector, the renovation of the building stock – which contains a significant proportion of buildings of over 40 years old [3] – is put forth as one of the main energy efficiency strategies. Within the design decisions made for the renovation of a building, the relevance of the concept of building-integrated photovoltaic (BIPV) systems, functioning both as envelope material and on-site electricity generator, is only starting to emerge [4,5]. Together, renovation integrating BIPV strategies have the potential to strongly contribute towards the carbon emission reduction objectives.

However, at the moment when the design team considers the fulfillment of the objectives for a future horizon such as 2050 or even 2100, the question of the robustness of the design decisions to the different climate change (CC) scenarios arises. Designing today, but taking into account various climate evolution pathways, is a new challenge that architects and building engineers must face. Based on publications from the Intergovernmental Panel on Climate Change (IPCC) [6], we know that CC, characterized by global warming, is a reality and its effects are already visible. In this context, actors from the construction sector must learn to design by integrating uncertainty related to CC. One of the tools available to take these changes into account is the use of artificial weather files representing different possible scenarios.

There are recent publications about research projects [7,8] that are concerned with this issue from the point of view of resilience – generally defined as the ability of humans to adapt positively to adverse situations – measured in terms of the structural resistance to catastrophic events such as earthquakes, etc. Some articles apply this concept to the energy performance of buildings, using building performance simulation (BPS) to study various design scenarios and evaluate the changes in the energy efficiency as a function of climate evolution (increase in average temperature, increase in cloudiness, decrease in effective solar radiation, ...) [9,10,19–23,11–18].
However, there is lack of studies convening the renovation of residential buildings and BIPV. This article proposes a new approach focusing on the evaluation of the robustness of decision making in renovation projects that integrate photovoltaic strategies (using facades and roofs). The notion of robustness is here understood as the stability of a building energy performance over time in the face of changing climate conditions. In the sense it can be seen as a part of the resilience concept.

Focusing on the energy performance of an existing multi-family building, this article compares the results obtained for a series of BIPV renovation variants based on three different IPCC scenarios (A1B, B1 and B2) for time horizons from 2020 to 2100.

The question to be answered by this research is related to the sizing method of photovoltaic installations based on a trade-off between self-consumption and self-sufficiency (the full calculation method is exposed in [24,25]). To calculate these two parameters, hourly simulations are carried out, taking into account the urban context and using a TMY climate file (with historical data from the last 30 years).

Due to the global warming that is already evident, we can state beforehand that, if the average temperature increases, the demand for heating would tend to decrease and the opposite for the demand for cooling. However, the electricity production by a photovoltaic installation, and the match between demand and production, are more difficult to anticipate or predict.

For this reason, this article explores the variations in terms of energy consumption and production, as well as the match between the two, to assess whether the use of artificial climate files – reflecting future scenarios according to the IPCC – could substantially change the decisions made using a TMY climate file.

2. METHODOLOGY

The research involves four main phases: 1) detailed analysis of the building and implementation of design scenarios embodying BIPV solutions and different levels of intervention; 2) iterative process between design and building-performance simulation (BPS) to define the construction strategies and to obtain the final energy needs and the photovoltaic performance using a TMY (typical meteorological year) weather file with historical data from 1991 to 2010; 3) BPS process for all renovation variants and CC scenarios using the different artificial weather files according to the IPCC; 4) comparison of the results in terms of energy consumption and production. While further details on the implementation of each renovation scenario (phase 1) and the simulation conditions (phase 2) can be found in [25], the emphasis is here placed on the comparison of the different IPCC synthetic weather files and comparison of the energy performance results, to analyse the level of robustness of the different renovation scenarios originally designed using a traditional TMY weather file.

The case study presented in this paper corresponds to a multi-family building built in 1968, with 7 stories, 48 apartments and 4,415 m² of floor area. This building is highly representative of the Swiss building stock from the late 60’s – early 70’s [25]. It has a low-performance building envelope: non-insulated façade composed by ceramic brick with a 4 cm air gap and double-glazed windows. The flat roof holds 6 cm of EPS insulation protected with 5 cm of gravel. Five renovation strategies, including both passive (e.g. insulation addition) and active (i.e. related to the systems) strategies are implemented. The E0 scenarios corresponds to the current status of the building and the S0 scenario represents the achievement of minimum legal requirements in terms of energy performance [26], both are without BIPV. The S1, S2 and S3 scenarios include BIPV strategies and respectively correspond to three levels of interventions regarding both architectural expression modification and energy performance targets (from current practice to Swiss targets for 2050 [1]). Passive strategies (Fig. 1) mainly involve, the increase of the global thermal insulation of the roof and façades (adding insulation on the opaque parts of the building envelope and replacing the existing windows).

For scenarios S1, S2 and S3, the strategies include BIPV elements on the façade (as cladding material) and a standard PV installation on the flat roof (with south-oriented panels inclined at 45°). In terms of active strategies, for this study, a typical central HVAC system based on an electric heat-pump is proposed to cover heating, cooling and domestic hot water (DHW) needs.

To conduct the BPS process (to obtain hourly-step energy consumption and PV production), four different weather files were used for the analysis: the TMY based on historical data from 1991 to 2010, and three synthetic files generated with Meteonorm [27] corresponding to the three main IPCC scenarios (B1, A1B and A2). These files have been extracted for 5 time-horizons: 2020, 2030, 2040, 2050 and 2100. Apart from the BPS using
DesignBuilder [28] to obtain the energy needs, a detailed calculation of the PV performance (on-site production, self-consumption (SC) and self-sufficiency (SS) rates) is conducted considering the BIPV surfaces proposed for each scenario (the full calculation method is exposed in [24,25]). Figure 2 shows the results of the irradiation study for each BIPV scenario using the TMY weather file.

In its Fourth Assessment Report (AR4) [6], the IPCC has developed 40 emission’s scenarios that are grouped into four families, each based on some assumptions related to, for instance, human activity and projected global average surface warming until 2100. Each scenario follows different hypotheses for future greenhouse gas emissions, land-use, technological development as well as future economic development. It is important to know that all these scenarios are defined as “neutral” by the IPCC, meaning that they don’t take into account future catastrophes (e.g. geopolitical conflicts, war, pandemics, and/or environmental collapse).

Figure 2: Example of annual irradiation study results for each BIPV scenario (façade and roof) using the TMY weather file (1991-2010).

Figure 3: Dry-bulb temperature (DBT), direct normal radiation (DNR) and diffuse radiation (DF) of the different weather files and horizons.

For this publication, three scenarios that follow distinct paths and that are part of three different families are considered: A1B, B1 and A2.

A1B is characterized by a) rapid economic growth, b) population increase to 9 million by 2050 followed by a gradual decline, c) quick application of cutting-edge efficient technologies emphasising a balance on all energy sources, d) globalisation approach with extensive social and cultural interactions worldwide. The projected
global average surface warming (PGASW) until 2100 is between 1.4-6.4°C.

**B1** is characterized by a) an integrated and more ecologically friendly world, b) rapid economic growth with rapid changes towards a service and information economy, c) population increase to 9 million by 2050 followed by a gradual decline, d) introduction of clean and efficient technologies. The PGASW range until 2100 is of 1.1-2.9°C, lower and narrower than A1B.

**Figure 4** shows the results of the heating and cooling needs for the different renovation and CC scenarios for 2100. Compared to the results obtained with the TMY of each scenario (also shown on the graph), the demand for heating decreases between 7.9-23% and cooling increases between 112-1,015%, reflecting the effect of global warming from the CC scenarios.

Comparing, this time, the total final energy consumption (heating, cooling, domestic hot water (DHW), lighting and appliances) and the onsite PV production, **Figure 5** shows – for the 2100 horizon – that the deepest renovation scenarios (S1, S2 and S3) present less difference (between 1.1 and 3.8%) compared to the results obtained with the TMY than E0 and S0 (between 2.7-9.5%). In terms of on-site PV production, the reduction is between 1.9-4.8%.

In order to explore the robustness of the different BIPV scenarios to CC perspectives, we propose to analyse the results using standardized boxplot charts showing the distribution of the data. In general, the wider the interquartile box, the greater the spread of the results, which could thus be interpreted as a lower robustness.

**Figure 6** shows, as already observed in **Figure 5** for the 2100 horizon, that the deepest renovation scenarios (S1, S2 and S3) present more concentrated results, meaning that the electricity needs show less variation across the CC scenarios. The shallow renovation (S0) also shows less variation than the non-renovated scenario (E0), whose energy efficiency depends heavily on the CC conditions. In that sense, it can be seen as less resilient.

**3. RESULTS**

The results presented here correspond to the application of the method for the horizons from 2020 to 2100 using A1B, B1 and A2 scenarios compared to TMY.

Finally, **A2** is characterized by a) continuously increasing population, b) low emissions, c) regional oriented economic development with self-reliant nations. The PGASW until 2100 is between 2.0-5.4°C.

Before applying the IPCC weather files to the BPS, we conduct an analysis of the different files using the climate consultant application [29]. Key information such as dry-bulb temperature (DBT), direct normal radiation (DNR) and diffuse radiation (DF) is visualised to understand the differences and their correlation with the IPCC emission’s scenarios [6]. **Figure 3** shows that, compared with the TMY, the IPCC scenarios present lower solar radiation, specially A1B-2050 and B1-2100. For all IPPC scenarios, the yearly average dry-bulb temperature increases up to 2.7°C.

On the other hand, among the BIPV scenarios, those with installations covering more surface (particularly façade surfaces) – S2 and S3 – show greater sensitivity to weather scenarios across time horizons.
The self-sufficiency (SS) and self-consumption (SC) ratios are shown in Figure 7. The most stable result is the SC of the S1 scenario, which varies within a 0.5% range across all weather files (TMY and CC scenarios for all horizons). Less stable is the SS of S2, showing a (still low) 2% variation.

![Figure 7: Self-consumption and self-sufficiency ratios for each renovation scenario (all CC scenarios and horizons combined). No BIPV installation for E0 and S0 scenarios.](image)

Comparing the energy balance calculated by subtracting the energy needs to the onsite PV production (Figure 8), we observe that the uncertainty within the renovated scenarios, with or without BIPV strategies, is less important than for scenario E0. For S2 and S3, the building remains energy-positive.

![Figure 8: Energy balance (onsite PV production – electricity needs) for each renovation scenario (all CC scenarios and horizons combined).](image)

From all these graphs, we observe that the distribution of the results is not distinct enough to say that the decisions made using a TMY weather file would be different if a CC scenario was considered. Indeed, design choices and BIPV sizing made based on the TMY appear as valid for the future, although uncertain. This is supported by the relatively narrow variations between the CC scenarios and horizons – as illustrated by the box charts – as well as the stability in the pattern among renovation scenarios (with S2 and S3 always performing better).

### 4. CONCLUSION

This paper presents a comparison of the simulated energy consumption and production (through BIPV) of different renovation strategies using distinct weather files: the commonly used typical meteorological year and three climate change scenarios for 2020 to 2100.

Despite the fact that the overall energy performance of the building varies between scenarios, results show that, if the renovation strategies were devised based on future climate scenarios, the influence would be minimal. Indeed, tendencies show no contradiction with respect to the TMY results, on which the strategies were based.

Results also serve to reiterate the importance of renovating the building stock, by highlighting the important energy efficiency gains that can be achieved through various renovation strategies, some involving BIPV systems.

Future work foresees the analysis from the point of view of the increase in hours of discomfort, especially in summer since in the Swiss context, it is very probable that no cooling system will be installed. In addition, an analysis of the insulation thickness dimensioning using the different climate change scenarios and their impact on the whole life cycle analysis, including the embodied energy of the BIPV installation, is being integrated into the study.

### REFERENCES

ABSTRACT: The presence of moisture in the building is one of the main factors responsible for the users’ discomfort as well as the marked degradation of the building elements. Water can also have other direct effects, such as freezing deterioration and loss of bonding between layers due to vapor condensation at the interface between building layers and indirect effects as chemical attack on natural stones, corrosion of concrete elements, among others. This work aims to analyse six different wooden vertical sealing systems for moisture flow by capillary and vapor transport and thermal performance to the Southern Brazilian Bioclimatic through WUFI Pro software. It is possible to verify that all systems indicated positive results for capillary transport flow. Regarding the vapor transfer, the systems made of 0.95cm panel, 10cm mineral wool with 0.95cm OSB (S3), 5cm air, 0.95cm OSB (S4) and that composed of 0.95cm panel, 5cm air, 10cm mineral wool, 0.95cm OSB (S5) showed positive results, directing the vapor outside the building. The S4 system presented the highest risk of condensation when compared to all positions of the other systems. The S5 system (with mineral wool tangent to the OSB plate) presented the best overall performance for considered climate.

KEYWORDS: Hygrothermal analysis, wooden sealing, vapor transport, thermal performance, WUFI Pro.

1. INTRODUCTION

Since the end of the 1990-decade, civil construction and, especially research in this area have turned their attention to the sustainability of buildings. Temperature and humidity can be optimally controlled in both the envelope and the internal environment from the evaluation of materials and construction techniques [1]. The hygrothermal performance assessment of buildings allows identifying the envelope behaviour under climatic conditions [2]. Therefore, moisture effects on the internal environment, material durability and maintenance demands building systems analysis. The presence of moisture in the building is one of the main factors responsible for the users’ discomfort as well as the marked degradation of the building elements [3]. Water can also have other direct effects, such as freezing deterioration and loss of bonding between layers due to vapor condensation at the interface between building layers. In addition, can indirect affect as chemical attack on natural stones, corrosion of concrete elements, among others [4]. Thus, it is of utmost importance to analyse the hygrothermal behaviour of building materials and building systems considering the weather conditions to which they are exposed, to predict their durability and internal environment quality.

The WUFI Pro (Wärme Und Feuchte Instationär) is a useful computational calculation tool for simulating the hygrothermal behavior of building envelopes, developed by the Fraunhofer Institute for Building Physics (IBP) [5]. Based on the initial conditions and the interior and exterior contour conditions of this system, the software determines the thermal and hygrothermal integrity of building envelope sets in different climates [6].

This work aims to analyze the hygrothermal performance of six different wooden wall systems in the Brazilian Bioclimatic Zone 3 (ZB3) [7] by WUFI PRO simulation.

2. METHODOLOGY

The methodological procedure of this research was based on computer simulation, using WUFI® Pro software (version 6.3), to identify the moisture flows and the thermal performance in a building located in ZB3, in Brazil [8]. The methodology followed three stages: (I) definition of the wood façade system, (II) software parameters characterization, (III) analysis of simulation and results.

The city of Porto Alegre, located at latitude 29.99° south, longitude 51.17° west and altitude of 3 m, was chosen to represent the ZB3. The climatic file used was
Test Reference Year (TRY) provided by the Laboratory of Energy Efficiency in Buildings (LabEEE) [9].

Six models of wooden walls were analysed. The first model was a conventional Brazilian system (simple softwood panelling). The other five systems were composited by adding layers, with lower thermal transmittance values (U) (calculated according to the NBR 15220-2 [10]).

Table 1 presents a graphic representation, the description and the U value of the six construction systems. Table 2 presents the characteristics of each used material. All the layers properties were obtained from the software database.

Table 1: Description of the construction systems adopted.

<table>
<thead>
<tr>
<th>System</th>
<th>Representation of the constructive system</th>
<th>Description (from outside to inside of building)</th>
<th>U value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td></td>
<td>0,95 cm of soft wood (coniferous)</td>
<td>3.675</td>
</tr>
<tr>
<td>S2</td>
<td></td>
<td>0,95 cm of soft wood (coniferous) + air layer (5 cm) + 0,95 cm of OSB Panel</td>
<td>1.962</td>
</tr>
<tr>
<td>S3</td>
<td></td>
<td>0,95 cm of soft wood (coniferous) + 10 cm of mineral wool + 0,95 cm of OSB Panel</td>
<td>0.340</td>
</tr>
<tr>
<td>S4</td>
<td></td>
<td>0,95 cm of soft wood (coniferous) + 10 cm of mineral wool + air layer (5 cm) + 0,95 cm of OSB Panel</td>
<td>0.297</td>
</tr>
<tr>
<td>S5</td>
<td></td>
<td>0,95 cm of soft wood (coniferous) + air layer (5 cm) + 10 cm of mineral wool + 0,95 cm of OSB Panel</td>
<td>0.297</td>
</tr>
<tr>
<td>S6</td>
<td></td>
<td>0,95 cm of soft wood (coniferous) + 1 cm of hydrophobic blanket + air layer (5 cm) + 10 cm of mineral wool + 0,95 cm of OSB Panel</td>
<td>0.248</td>
</tr>
</tbody>
</table>

Table 2: Properties of the construction materials.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Softwood</th>
<th>Hydrophobic blanket</th>
<th>Air layer</th>
<th>Mineral wool</th>
<th>OSB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent density [kg/m³]</td>
<td>400</td>
<td>146</td>
<td>1.3</td>
<td>25.2</td>
<td>595</td>
</tr>
<tr>
<td>Porosity [m³/m³]</td>
<td>0.73</td>
<td>0.92</td>
<td>0.999</td>
<td>0.95</td>
<td>0.90</td>
</tr>
<tr>
<td>Specific heat [J/(kg.K)]</td>
<td>1400</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1400</td>
</tr>
<tr>
<td>Thermal conductivity [W/(m.K)]</td>
<td>0.09</td>
<td>0.014</td>
<td>0.28</td>
<td>0.035</td>
<td>0.13</td>
</tr>
<tr>
<td>Water vapor diffusion resistance factor</td>
<td>200</td>
<td>4.7</td>
<td>0.32</td>
<td>1</td>
<td>165</td>
</tr>
</tbody>
</table>

For the calibration of the six models, the following parameters were defined: solar orientation to the north; small building (less than 10 meters high); external and internal walls with acrylic paint; ground reflectivity (short wave) of 0.2; incident rainfall reduction factor of 0.7. The analysis parameter was ANSI / ASHRAE 160, which delivers the wider rain amount on façade, representing the most critical situation [11]. The parameter is indicated for simulations in Brazil since there are no methodologies defined to quantify amounts of rainfall incidents in facades in the country [12].

The simulation period was two years with a time interval of 1 hour. The point analysis mesh was adopted as fine with 100 points. The average temperature was 19.7°C; maximum temperature 37.0°C; minimum temperature 2.0°C; sum of radiation 3,297.1 kWh/m²year; average cloudiness index of 0.67. Average relative humidity of 78.1%; maximum relative humidity of 100%; minimum relative humidity of 26%. Average wind speed of 2.6 m/s and the sum of normal rainfall of 922.2 mm/year.
Due to the external and internal surfaces receiving colorless acrylic paint, with brown color visible, the wall absorbance was considered as $\alpha = 0.74$ according to NBR 15220-2 [10]. The use of acrylic paint is a common practice in wooden buildings in Brazil. The painting affects the surface porosity, changing the vapor transport between the wall and the environment. It reduces the moisture content variation within the wall system, which can improve its life cycle, also limits the system's hygroscopic characteristics and ability to control environmental humidity. These effects may vary according to the painting, wood, and climate characteristics.

The parameters considered in the hygrothermal analysis were capillary transport integration ($kl$) and steam transport flows ($dl$); total moisture content; condensation risk, heat fluxes and relative humidity integration over two years.

3. RESULTS

3.1 Flow integration test

Transport flow analysis indicates whether the moisture flows in or out of the building. The results of this stage present the capillary transport ($k$), vapor transport ($d$) and flux integration for each integration system and its respective moisture balance (Table 3).

Table 3: Integration of flows by capillary transport and steam transport

<table>
<thead>
<tr>
<th>Construction system</th>
<th>Capillary transport on the outer side (kl) [kg/m²]</th>
<th>Capillary transport on the inner side (kr) [kg/m²]</th>
<th>Steam transport on the inner side (dl) [kg/m²]</th>
<th>Steam transport on the inner side (dr) [kg/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>0.0</td>
<td>0.0</td>
<td>-0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>S2</td>
<td>0.0</td>
<td>-0.72</td>
<td>-0.07</td>
<td>0.68</td>
</tr>
<tr>
<td>S3</td>
<td>0.0</td>
<td>-0.04</td>
<td>-0.45</td>
<td>-0.25</td>
</tr>
<tr>
<td>S4</td>
<td>0.0</td>
<td>-0.04</td>
<td>-0.45</td>
<td>-0.25</td>
</tr>
<tr>
<td>S5</td>
<td>0.0</td>
<td>-0.04</td>
<td>-0.45</td>
<td>-0.25</td>
</tr>
<tr>
<td>S6</td>
<td>0.0</td>
<td>-0.58</td>
<td>-0.06</td>
<td>0.55</td>
</tr>
</tbody>
</table>

The results indicate that the constructive system S1 presented excellent performance regarding the capillary transport, noting that there was no capillary transport during the period of 2 years. The S2 system resulted in the system more susceptible to capillary transport (0.72kg/m²), followed by S6 (0.58kg/m²), but when this phenomenon occurs, its flow is directed outside the building in both cases.

As for steam transported, the S1 system had the lowest moisture content due to the fact that softwood is the material that retains less steam within the system (Table 3). The S2 system had the highest moisture content of steam incorporated, also, its positive flow indicates that its transport will occur towards the internal side.

Comparing all systems as to the flow of steam transport, S1, S2 and S6 systems transported steam into the building, whereas S3, S4 and S5 transported it out of the building.

Regarding the balance between the integration of flows on both sides of the wall, it is essential that these values are equal, that is, verifying the change in the total water content during the calculation and the sum of the surface flows (+ $kl$, + $dl$, - $kr$ and - $dr$). Table 4 shows that the Balance 1 was the same as the Balance 2 for the six construction systems analyzed, all with a flow direction going from the internal to the external environment.

Table 4: Balance between outer and inner flow integration.

<table>
<thead>
<tr>
<th>Construction system</th>
<th>Balance 1 [kg/m²]</th>
<th>Balance 2 [kg/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>-0.02</td>
<td>-0.02</td>
</tr>
<tr>
<td>S2</td>
<td>-0.03</td>
<td>-0.03</td>
</tr>
<tr>
<td>S3</td>
<td>-0.16</td>
<td>-0.16</td>
</tr>
<tr>
<td>S4</td>
<td>-0.16</td>
<td>-0.16</td>
</tr>
<tr>
<td>S5</td>
<td>-0.16</td>
<td>-0.16</td>
</tr>
<tr>
<td>S6</td>
<td>-0.03</td>
<td>-0.03</td>
</tr>
</tbody>
</table>

3.2 Total moisture content - TMC

The total moisture content (TMC) indicates the ability of the system to dry over time [4]. Thus, the total moisture content at the beginning and at the end of the two-year simulation period were compared. All building systems were approved in this criterion. It was observed that the systems composed of more layers tend to lose less moisture over time. The TMC for S1 decreased 3.51% (from 0.57kg/m² to 0.55kg/m²), while S6 reduced 1.89% (from 1.59kg/m² to 1.56kg/m²). The systems S3, S4 and S5 presented better results, TMC decreased 11.18% (from 1.52kg/m³ to 1.35kg/m³) at the end of the two-year simulation.

Moisture content analysis (illustrated on Table 5) allows to identify the efficiency of the materials in terms of moisture protection and, consequently, regarding the proliferation of fungi and moisture retention.

Table 5: Moisture content per layer.

<table>
<thead>
<tr>
<th>System</th>
<th>Layer</th>
<th>Begin kg/m³</th>
<th>End kg/m³</th>
<th>Min. kg/m³</th>
<th>Máx. kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Soft wood</td>
<td>60.00</td>
<td>58.27</td>
<td>41.20</td>
<td>71.94</td>
</tr>
<tr>
<td>S2</td>
<td>Soft wood</td>
<td>60.00</td>
<td>58.58</td>
<td>45.94</td>
<td>67.36</td>
</tr>
<tr>
<td></td>
<td>Air layer (5 cm)</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>OSB Panel</td>
<td>95.00</td>
<td>93.06</td>
<td>80.53</td>
<td>100.62</td>
</tr>
<tr>
<td>S3</td>
<td>Soft wood</td>
<td>60.00</td>
<td>59.16</td>
<td>41.11</td>
<td>70.25</td>
</tr>
<tr>
<td></td>
<td>Mineral wool</td>
<td>0.46</td>
<td>0.43</td>
<td>0.40</td>
<td>0.47</td>
</tr>
</tbody>
</table>
Adding materials, such as thermal insulation and hydrophobic blanket, helped in different ways to reduce the moisture content of the internal closure (OSB panel) since these insulations had lower final values than the initial ones. The moisture content of the thermal insulation, in the different construction systems, remained the same, regardless of its position (system S4 and system S5).

Additionally, the application of the hydrophobic blanket did not contribute to the containment of moisture in the final system (OSB panel). It even showed an increase of 14.80 kg/m³ when compared to the S2 system (without mineral wool). In this analysis, the application of mineral wool showed greater efficiency in containing moisture, resulting in a decrease of 14.51 kg/m³ in the final analysis when compared to the S2 system (without mineral wool). Among the wood materials used, it was verified that the OSB panel has the highest final moisture content due to the use of soft wood that has a porosity of 0.73 m³/m³ and the OSB of 0.90 m³/m³.

### 3.3 Condensation risk

Condensation risk is an important factor to be analyzed, as it indicates whether there is a possibility of occurrence of water in the liquid state somewhere in the system. This factor that can cause the degradation and growth of fungi, for example. The condensation risk points can be identified by comparing the surface temperature (ST) and the dew point temperature (TD). The risk of condensation is verified when the dew point temperature is higher than the temperature in a certain position of the construction system, reaching a relative humidity of 100% [4].

However, relative humidity values below 100% do not mean that there is no condensation for all types of materials. Hygroscopic materials show condensation for values below 100%. Wood, for example, may show fungal growth for values close to 90%. Considering the uncertainty regarding the relative humidity value for which the presence of liquid water may exist, some regulations (on which the WUFI is based) consider that there is a risk of condensation and growth of fungi for values of relative humidity from 80% for hygroscopic materials [13].

In Figure 1, the temperature (red line) and the dew point (violet line) show that in all systems the dew point was below the average temperature during the two simulated years, demonstrating that there is no risk of condensation. The lowest risk of condensation occurred in the S3, S4 and S5 systems due to the greater difference between the internal temperature and the dew point temperature.

Figure 2 shows the relative humidity and moisture content of the systems analyzed. The blue and green lines represent, respectively, the moisture content and the relative humidity of the construction systems at the end of the simulation period. The blue and green spots represent, respectively, the maximum and minimum values of the moisture content and relative humidity reached in each position of the construction systems throughout the simulation period.

For the S1, S2 and S6 systems, the average relative air humidity was below 80%, however there were some moments during the simulation that presented relative humidity slightly above 80% on the surface. For the S3 system there were also some moments during the simulation that presented relative humidity close to 90%, mainly in the contact between the mineral wool and the OSB panel. In system S4, there were also times when the relative humidity was close to 90%, presenting a greater risk of condensation in the air layer. Finally, for the system S5, the relative humidity also reached almost 90% at some points during the simulation for the air layer and on the contact surface of the mineral wool and the OSB panel, with a great risk of condensation occurring at these points.

The air layer of the S4 system presented a higher risk of condensation when compared to the same positions of the other systems. In this position, the final relative humidity was greater than 80%, and presented values close to 90% at some points during the simulation.

When comparing all systems, the S2 system presented the best result regarding the probability of water condensation. However, all systems showed relative humidity above 80% at some position in the system and at some point during the simulation. It becomes necessary, then, in future work, to analyze the percentage of time in which there was an
occurrence of relative humidity above 80% for each system, in order to identify the one with greater or smaller risk of condensation between the construction systems.

3.4 Integration of two-year time flows

Regarding heat flux, the software WUFI analyzes that incident solar radiation creates a heat flux vector in the positive x direction and, as this energy is absorbed into the material and converted to heat, much of it also flows as a heat flux out of the component, in the negative x direction. All systems arranged the heat flow outside (Table 6).

In view of the moisture flow analysis, all systems directed the moisture flow outside the building except...
for the system S1. It was also found that the S2 and S6 systems showed the best results. It is noteworthy that the S6 system presented the lowest value when compared to systems that contained mineral wool, air layer and OSB panel, due to the hydrophobic blanket. Verifying the influence of mineral wool position on the outer or inner side of the building system, it was observed no significant interference with the flow and moisture content, however, the S5 system (with mineral wool tangent to OSB panel) presented the best heat flow performance.

Table 6: Integration of heat and moisture flows over time.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>0.10</td>
<td>-0.02</td>
<td>-0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>S2</td>
<td>0.12</td>
<td>-0.00</td>
<td>-0.07</td>
<td>-0.04</td>
</tr>
<tr>
<td>S3</td>
<td>-87.14</td>
<td>-27.79</td>
<td>-0.45</td>
<td>-0.28</td>
</tr>
<tr>
<td>S4</td>
<td>-82.23</td>
<td>-82.88</td>
<td>-0.45</td>
<td>-0.28</td>
</tr>
<tr>
<td>S5</td>
<td>-82.43</td>
<td>-83.08</td>
<td>-0.45</td>
<td>-0.28</td>
</tr>
<tr>
<td>S6</td>
<td>0.07</td>
<td>-0.04</td>
<td>-0.06</td>
<td>-0.03</td>
</tr>
</tbody>
</table>

4. CONCLUSION

The results show the importance of evaluating the construction systems chosen for the climate in which it will be exposed. For each environment, the panel performance can vary, and it is necessary to assess it to ensure building sustainability, energy efficiency, environmental comfort, and resistance to the proliferation of fungi and molds.

The systems presented varied results for the parameters analyzed. All systems presented positive results for capillary transport flow. S3, S4, and S5 showed positive results for vapor transfer, directing the vapor outside the building. S4 presented the highest risk of condensation among systems in the surface between the inner OSB panel and the adjacent layer. S6 presented the most constant relative humidity content in the system during the 2 year simulation period. S5 (with the mineral wool tangent to the OSB panel) presented the best overall performance for ZB3.

The varied hygrothermal performance among panels points to the possibilities offered by the systems. The layers composition can be adapted in order to achieve better results for each climate, with the assistance of hygrothermal simulation.

As a continuation of this work, new simulations will be carried out, including the analysis of different composite materials with wood that have less porosity, the use of other insulating materials, as well as the performance of construction systems for different orientations. For future work, it is of interest of the authors to validate the results through actual tests and measurements.

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REFERENCES

The energy demand of a social dwelling for acclimatization
Sensitivity to climate change and interventions

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ABSTRACT: Buildings energy simulation is a powerful tool that allows addressing climate change impact studies on the Built Environment. Future weather files are required as forcings, so a methodology to generate them based on outputs from several climate models was proposed in this work. This approach retains both physical and temporal consistency from climatic variables and removes the climate models’ systematic errors. The variety of models allows assessing the uncertainties that are related to models and projections. The generated weather files were employed to evaluate the sensitivity of a social dwelling in Rosario city (Argentina) to design modifications and climate change projections. The proposed interventions are found to produce higher energy demand savings when the projected greenhouse gases concentrations are lower. As such concentrations increase, addressing impact studies becomes more difficult since the uncertainties associated to the results increase as well. However, as the house’s efficiency enhances, experiments start to converge and related uncertainties diminish.

KEYWORDS: building simulation, climate change, weather file, uncertainties, energy demand

1. INTRODUCTION

As one-third of the total energy demand in Argentina corresponds to the residential sector [1], there is an urgent need to improve the energy efficiency of the Built Environment. Buildings energy simulation (BES) emerges as a powerful resource since it allows estimating the energy consumption associated with the use of housing, among other things. Therefore, design improvements and modifications can be evaluated for new and already built dwellings. The energy requirement is strongly dependent on the climatic conditions of the place where the house is located. The climatic trends observed since the second half of the past century are expected to maintain or worsen in the upcoming years. In particular, in central-eastern Argentina, both the mean temperature and its extremes are expected to keep rising, with warm spells becoming more frequent, longer and more severe [2]. Such future climate conditions may cause overheating of buildings and serious discomfort issues [3,4]. Therefore, it is essential to incorporate climate change impact studies when planning and designing the Built Environment.

BES experiments require a description of the building’s infrastructure and the physical properties of the involved materials. In addition, the weather forcing of BES (i.e., a full-year climate file of hourly data of several climatic variables for the desired location) is necessary. The results of the simulations will be directly influenced by such file, so the quality of the climatic information is crucial.

Present climate weather files have mainly been used to conduct BES. However, the need to estimate the response of the energy demand to climate change also leads to the construction of appropriate future climate weather files. This involves using climate projections derived from climate models. Such projections follow different greenhouse gas emissions’ scenarios (Representative Concentration Pathways, RCPs), which are based on different global socio-economic factors [5]. Climate models’ outputs must be utilized properly to create future weather files. They have high levels of uncertainty which derive from different sources: estimates of future anthropogenic forcings, the response of the models to a given forcing and the natural variability of the climate system [6]. The assessment of such uncertainties can result in economics benefits when facing adaptation costs.

Overall, regional climate models (RCMs) can capture the physics underlying the climate system and reproduce the detailed behavior of particular locations. Moreover, the use of high-frequency (hourly) outputs from several RCMs as forcing to BES can provide a measure to assess the aforementioned uncertainties and they capture climate change signal at high temporal resolutions (e.g., diurnal cycle). The implementation of RCMs’ outputs has been explored in previous works in which
the forcing time series were the result of concatenating typical months or calculating the models’ mean ensemble [7,8]. These manipulations can lead to physical inconsistencies, misrepresenting the natural climate variability and potentially negatively impacting on the assessment study. In addition, the lack of uncertainty analysis limits the BES’ outputs analysis and interpretation. Finally, climate models possess intrinsic systematic errors that are not accounted for in most literature. They may result in underestimating or overestimating the climatic variables [9], so they must be removed when addressing impact studies.

In Argentina, climate change impacts studies on the built environment are incipient. In the most recent research, to the best of the authors’ knowledge, a house’s behavior under climate change projections for different cities is analyzed [10]. However, outdated climate projections with a coarse grid resolution were used, while uncertainties were left unaddressed. Santa Fe province has recently approved a legislation to classify buildings according to their energy performance [11], which emphasizes the relevance of such impact studies. Therefore, a methodology to create weather files with RCMs’ outputs is proposed in this work. Such files are used to conduct BES experiments that allow analyzing the behavior of a social dwelling in Rosario City (Santa Fe).

In this work, we (i) evaluate design improvements and (ii) estimate changes in the future cooling energy demand due to climate change projections, based on two greenhouse gases (GHGs) concentrations’ scenarios. The analyses are for a near future period, and include considerations about the uncertainty of the results.

2. DATA AND METHODOLOGY

2.1. Climate data and weather files

To perform BES studies for Rosario city (32° 57’ S, 60° 37’ W, Fig. 1), 21-years of high frequency data (three-hour or hourly) from four CORDEX RCMs [12] were adapted to generate present and future weather files. The 1985-2005 and the 2045-2065 periods were chosen as representative of present and near future climate, respectively. Climate projections follow to two greenhouse gas emissions’ scenarios, an intermediate one (RCP4.5) and another with high emissions (RCP8.5). Overall, the proposed methodology consists of forcing multiple BES experiments with individual RCMs to assess the potential future energy demand and the associated uncertainties.

For each RCM, several climatic variables were retrieved: surface temperature (T), surface pressure (SP), relative humidity (RH), downward shortwave radiation (SWR), downward longwave radiation (LWR), zonal wind component (U-wind) and meridional wind component (V-wind). The employed models and scenarios were: WRF (present, RCP4.5), RCA4 (present, RCP4.5, RCP8.5), REMO (present, RCP4.5, RCP8.5) and RegCM (present, RCP8.5). Also, hourly data from the Argentinian Meteorological Service was collected for the present period. Argentina lacks a solarimetric network, so radiation hourly outputs from the ERA5 reanalysis were retrieved as well [13]. The combination of both data sets was taken as an observational reference (OBS).

The hourly climatology of each variable was calculated to construct weather files for mean climate conditions. That is, the 1st of January at 00:00 a.m. for present conditions was obtained as the mean value of all the twenty-one values corresponding to the 1985-2005 period, and so on. Analogously, the hourly climatology of each variable was obtained for the two future scenarios. Climatological time series were implemented to maintain temporal coherence and consistent climate variability. This procedure was applied to all RCMs’ outputs and observations.

For the eleven datasets, the resulting 8760 time-step series of all climatic variables were employed to construct present and future weather files with the Weather Converter software [17], choosing the closest point to Rosario for each RCM.

Figure 2 shows the ranges of the annual cycle of mean surface temperature as spanned by the models available for each scenario. The observational

Figure 1: Rosario city (Santa Fe, Argentina).

Figure 2: The annual cycle of mean surface temperature for Rosario city. Belts show the models’ spread for present (1985-2005, light grey) and future climate conditions (2045-2065) according to RCP4.5 (dark grey) and RCP8.5 (light black) scenarios. Diamonds are observations. Units are °C.
monthly mean values are also displayed. Overall, a raise in the mean temperature throughout the all year is evident in the future. The RCMs span widens during cold months, which is an indicator that forcing BES with a models’ ensemble mean could result in loss of information, especially during the winter. On the other hand, observations are confined within the present period range, which is a positive indicator of the utilized RCMs. Temporal scales are downscaled in Figure 3, which shows the climatological diurnal cycle of mean surface temperature for January. Models overestimate temperature during daytime hours, especially in the afternoon. If unaddressed, such misrepresentation could result in overestimation of the needed cooling energy when carrying out BES.

The implementation of several RCMs allowed for the creation of representative weather files for present and near future periods, while maintaining physical consistency among climatic variables. Temporal coherence was also conserved while the mean state of the climate system was properly represented. Moreover, with this approach, the number of realizations depends on the number of available RCMs alone, independently of the number of years of the study period.

2.2. Building energy simulation (BES)

BES experiments were performed using Energy Plus (E+) [18]. In addition to the full-year climate file of hourly data, E+ requires a description of the building infrastructure and the materials’ physical properties (e.g., conductivity, density, etc). It is optional to specify Heating, Ventilation and Air Conditioning (HVAC) systems and the Ideal Loads System (ILS) option is available when they are not defined. ILS object consists of an ideal unit that supplies conditioned air to the zone and consumes no energy. It allows for a primary analysis of the building’s performance since it is used for loads calculations, and can be thought as a previous step to a more realistic model [18]. As evaluating the performance of HVAC systems was beyond the scope of this study, the ILS object was utilized in this work.

2.2.1. Case study

The floor plans of a social dwelling were provided by Santa Fe’s Department of Urbanism and Housing. It is a one-storey house, consisting of a living room and kitchen connected with the bathroom and two bedrooms through a hallway (Fig. 4). It has two inclined metal roofs with air chambers, covering the kitchen-dining room and the bedrooms, respectively. The bathroom has a horizontal reinforced concrete roof without any insulation. Each room was modelled as a thermal zone, with the main one oriented northward. The air chambers were defined as sealed thermal zones without air infiltrations. Traditional construction materials were used for defining the walls, blinds were set to optimize solar gains and infiltrations were set to 2 air changes per hour [19].

The diurnal cycle of mean surface temperature for January. Belts show the models’ spread for present (1985-2005, light grey) and for future climate conditions (2045-2065) according to RCP4.5 (dark grey) and RCP8.5 (light black) scenarios. Diamonds show observations. Units are °C.

The energy needed to maintain the house’s temperature below 26 °C during January was calculated for two set of experiments. This threshold is used in literature as a domestic comfort value [20]. Firstly, the house’s sensitivity to design improvements was evaluated for present climate conditions. The original specifications of the social dwelling do not comply with Rosario’s legislation [21], so the four RCMs’ outputs and the observational set were employed to conduct the following BES:

(i) Base Case (BC) where the house’s specifications remained unchanged
(ii) Roof Intervention (RI): insulation in roofs was increased to comply with the legislation (thermal transmittance $U_{\text{roof}} < 0.32 \text{ W/m}^2\text{K}$)
(iii) Roof-Wall Intervention (RWI): insulation in walls was increased as well to comply with the legislation ($U_{\text{walls}} < 0.5 \text{ W/m}^2\text{K}$).

Then, to evaluate sensitivity to changes in the mean climate conditions, the same set (i-iii) was forced by climate change projections from the available RCMs, according to the emission scenarios.

It is crucial to proper deal with the systematic errors from climate models (e.g., overestimation of
daytime temperature, Fig. 3). Therefore, a BES future climate experiment driven by a particular RCM was compared to the BES present climate experiment driven by the very same RCM. If the results of future climate experiments were contrasted to those from conducting with observations, systematic errors from the forcing RCM would be kept intact and overestimations or underestimations of the energy demand may occur. Therefore, the estimated future energy demand (FED) was calculated as follows:

\[
\Delta \text{E}_{\text{model,scenario,case}} = \text{E}_{\text{model,scenario,case}} - \text{E}_{\text{model,present,case}} \quad (1)
\]

\[
\text{FED}_{\text{model,scenario,case}} = \text{E}_{\text{OBS,case}} + \Delta \text{E}_{\text{model,scenario,case}} \quad (2)
\]

where:

\( \text{E}_{\text{OBS,case}} \) is the estimated energy demand when BES is driven by the observational dataset, for a given intervention (MJ/m²);

\( \text{E}_{\text{model,scenario,case}} \) is the estimated energy demand when BES is driven by a particular RCM, following a specific climate change scenario, and for a given intervention (MJ/m²);

\( \text{E}_{\text{model,present,case}} \) is the estimated energy demand when BES is driven by a particular RCM, under present climate conditions, and for a given intervention (MJ/m²);

\( \Delta \text{E}_{\text{model,scenario,case}} \) is the intrinsic estimated change in the energy demand when climate warms, according to specific model-scenario combination, and for a given intervention (MJ/m²). This is a bias-corrected result, where the mean systematic error of such RCM has been removed.

Equation (2) indicates that, for each case of intervention, the energy delta \( \Delta \text{E}_{\text{model,scenario,case}} \) was added to the estimated energy demand based on observations, being the result the estimated future energy demand, following a specific climate change scenario and according to given models' projections.

In addition, for each driving model, the percentage savings (S) of the RI and RWI cases in respect of BC were calculated for each scenario:

\[
\text{S}_{\text{model,scenario,intervention}} = 100 \left( \frac{\text{FED}_{\text{model,scenario,BC}} - \text{FED}_{\text{model,scenario,BC}}}{\text{FED}_{\text{model,scenario,BC}}} \right) \quad (3)
\]

3. RESULTS

3.1. Present climate

Figure 5 shows the results of the present climate experiments. They are clustered by interventions and account for the integrated energy demand under mean climate conditions.

It is evident that the original design (BC) presents the worst performance for all forcing sets. The original roof is particularly deficient, with 14% of the total ceiling made of concrete without any insulation. Therefore, upgrading the roof’s complete insulation (RI) results in approximately 50% less consumption for three out of five forcing sets (i.e., RCA, REMO and RegCM). An additional 13% of savings is obtained if the complete envelope is upgraded (RWI). RI savings ascend to 75% when forcing with WRF, and to 88% when conducting with observations. Except for WRF, RCMs overestimate nighttime temperature (not shown), which could explain the lower consumption saving that the rest of models show for RI. Lower minimum temperatures (OBS and WRF) enhance heat losses during nighttime, the house’s temperature drops and, therefore, less cooling energy is needed. On the other hand, the RWI intervention makes almost no difference for the observational set, while it produces a small increase in the cooling energy when forcing with WRF. A possible hypothesis to explain this is that WRF’s diurnal cycle presents the highest amplitude (not shown), so increasing the envelope’s insulation restricts heat losses during nighttime. Such increase in the cooling energy seems to be an isolated case for this study. However, it shows that it is crucial to analyze the temperature diurnal cycle of the city of interest since it plays a defining role on the impact of design strategies. These findings suggest that buildings placed in cities with elevated summer temperatures and high thermal amplitude could considerably benefit from just an efficient roof during summer.

Moreover, the cooling energy demand is overestimated when conducting BES with all RCMs. This is a direct consequence of the models’ warm bias during daytime hours (Section 2.1.) that shows the importance of removing systematic errors when projecting future energy demand estimations.

3.2. Future climate

Figure 6 shows the projected energy demand change for all the house prototypes during January, with bars showing the reference energy demand under mean observed climate conditions (as in Fig. 5). Analogue to present climate results, all experiments simulate the original design (BC) as the least efficient (highest FED projection). It also
becomes evident that the RWI is the best option for all scenarios, which highlights the importance of adequately insulating the house’s envelope to ensure comfort conditions.

Figure 6: Energy demand estimations to maintain temperature below 26 °C in January. Light grey bars represent the present energy demand when driven by observations for base case (BC), roof intervention (RI) and roof-wall intervention (RWI). Points illustrate the estimated future energy demand under RCP4.5 (empty) and RCP8.5 (filled) emissions’ scenarios, according to each RCM. Vertical segments define the uncertainty range for each intervention-scenario. Values in parentheses show the percentage savings range of each intervention in respect of the BC prototype under the RCP4.5 (grey) and RCP8.5 (black) scenarios. Such ranges are determined by calculating the percentage savings for each RCM-scenario driving experiment. Units are MJ/m².

For each intervention, values in parentheses show the percentage savings span of the RI and RWI cases in respect of the BC prototype under a given scenario (S, Equation 3). Such ranges are defined by calculating S for the BES experiments when driving by the individual RCMs. The RI case produces the major impact on savings for all experiments. Analogously to present climate conditions (Fig. 5), insulating the complete envelope (RWI) contributes to a lesser extent once the roof is suitable. These prototypes still require cooling energy for acclimatization, so more ambitious strategies are needed. However, the proposed interventions produce substantial decreases in the energy consumption. For the most adverse energy demand projection (RegCM, RCP8.5), RI results in savings of 26%, while RWI, of 49%. Whereas for the most auspicious projection (RCA4, RCP4.5), RI results in savings of 51% and RWI, in savings of 65%. This shows that the lower the projected emissions, the more percentage savings are simulated by the same intervention. Such result is reinforced when comparing FED projections when conducting with RCA4 and REMO (RCMs available for both scenarios). Both models simulate bigger percentage savings under the RCP4.5 scenario (values not shown). Although January shows the greatest inter-scenario gap for temperature (Fig. 2), its values do not differ much between both scenarios. However, FED estimations substantially differ between scenarios, as their uncertainty range stretch from RCP4.5 to RCP8.5: going from around 12-21, 6-13 and 4-10 MJ/m² for the BC, RI and RWI cases to 24-37, 17-27 and 12-19 MJ/m², respectively. Interventions’ uncertainty ranges widen as the GHG emissions increase, becoming more difficult to evaluate the impact of proposed strategies. However, uncertainties are reduced when the house’s efficiency enhances and experiments begin to converge.

4. CONCLUSION

The Built Environment and its energy demand are projected to keep growing [5], so migrating towards low energy and zero-carbon new buildings, and improving the efficiency of already existing building stocks is essential. Building Energy Simulation (BES) is a powerful tool that allows analyzing a house’s performance and its response to climate. Therefore, a key component of BES is its forcing weather file. To assess climate change impacts, future weather files must be based on climate models’ projections, which have high levels of uncertainty associated to their reproduction of the climate system and the estimation of GHG emissions. Thus, a methodology to create weather files based on high frequency outputs from climate models was proposed in this work. Such approach maintains temporal coherence and consistent climate variability, and allows to evaluate BES results and their uncertainties. The generated weather files were used as BES forcings to evaluate design improvements and estimate future energy demand projections for a social dwelling in Rosario city (Argentina). Three cases were evaluated for present climate conditions and under climate change projections from the RCP4.5 and RCP8.5 emissions scenarios: the original prototype (BC), a roof-intervened case (RI, insulation in roofs was increased) and a roof-wall-intervened case (RWI, the envelope’s insulation was increased).

For present conditions, it was found that the RWI proposal (which encloses the RI one) is the most efficient one. However, the RI intervention produces the major percentage savings in respect of the BC case. The main reason for this is that the original design’s roof is inefficient and our results remark the importance of an adequate roof to reach comfort conditions, since it limits heat transfer due to incident solar radiation. In addition, the cooling energy demand was overestimated when conducting BES with climate models, a direct consequence of the warm bias such models show during daytime hours.
Such systematic errors were removed when projecting future energy demand estimations. Analogously to the present period results, although the RWI prototype is the most efficient under all climate change projections, the RI one produces the major impacts. Savings are about 44% (RCP 4.5) and 29% (RCP 8.5) for the RI case; and about 59% (RCP 4.5) and 51% (RCP 8.5) for the RWI one. The experiments depict a greater percentage impact of the same intervention as GHG emissions decreases, which highlights the advantages of cutting off emissions. However, these interventions are not enough to turn off acclimatization systems, so more ambitious strategies are required. For instance, cross-natural ventilation and its efficiency under climate change projections is an essential resource during warm months to be studied in future work. It is clear, though, that analyzing local climate variations makes the most of the planning stage.

As the building’s efficiency enhances, experiments converge and the inter-model span narrows. This occurs likely because the house’s thermal behaviour becomes less sensitive to climate variations. On the other hand, as GHG emissions increases, so does the experiments’ uncertainty range and evaluating climate change impacts becomes more difficult. The use of additional RCMs would help coping with this, at the expense of a higher computational demand. However, our findings highlight the advantage of working with the greatest variety of RCMs as possible since it provides a more robust approach to evaluate impact studies.

We discourage the use of a models’ ensemble mean as unique forcing to BES experiments because valuable information regarding the uncertainty generated by each model’s outputs is lost. This specially happens during cold months, when the models’ temperature span widens. However, such approach is currently under study, as well as analyzing whether our results maintain throughout the whole year.

This research analyses mean cooling energy demand projections under climate change scenarios. Further studies are being pursued in order to evaluate energy consumption peaks projections due changes in the frequency of occurrence and in the characteristics of extreme events (e.g., heat waves).

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REFERENCES

Assessing Buildings’ Adaptation to Climate Change
The case of a winery at design project stage.

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ABSTRACT: This paper presents the thermal and energy analysis of a winery project in the current situation and in 3 tentative scenarios (2020-2050-2080). The winery will be build in the Uco Valley, a cold inter-mountain valley in Province of Mendoza (33° 34´ 57.4 "SL; 69º 02´ 47.8" WL and 1,025 masl) (GD base 18 = 1963 / GD base 20 = 2466). An Energy Plus model of the architectural proposal was made with the current climatic conditions, and in the future according to scenario A2 of the IPCC. Meteorological conditions were adopted using one of the IPCC GCMs. EPW files were generated by Climate Change World Weather File Generator (CCWorldWeatherGen, University of Southampton). According to the initial project, current consumption was estimated at 35.70 kWh/m² (135,374.40 kWh year), and when the proposed improvements were made to the envelope consumption was halved to 18.28 kWh m² (69,317.76 kWh year). With these results, future consumption is evaluated in the three mentioned scenarios. The building with improvements turns out to be resilient and adapts to climate change, maintaining the energy consumption of refrigeration throughout its useful life, unlike the initial project in which energy consumption for refrigeration tripled by 2080.

KEYWORDS: thermal and energy simulation, future climate, climate change, resilience.

1. INTRODUCTION
The prediction of thermal and energy behaviour of buildings at the design project stage, that is prior to its construction, allows the design of a better response to the climate of the site. It is possible to evaluate different options in order to reduce energy consumption for the functioning of the building that will impact for many decades, even a century, on the economy and on the environment. These assessments will ensure the construction of a building resilient to climate change. In this work, a winery project in the Uco Valley, Province of Mendoza, Argentina is analyzed.

Wine production is the most important regional industry since it corresponds to an emerging economy, and therefore its energy consumption multiplies every year. From 2000 to 2009, the area cultivated with vine plants went from 201,113 hectares to 228,575 hectares. In 2000, the quantity of high-quality grapes produced was 1,275,772 tons, in 2013 this figure increased to 1,997,442 tons and it increased again to 2,568,726 tons in 2018, marking a clear growing trend. [1 - 3]

The Ministry of the Environment, Rural and Marine Affairs [4] carried out a survey of energy consumption in 20 wineries. It reports that the electrical consumptions of the studied wineries are in a range between 28,718 and 709,257 kWh per year, and that on average they consume 275,691 kWh of electric power per year. There are wineries that consume only 10% of the average energy consumption and others that consume three times the average energy consumption. The considerable variations depend on the size of the winery, but mostly on design decisions concerning orientation, shape and materiality. It is evident the opportunity to reduce energy consumption by improving the architecture of the building.

First studies carried out in wine establishments in the North Oasis of the Province of Mendoza, Argentina (33° 34’ 57.4" SL; 69º 02’ 47.8" WL and 1,025 masl) during the harvest season (January-February-March for the South Hemisphere) clearly demonstrate the potential of integration of passive thermal conditioning strategies in the architectural envelope. [5]

In the harvest season, the demand for refrigeration is higher because tons of raw material (around 26-30ºC of temperature) must be processed at 8ºC, while outside temperatures are around 38ºC. With consumption in the order of 100,000 kWh per month (January, February and March) of non-renewable auxiliary energy, indoor temperatures still remain around 18ºC. To achieve desirable stable indoor temperatures of 15 ºC would require consumptions in the order of 390,000 kWh (only for these three months). [6]

Likewise, it has been demonstrated that the level of interior temperature necessary for the production of wine (15ºC), in some cases, is feasible to be reached only with passive strategies integrated in the architectural envelope. Some interesting options to
consider would be to locate the most thermally compromised spaces in underground cellars, and also adding sun screen protections, thermal insulation and nocturnal ventilation to aboveground spaces.

To carry out a comprehensive energy analysis of a building, dynamic simulation programs are used. In this regard, Crawley et al. [7] exposed in ASHRAE JOURNAL that various energy simulation programs developed throughout the world are reaching maturity. Many use simulation (and even code) methods originally developed in the 1960s. Without substantial redesign or restructuring of the program, continuing to expand its capabilities is difficult, time-consuming, and prohibitively expensive. However, phenomenal advances in analytical methods and computational power have increased the opportunity for significant improvements in the flexibility and comprehensiveness of these tools.

Likewise, in addition to the aspects contemplated in the different regulations stated, in this work it is proposed to work with evaluations that include in the thermal and energy prediction different climatic situations in the future to be able to assess the resilience that the building will have once built against adaptation to climate change. Resilient design aspects are important in reducing negative climate impacts (mitigation) as well as preparing for extreme events resulting from climate change (adaptation). Climate change must be holistically addressed by merging resilience and sustainable strategies into an encompassing adaptation strategy. [8]

2. METHODOLOGY

The methodology follows the recommendations of the International Energy Agency (IEA) in its Annex 21 “Thermal Response Test” [9] that develops the concept of a “performance assessment method” (PAM). A PAM is a guide to evaluate the building performance through the energy simulation of a building, which requires the establishment of a basic design case, the calibration of the model, the evaluation of the boundary conditions, the identification of problems, the generation of possible solutions and their evaluation. In this paper, simulations were performed with the Energy Plus software version 9.3. [7]

2.1 Dynamic Simulation with Energy Plus steps
- Preparation of an EPW statistical climate data file for the site where the project will be built.
- Preparation of a library of physical properties of materials.
- Generation of a geometric physical model in Open Studio
- Identification of 22 thermal, energy zones.
- First general run of 1 year duration: 8760 hours.
- Assessment of results and recommendations for improvement.
- Development of a new library of physical properties of materials.
- Second general run of 1 year duration: 8760 hours.
- Work with models of future climates.
- Analysis of sustainability and resilience of the results obtained. Possibilities of the winery to adapt to climate change.

2.1 Climate and future climate models

The meteorological data used to build energy simulations are generally based on current or past weather conditions. However, most buildings have a lifespan of several decades, during which the climate can change gradually [10]. It would be convenient that building energy simulations incorporate predictions to ensure that buildings adapt to future conditions.

In Argentina a comparison of temperatures between 1961 and 2016, displayed in Figure 1, indicates that the annual mean temperatures increased throughout the country between 0.3°C and 2°C, being the higher increments in West Patagonia. The exception is the central zone, where the annual mean temperature remained constant, probably due to higher cloudiness and precipitation levels. In summer (December to February), the mean maximum temperature increased between 0.3 °C and 2°C. As in the annual average, higher increments were in the West Patagonia region and the exception is the central zone where it decreases between −0.3 and −1 °C. In winter (June to August), average maximum temperature increased between 0.5°C and 1°C. The most affected regions were the Patagonia (South), the Andean region (West) and the Littoral (North-east). Future projections for Argentina indicate that the observed tendencies described below will deepen in the future. [11]

Projections by the end of the 21st century show both, an increase of mean temperature ranging from 1.5 to 5.5 °C (depending on the season and region, with the highest increases over subtropical latitudes), and an increase of precipitation in central Argentina. This regional model also projects a maximum temperature increase (between 4 and 5 °C) over subtropical latitudes mainly during spring. [12 - 13] In the middle of December 2013, an intense heat wave began that lasted, with few interruptions, until almost mid-January. It covered the centre of Argentina: from Buenos Aires to Córdoba and Mendoza, with maximum temperatures above 40 °C and minimums greater than 24 °C. It was the longest and most intense recorded in the region. The distribution of electricity collapsed in many sectors of the metropolitan area of Buenos Aires.
Climate projections indicate that there will be an increase in days with heat waves in most regions of the country. The projected increase in the number of days with heat waves would be greater in the North, and especially in the North-west of the country, where it would increase by more than 60 days in the near future. As the North of the country is the region with the greatest social vulnerability to disasters, it would be the region with the greatest risks of social impacts due to heat waves. [15]

For the creation of meteorological scenarios, the Climate Change tool WorldWeather File Generator (CCWorldWeatherGen) developed by Sustainable Energy Research Group, University of Southampton was used.[16] This tool allows to generate hourly weather files in ".epw" format for EnergyPlus based on the future monthly climate data predicted by HadCM3 for scenario A2 of the IPCC. [17]

Scenario A2, is characterized by simulating a heterogeneous world with independent self-sufficient countries, continuous growth of the population and an economic development oriented to the region.

Comparing the temperatures between the TMY, 2020, 2050 and 2080 scenarios, annual values show that climate would increase its temperatures towards 2080. The most compromised values would be the minimum average temperatures, since the difference between the TMY and the 2080 scenario exceeds 4.50 °C. Average maximum and average temperatures increase on average 3.10 °C and 3.6 °C respectively. See Figure 2 for a graphical comparison.

3. CASE STUDY

This work presents a project of a winery of 3792 m², distributed 1867 m² at the underground level (semi-buried) and 1925 m² at the ground level.

The different stages corresponding to the production of the wine and the operation of the winery are detailed below subdivided into 5 groups:

1. Fermentation: 870 m² (ground level)
   The temperature is more important in the containers than in the building as a whole. Tubes are placed between the double walls of the vats where the fermentation takes place. Then, hot or cold water is circulated, depending on the process need.
   - CO₂ is released by chemical reactions. Due to its higher density, it falls and accumulates near the floor where there must be a constant ventilation.
   - Occupation: 0.01 person per m².
   - Thermostat: Without thermostat.
   - Total renovations: 1.50/hour.
   - Mix of airs between zones: 1/hour always on.

2. Breeding: 579 m² (underground)
   From this phase on, stability is important within the following reference ranges:
   - Air temperature between 12-16 °C.
   - Relative humidity within the margins 70-82%.
   - Minimum light.
   - Occupation: 0.01 person per m².
   - Thermostat: 15 - 17 °C.
   - Total renovations at 0.50/hour.
   - Mix of airs between zones 1/hour always on.
3. Aging: 644m² (underground)
Keeping the four parameters (temperature, humidity, lighting and ventilation) stable and controlled is essential to ensure that the wine turns out well. Since the wine is bottled at this stage, it will no longer be touched until it is ready.
- Air temperature between 12-16 ºC.
- Relative humidity in the margins 70-82%.
- Very low lighting levels. The wine is in a glass bottle that lets the light through, especially the ultraviolet rays, which affect the final quality of the product.
- Occupation: 0.01 people per m².
- Thermostat: 15 - 17 °C.
- Total renovations at 0.50/hour.
- Mix of airs between zones 1/hour always on.

4. Offices and Tourism: 719 m² (ground floor)
These spaces are above ground and are prepared to receive the visitor or tourist. They also include spaces for the staff of the winery.
- Occupation: 0.02 people per m².
- Thermostat: 20 °C - 24 °C.
- Total renovations at 0.50/hour.
- Mix of airs between zones 1/hour always on.

5. Machine room and warehouses: 980 m²
- Occupation: 0.01 people per m².
- Thermostat: without thermostat.
- Total renovations at 0.50/hour.
- Mix of airs between zones 1/hour always on.

4. RESULTS AND DISCUSSION
In the case of the winery under study, the U value of the original project is 3.89 and the U value of the original project is 0.843 in the case of the improved project. The Argentine IRAM 11604:2001 Standard [18] establishes a maximum admissible U for the climate of the place of U = 1.16, so that the proposals for improvement are framed within the requirements of the aforementioned regulations.

Figure 2. Comparison of TMY, 2020, 2050 and 2080 scenarios. From left to right: (a) Minimum temperatures, (b) Maximum temperatures and (c) Average temperatures. Source: Own.

Figure 3. TMY consumption in kWh m². From bottom to top: (a) Original Project and (b) Improved Project. Source: Own.
According to the initial project, energy consumption was estimated at 35.70 kWh/m² (135,374.40 kWh year), and when the proposed improvements were made to the envelope, consumption was halved, to 18.28 kWh/m² (69,317.76 kWh year). See Figure 3.

Based on these results, future consumption in the three tentative scenarios 2020, 2050 and 2080 is evaluated. In Figure 4 the results can be observed respectively in a comparative way.

The estimated consumption for the year 2020 results in a consumption of 30.55 kWh/m² (115,845.60 kWh year) in the case of the original project and 16.82 kWh/m² (63,781.44 kWh year) in the improved project case. In the case of the prediction of energy consumption for the year 2050, the original project would consume 27.96 kWh/m² (106,024.32 kWh year) and the improved project 15.02 kWh/m² (56,955.84 kWh year). And, in the case of the estimated consumption for the year 2080, the original project would consume 24.85 kWh/m² (94,231.20 kWh year) and the improved project 14.12 kWh/m² (53,543.04 kWh year).

Note that as it is a cold climate, the temperature increase predicted by the climate prediction in three future scenarios is favourable in terms of total building consumption. In the case of the original project, heating consumption is reduced from 6.3 kWh/m² in the current month of July (TMY) to 4.3 kWh/m² in the month of July in the 2080 scenario. However, consumption of refrigeration tripled in the month of January respectively. (From 0.5 kWh/m² in the current month of January (TMY) to 1.3 kWh/m² in the month of January in the 2080 scenario).

4. CONCLUSIONS

Figure 5 presents a comparison between the total energy consumed per kWh/m² in the four compared scenarios in the case of the original project and in the case of the project with improvements.

Under the conditions of this study, the thermal transmittance of the envelope seems to have the greatest impact on thermal flexibility. It was also observed that the thermal mass has a secondary influence for the evaluated indicators; its variation
only affects the thermal flexibility if the thermal resistance of the envelope is sufficient.

This type of analysis is interesting in the case of industrial buildings dedicated to wine production in which the internal temperature requirements are different from those that should be considered in the case of the permanence of people (as is the case of housing, schools, offices, among others). In the analyzed case, this type of environments, with fixed thermostats between 20°C and 24°C, represents only 19% of the total m2 involved in the project.

In conclusion, the building with improvements turns out to be resilient and adapts better to climate change (according to the A2 emissions scenario of the IPCC) maintaining the energy consumption of refrigeration throughout its useful life, unlike the initial project in which the Energy consumption of refrigeration triplicates by the year 2080.

**Figure 5. Comparison of the total energy consumed in kWh/m². From top to bottom: (a) Original Project and (b) Improved project.**

**REFERENCES**


ABSTRACT: We describe the energy simulation of an urban neighborhood in Austin, Texas, consisting of about 650 buildings for multiple building refurbishment cases from the present to the year 2100, with consideration of climate change in that timeframe. The simulation considers not only building energy performance, but also building overheating in an ongoing blackout scenario. The results of the simulation are a) an overall energy use reduction of up to 13% annually by 2040 with improved glazing and insulation alone, b) an increasing magnitude of overheating in buildings during possible future blackouts, exacerbated by high performance insulation and glazing, and c) a notable disparity between the performance of West Campus buildings, depending on their use type.

KEYWORDS: Climate Change, Urban Energy, Overheating

1. INTRODUCTION

Buildings are responsible for 30-40% of global greenhouse gas emissions [10], and local governments are setting ambitious targets to reduce this impact [3]. The two major paths to improve the energy performance of buildings are improving the envelope insulation and increasing the performance of the indoor thermal system [4]. While 70% of the carbon reduction can be achieved in the non-residential sector [16], the residential sector still represents 60% of total energy consumption [1]. Therefore, the focus must be laid on all building types simultaneously. With increased temperatures due to climate change, the energy demand, especially during the cooling season will increase and potentially exacerbate resultant greenhouse gas emissions.

The aim of this paper is to investigate the impact of global warming scenarios on urban building performance, and the impact of mitigation potentials in the building stock. Recent findings have made it evident that common energy use mitigation strategies may not have lasting efficacy in the impending climate change conditions of San Francisco and Philadelphia [13]. In examining this problem, it is pertinent to measure not only the energy performance of the building stock, but the performance of buildings and livability of the indoor environment in the case of a disaster.

To accomplish this, we superimpose a climate scenario for the 21st century as projected by the Intergovernmental Panel on Climate Change (IPCC) with building refurbishment (envelope and windows) and evaluate both urban energy demand and building overheating in the West Campus neighborhood of Austin, TX. This neighborhood reflects well the building stock in Austin, composed of a mixture of many different building typologies, e.g., single and multi-family homes as well as offices and retail with varying ages: many of the buildings are from the 1960s or earlier, while most of the multi-family housing buildings having been developed and constructed in the past ten years to meet growing housing demand. The neighborhood itself is located adjacent north of Downtown Austin, and adjacent to the University of Texas main campus.

Building energy simulation at the urban scale is useful to obtain information about the potential energy behavior that cities can achieve [17]. Typical urban energy simulation studies use simplified models, i.e., archetypes for buildings, and show the impact of refurbishment only with respect to typical weather data. Additionally, there still exists a shortage of approaches that can quickly model multitudes of urban-scale scenarios with many predictands and variables [14]. In using a neighborhood that contains a diverse array of building types built over a span of many decades, we can model the individual characteristics. In addition, adjacencies of the buildings is also a concern as urban geometry is known to have a major effect on the comfort and energy profile of a city [9, 15.]
2. METHODOLOGY

2.1 Urban Energy Model

We combine a GIS database of Austin buildings with CitySim, a large-scale urban energy simulation tool that takes into account the urban area and surrounding buildings using Rhino/Grasshopper. The database contains footprints, heights, year built as well as building use type. The final West Campus neighborhood consists of 651 buildings (Fig. 1).

We used a year-built approximation to generate construction material properties. Each material group contains a different set of wall, window and roof assemblies. Tables 1 and 2 shows these data for the reference building stock (no refurbishment) based on the construction period (before or after 2000). Material assemblies were taken from [5]. For the refurbishment case, we used wall, roof and window material reflecting LEED Gold material standards.

<table>
<thead>
<tr>
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<td>0.1586</td>
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</tr>
</tbody>
</table>

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<tr>
<td>Refurbishment Scenario</td>
<td>Gyp Board</td>
<td>0.012</td>
<td>0.1586</td>
<td>1130</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Construction materials for wall assembly

<table>
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<tr>
<th>Reference (No refurbishment)</th>
<th>Period</th>
<th>U-value [W/m²K]</th>
<th>G-value</th>
<th>Type</th>
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<tbody>
<tr>
<td>Before 2000</td>
<td>4.8</td>
<td>3.1</td>
<td>0.45</td>
<td>Single Glazing</td>
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<tr>
<td>After 2000</td>
<td>3.1</td>
<td></td>
<td>0.45</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Glazing parameters for windows

GHCitySim, an extension for Rhino3D’s Grasshopper, was used to transfer the various facets input from the database to CitySim [11], especially to geometric data. Since GHCitySim runs in a parametric 3D modeling environment, the data parametrized. GHCitySim also utilizes functionalities from Honeybee and Ladybug [12]. In short, the process consists of collecting all the building information in Grasshopper, such as geometry, material info, occupancy info, and shading/ground surfaces so that GHCitySim can write a CitySim markup file to be used for the simulation.

The following limitations are applied: 1. each building was simplified to a single thermal zone. 2. Window cover was assumed to be a single general window-to-wall ratio across all wall surfaces. 3. 50% of the windows in each building are considered to be operable. 4. All roofs are considered flat.

2.2 Methods for Scenarios and Analysis

Figure 2 shows the average daily temperatures, including highs, means and lows, across the entire year in Austin are shown for three different climate scenarios developed by the IPCC. In order to model the maximum potential of mitigation strategies in West Campus, we use the B1 scenario, and assume for refurbishment cases that the entire building stock
would be retrofitted by 2040. For the reference year, we used climate data reflecting the typical meteorological year (TMY3) representing an average of decades of data, mostly from the latter quarter of the 20th century. For climate data on future SRES climate change cases, data was obtained from Meteonorm.

In preliminary testing, we examined the impact of complete building refurbishment in three separate improvement categories: glazing, insulation, and infiltration. Each of these three categories were improved individually, with glazing and insulation affecting the material profile of their respective materials according to their refurbishment values, and infiltration being a direct reduction in the air leakage value for each building, from a normal/reference value of 0.377/h to a refurbishment value of 0.176/h. From the three individual cases, glazing and insulation proved to have much higher individual impact than air leakage. As a result, the refurbishment cases considered for the simulation were the following: reference/no refurbishment, refurbished glazing, refurbished walls, and refurbished glazing and walls. Mechanical heating and cooling setting were kept to their default settings in CitySim.

Two types of results are analyzed representing different targets: energy demand and indoor temperature. Energy demand is analyzed for regular building HVAC operation. For indoor temperature we simulate the case of an ongoing electrical blackout, the occurrence of which increases with climate change due to the increased probability of occurrence and intensity of natural disasters, such as hurricanes and floods, which can cause a collapse in the electricity grid. The resulting potential overheating in buildings can create life threatening conditions, especially in the vulnerable population.

3. RESULTS

Figure 3 shows the annual consumption per area of all buildings. Each of the refurbishment cases has a distinct impact on the energy performance of the neighborhood as a whole. The reference case shows a considerable increase in energy consumption between the typical mean year and 2040, with a steady increase from 2040 onward. In the reference year for all scenarios, average energy consumption was found to be roughly 73.5 kWh/m². By 2040 in the base case, that number rose to 109.8 kWh/m², representing a 48% increase in energy consumption, and by the year 2100, the reference case had reached 123.5 kWh/m², representing an overall energy consumption increase of over 67%. The impact of climate change in this scenario is also shown to have the effect of exaggerating the energy consumption of the least efficient buildings proportionately, thus increasing the spread of consumption values. Between the reference year and 2100, the range where the median half of buildings fall grows by over 70%.

The refurbishment of wall material returned similar energy performance patterns to the reference case, though of a smaller magnitude. As opposed to an increase of over two thirds in the reference case the mean energy consumption increases by around 41% by 2100, or 104.0 kWh/m². The glazing scenario, however, showed the highest energy performance increase of any single refurbishment factor. Here, the spread of consumption values is much lower, accounted for by the different glazing materials of the reference case all being resolved to the same low-e glass type under the refurbishment. Building energy consumption still increases steadily through the warming scenario, however, rising to 92.9 kWh/m², 26% greater than the reference case.

The full refurbishment case was the only case that decreases overall energy consumption by 2100 compared to the TMY. Energy consumption values from 2040, the refurbishment deadline, returned a reduction of 13%, or 63.7 kWh/m². As with the other cases, cooling needs increased over time, building to an average yearly consumption rate of 72.3 kWh/m² – still roughly 1 kWh lower than the reference. Additionally, this case was the only instance where the set of energy consumption values shrank significantly in range, with 50% of buildings falling between 43.1 and 95.7 kWh/m², a range 13% narrower than the base case.

Figure 2: Climate change scenarios in Austin,
Figures 4 shows the average high temperatures during the hottest 90 days of the year without HVAC to understand the potential of overheating. For the reference case and TMY weather, we find high temperatures averaging 37 °C indoor temperature. Without refurbishment, these extreme temperatures increase, much like energy consumption does, with an increase between the TMY and 2040, and then a steady increase from 2040 to 2100. By 2100, mean daily highs in West Campus buildings are projected in the model to increase to 40.1°C on average for the hottest 90-day period.

In the full refurbishment case, overheating is projected to be much more exaggerated due to retention of heat in the more insulation buildings. By 2100 indoor high temperatures averaged 41.7 °C across all buildings, a 4.6° increase over 80 years. This represents an increase of more than 50% over that without refurbishment. The buildings that are more affected by overheating in general are also much more prone to suffer from runaway indoor heating in this case. With refurbishment, the upper quartile of buildings averages 42.7 °C during the hottest 90 days. Extreme indoor temperatures in the upper quartile rise over 68% more rapidly than in the no-refurbishment case.

Heat retention due to refurbishment is observed to affect West Campus buildings during the coldest 90 days as well (data not shown). In the reference case during a typical year, the average indoor low temperature is projected to be 5.92 °C. Without refurbishment, the indoor low rises to 8.7 °C on average by 2100. Similar to the overheating cases, this indoor temperature increase is more marked in the refurbishment case, with mean indoor low temperatures at 9.44 °C by 2100, representing an increase of 27% over the no-refurbishment case.

Figure 5 shows the average overheating potential by building type. We identify a correlation between building type and propensity for overheating. The division is clear in all three cases, but is especially pronounced in the 2100 refurbishment case, which, unlike the other cases, contains no variation in material throughout the building stock. For each of the different types, building geometry and occupancy are both possible predictors for their performance relative to each other. Multi-family housing buildings, which comprise the most massive buildings in the neighborhood with the lowest surface-to-volume ratio, perform most favorably in this case, with overheating temperatures over 1.5 °C lower than average.
The next best performing category are single family homes, a group comprised of typical mid-20th century suburban one-story homes. Many of these houses are sited in the westmost reaches of the neighborhood, at relatively wide suburban space intervals. Office buildings, which perform somewhat worse than average, are sometimes situated in reclaimed single-family houses, and in other cases resemble typical retail buildings. Retail buildings, which overheat more on average in all refurbishment cases, consist mostly of buildings along the eastern edge of the neighborhood that are relatively low and flat, have longer sides on their east and west faces, and are more densely occupied.

The differing impact of overheating between different building usage types in this study is, in some cases, of higher magnitude than that of all other predictors. In the 2100 refurbishment case, the average retail building was over 5 °C hotter than the average multi-family housing building, topping out at an average of 45.5°C.

4. DISCUSSION

It is significant that the ‘full refurbishment’ case is the only scenario in our simulation where the energy consumption of West Campus is reduced, even in a ‘best case’ climate change scenario. The City of Austin government has set goals to make new homes net-zero capable, in line with becoming entirely net-zero community wide by 2050 [2]. In working toward an overall goal of energy use reduction in buildings, the full refurbishment case’s energy use reduction of 13% by 2040 (offset to only 1.5% by 2100) would, alone, hardly be adequate.

The results shown in the overheating scenarios outline a potential disaster condition that could be very real for residents of West Campus and other urban environments within coming decades. For the last 20 years, concern has risen about the effect of climate change on energy critical infrastructure worldwide [6]. Overheating due to a high performing building envelope should be a major consideration when planning new constructions. Though the possibility of a prolonged blackout situation in a city with currently stable energy infrastructure like Austin is unlikely, the possibility of impact is real, and mitigation factors should be considered by architects, engineers and planners. The situation could be very dangerous: the temperatures found in this study in all cases are considered to be dangerous for people at risk of heat stroke [8].

5. CONCLUSION

Both types of building qualities discussed in this paper (envelope material and building typology) have an impact on building performance and disaster risk mitigation in Austin. Our results suggest that retrofit of materials alone is not a sufficient response to meet future performance goals. On the other hand, the relatively high performance of the multi-family residential buildings show that those buildings yield a general improvement over most others. They are not only more energy efficient, but also less prone to the extremes of overheating in an ongoing blackout.
It is thus evident that planners and designers in Austin and other cities should form a multilateral approach to building performance, characterized by both passive and active solutions that respond to climate change conditions holistically, as opposed to only reducing energy demand.

REFERENCES
Morphology Design of University Campus for Energy Saving Based on Multi-objective Optimization in Cold Region of China

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ABSTRACT: The energy consumption of buildings in winter is huge in cold regions. This paper focused on the conceptual design stage of campus buildings in cold regions of China, extracted the building prototypes of centralized, L-type, semi-enclosed and enclosed through the morphology survey of 10 university campuses in northeast of China. From the aspects of energy dissipation and passive solar radiation utilization in winter, the multi-objective optimization program was established by Rhino and grasshopper to realize the parametric modelling of prototypes and the calculation of building shape coefficient and the solar radiation in winter. After 26 generations of calculation by evolutionary algorithms SPEA2, more than 200 sets of optimal solutions were obtained for each prototype, which significantly reduced the building shape coefficient and improved the building surface solar radiation and achieved the overall objective of optimizing energy saving in winter.

KEYWORDS: University campus morphology, Energy saving, Multi-objective optimization, Cold region

1. INTRODUCTION
The climate of large inland areas between 45-40 degrees north latitude in China is cold with long winter. The average temperature in January reaches -15 to -30 centigrade. It has a heating period of nearly half a year. Energy saving design of buildings has become an important issue.

After the peak period of the construction of campus buildings in China from 1995 to 2015, the functions of campus buildings have been continuously improved, and the layout and form of campus buildings have shown certain distribution rules. In order to further improve the energy saving performance of the campus, this paper focused on the campus buildings morphology in cold regions of China, through the survey of the campus buildings, the morphological prototypes are extracted and evaluated aiming at energy saving.

Earlier studies have been done on energy utilization and saving of university campus based on regional climate [1]. For campus building in the daily operation stage, Lopez-Rodriguez F (2011) carried out the research on the utilization strategy of renewable energy under extreme weather conditions [2]. Through reducing the heat island effect of the external space of the campus in hot regions, Kong F (2016) presented a new and simple approach to quantify potential energy savings due to the temperature-regulating ecosystem services [3]. In addition, passive energy such as solar energy was introduced to reduce the energy consumption of campus building through the optimization of energy system [4]. However, there is still a lack of energy saving research on campus buildings in the architectural design and conceptual stage, and the research on cold climate conditions.

In order to improve the energy-saving performance of campus buildings in winter, it is necessary to minimize the heat dissipation of the building volume, and maximize the passive utilization of the solar radiation, which forms a problem of dual objectives and optimization. In the related research, it is necessary to evaluate the optimization level of each objective in order to achieve the overall optimization. In the field of economics, Pareto frontier theory was put forward to solve this problem, and non-dominated solution set was put forward to evaluate different optimization objectives [5]. Evolutionary algorithms were proposed, which can be used to accelerate the calculation process of optimization[6-7]. In the architectural research, the multi-objective optimizations were also carried out concerning the building energy consumption [8-9]

2. METHODOLOGY
2.1 Study area
This study focused on campus buildings in Northeast China influenced by the severe cold climate. The average temperature in January is lower than -10 centigrade, and the average temperature in July is lower than 25 centigrade. Taking Harbin as an example, the annual hourly average dry-bulb temperature is 4.12 centigrade, and the annual solar radiation is
1274338kwh. The temperature distribution and solar radiation are shown in the Figure 1 and Figure 2.

Figure 1 Annual hourly dry-bulb temperature

Figure 2 Annual hourly solar radiation

2.2 Evaluation index of energy saving

From the perspective of energy dissipation and absorption under natural conditions. For one thing, it is to reduce the heat dissipation of building volume in winter, and it was evaluated by shape coefficient in this study. The smaller the shape coefficient is, the better the energy saving performance is. For another, the amount of solar radiation received by the building surface was evaluated. The more solar radiation received on the building surface during the heating period in winter, the more conducive to energy saving.

(1) Shape Coefficient

Shape coefficient is the ratio of the area exposed to the air and the volume of the building. It is an important index for evaluating building energy efficiency. It can be calculated by the sum of building surface area divided by building volume.

\[
T_x = \frac{F}{V}
\]

\(T_x\): Shape coefficient; \(F\): Surface area of building; \(V\): Volume covered by the surface of the building.

(2) Solar radiation calculation

Solar radiation (Globaltot) is the main way of passive energy utilization of buildings. In this study the solar radiation of building surface is calculated by simulation, based on the Ladybug plug-in from Grasshopper on the Rhino 6.0 platform. The climate data of Harbin (45.77°N, 126.68°E) was obtained from the EnergyPlus Weather file(.epw). The analysis period was from October 20 to April 20 which is the heating period of Harbin city. Because the octopus plug-in seeks for the minimum value of the target by default, the sunshine radiation was multiplied by - 1 as the optimization target value.

2.3 morphology parameters

In this study, 10 university campuses in Northeast of China were selected and surveyed through the satellite image data (Figure 3). Through the simplification and extraction of campus building morphology, the prototypes of campus building were obtained.

Referring to the morphological classification method of Martin Research Center of Cambridge University for European urban pattern in 1972[10], describe the different building prototype by the parameters of the length(L) and width(W) of the outline of building, the height(H) and the depth(D) of the building. And established the parametric model by the Grasshopper on the Rhino 6.0, so that the building prototypes can change with the morphology parameters. The variation range of each parameter was obtained from the survey of university campuses (Table 1).

Table 1: Parameters settings

<table>
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<th>Decision Variables</th>
<th>Unit</th>
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<tr>
<td>depth(D)</td>
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2.4 Multi-objective optimization

The multi-objective optimization was based on evolutionary algorithm SPEA2[7], and the parametric program was established by Grasshopper on the Rhino 6.0 platform, so that the morphology of building prototypes and optimization objectives can be linked and evaluated constantly(Figure 4). The optimization calculation consisted of four steps. The first was to establish a parametric building prototype model, the second was to calculate the shape coefficient based on the model, the third was to calculate the solar radiation on the building surface through simulation, and the fourth was multi-objective optimization calculation. The octopus tool set was used to load the SPEA2 evolutionary algorithm, and the optimization algorithm settings are shown in the Table 2.

Table 2: Optimization algorithm settings

<table>
<thead>
<tr>
<th>Elitism</th>
<th>Mutation Probability</th>
<th>Mutation Rate</th>
<th>Crossover Rate</th>
<th>Population Size</th>
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3. RESULTS AND ANALYSIS

3.1 Morphology simplification

Due to the diversification of functions, campus buildings have different requirements for space scale and natural daylighting, showing different types of building form. According to the layout of buildings in the campus, the campus buildings are divided into two main types: centralized and enclosed. For example, large public spaces such as libraries, gymnasiaums, canteens, etc. mostly use centralized layout, while teaching buildings and dormitories usually appear as determinant and enclosed form.

The building morphology in university campus was simplified into four prototypes: centralized, L-type, semi-enclosed and enclosed (Table 3).

<table>
<thead>
<tr>
<th>Typical campus</th>
<th>Centralized</th>
<th>L-type</th>
<th>Semi-enclosed</th>
<th>Enclosed</th>
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<tr>
<td>Harbin Institute of Technology</td>
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</table>

3.2 Calculation of objectives

By calculating and comparing the variation law of building shape coefficient with volume ratio under different layout modes, it was found that the centralized and four-sided enclosed types have lower shape coefficient, that is, they have advantages in energy dissipation, and the smaller the volume ratio, the more obvious the advantages(Figure 5).

<table>
<thead>
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<td></td>
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<tr>
<td>D=50</td>
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</tbody>
</table>

Figure 5: Shape coefficient change with volume ratio.

3.3 Multi-objective optimization

After 26 generations of optimization calculation for each building prototype, the objectives of shape coefficient and solar radiation had achieved significant optimal results. Over 200 sets of non-dominated solutions in the form of points formed the Pareto frontier. Each point represented a case of prototype. The closer located to the coordinate origin, the better the optimization performance was. With the calculation of generations, the point kept approaching to the origin. The high-density distribution area of the red dots represented the concentration area of the optimal solutions. The objective values distribution of optimal solutions was different according to the different prototypes.

(1) Centralized prototype

379 sets of optimal solutions were obtained. The value of shape coefficient was distributed between 0.08-0.27. The solar radiation on the building surface was increased from 212.41kw · H / m² to 250.91kw · H / m². The distribution of optimization solutions is shown in the Figure 6.

(2) L-type prototype
238 sets of optimal solutions were obtained. The value of shape coefficient was distributed between 0.23-0.42. The solar radiation on the building surface was increased from 212.27kw · H / m² to 250.52kw · H / m². The distribution of optimization solutions is shown in the Figure 7.

(3) Semi-enclosed prototype

222 sets of optimal solutions were obtained. The value of shape coefficient was distributed between 0.23-0.41. The solar radiation on the building surface was increased from 156.70kw · H / m² to 225.27kw · H / m². The distribution of optimization solutions is shown in the Figure 8.

(4) Enclosed prototype

326 sets of optimal solutions were obtained. The value of shape coefficient was distributed between 0.16-0.42. The solar radiation on the building surface was increased from 150.71kw · H / m² to 227.80kw · H / m². The distribution of optimization solutions is shown in the Figure 9.

3.4 Data analysis of optimal solutions

The objectives and the parameters of optimal solutions obtained from four prototypes were compared by numerical analysis, and the corresponding design strategies were proposed.

(1)Analysis of objective values

By comparing the building shape coefficient values of the optimization solutions, it can be seen from the Figure 10 that centralization (the values were mainly distribute in the range of 0.12-0.18) has obvious advantages, and the other three types are relatively close, among which the L-type is mainly concentrated between 0.25-0.31, the semi-enclosed type is mainly distributed between 0.26-0.3, and the enclosed type is mainly concentrated between 0.24-0.3. In the campus building design, the centralized layout can be selected preferentially for the large space with low lighting requirements, such as the auditorium, projection hall, etc.

From the perspective of solar radiation, centralized (the values mainly distributed in 221.59 kw · H / m² to 233.47 kw · H / m²) and L-type (mainly distributed in 220.92 kw · H / m² to 234.04 kw · H / m²) have comparative advantages, followed by semi-enclosed, which solar radiation value is mainly distributed in 198.36 kw · H / m² to 214.68 kw · H / m², and the corresponding numerical distribution range of enclosed prototype was large, but it was mainly distributed in
188.29 kW·H/m²-211.37 kW·H/m². For the different building morphology in campus, centralized and L-type were better for the passive utilization of solar radiation (Figure 11).

For the different building morphology in campus, centralized and L-type were better for the passive utilization of solar radiation (Figure 11).

(2) Analysis of parameter values

Through the analysis of the morphological parameters of the optimal solutions, it can be seen that in the width value (in north-south direction) distribution, the values of the centralized type were slightly lower than others which was 40m-80m. The value distribution range of the enclosed type is the largest which was 30m-90m, and the width parameter value distribution of the semi-enclosed type was narrower, the width parameter was mainly in range of 60m-90m. The width parameter of the L-type layout was between 50m and 90m. It can be seen that the four types all have flexible scale adaptability(Figure 12), and can achieve better energy-saving performance in the site with the scale of 30m-90m.

For the length parameters of the building prototypes (east-west direction), it can be seen from the Figure 13 that the parameter range of L-type was the maximum within 30m-80m, the parameter values distribution of semi-enclosure and enclosure were similar, both were in range of 60m-90m, and the parameters of centralized were mainly distributed in 35m-80m. Comparatively, types of semi-enclosed and enclosed were more compatible for the terrain with the length scale larger than 60m.

For the building height parameter, it can be seen from the data analysis results, the distribution of the four types were relatively similar(Figure 14). Comparing the main range of the parameter values, the enclosed type is more flexible for the building height of less than 40 m, and the centralized type had a main range of 25m-45m with the better adaptability.

In terms of the depth scale of buildings (Figure 15), the scale of centralized layout varied widely, and the depth scale of the other three types was similar, all of which were mainly concentrated between 17m-22m.

4. CONCLUSION

Based on the survey of 10 university campuses in Northeast of China, the study simplified the form of campus buildings, and proposed four types of building prototypes. Taking the low energy consumption in
winter as the overall optimization goal, a parameterized modeling and calculation platform based on grasshopper and Rhino was established.

The multi-objective optimization of building shape coefficient and solar radiation of four building prototypes was carried out based on the genetic algorithm SPEA2. After 26 generations of calculation, each building prototype achieved more than 200 sets of optimal solutions, and the objective values of the optimization solutions and the corresponding morphology parameters were analyzed.

Through the multi-objective optimization calculation, the shape coefficient of the centralized prototype was reduced from 0.27 to 0.08, and the solar radiation was increased from 212.41 kw · H / m² to 250.91 kw · H / m², which had a significant advantage in shape coefficient. When the length and width of the building was 40m-80m, it was more conducive to energy conservation. The shape coefficient of L-type was reduced from 0.42 to 0.23, the solar radiation was increased from 212.27 kw · H / m² to 250.52 kw · H / m², with the building height was 35m-45m, and the building depth was 17m-22m, which was more conducive to energy saving. The shape coefficient of the semi-enclosed type was reduced from 0.41 to 0.23, the solar radiation was increased from 156.70 kw · H / m² to 225.27 kw · H / m². The better energy saving performance can be achieved when the building height was 28-45m, the building outline scale is 60-90m, and the building depth was 17-22m. The shape coefficient of the enclosed type was reduced from 0.42 to 0.16, the solar radiation was increased from 150.71 kw · H / m² to 227.8 kw · H / m², the optimal solutions suggested that when the length and width scale of the building was 60-90m, the height is below 40m, and the depth of the building is 17m-22m, it can be more conducive to building energy conservation.

REFERENCES

Simultaneous Influences of Temperature and Airflow on Comfort Perceptions in Residential Buildings in Vietnam

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¹ Department of Architecture and 3D Design; School of Art, Design and Architecture; University of Huddersfield, Huddersfield, UK

ABSTRACT: ASHRAE Standard 55 has suggested that airspeeds of 0.2m/s and 0.8m/s set a discomfort limit in air-conditioned and non-air-conditioned buildings, respectively. Some previous studies have attempted to determine thermal comfort conditions and desirable air velocities in naturally ventilated buildings in the tropics. They have found that the real indoor airflow has been low and inhabitants have desired more airflow for their satisfaction, with airspeeds higher than the recommended values up to 1.6m/s. Additionally, these studies have mostly focused on the maximum acceptable airspeeds that extend the upper comfort limit. However, referring to the adaptive comfort approach, although building occupants may accept 'slightly warm' temperatures, elevated airspeeds concurrently affect their overall thermal acceptability, particularly in warm-humid environments. This paper examines a simultaneous correlation between thermal and air movement perceptions and expectations of occupants in non-air-conditioned residences in Vietnam. On-site thermal environments and subjective responses to those were investigated in houses of Ho Chi Minh City, which is the context of the study. Within the environments which people found comfortable, most of them preferred more airflow up to 0.8m/s. The value of 0.5m/s can be determined to be a suitable reference point for airflow acceptability to restore human thermal satisfaction indoors.

KEYWORDS: Comfort; Thermal sensations; Thermal acceptability; Airflow; Residential buildings; Vietnam

1. INTRODUCTION

Research into thermal sensation and comfort has been carried out for more than 100 years. Findings have indicated that contextual factors (building type, cooling type, people type, climate type, and cultural type) have influences on human thermal perceptions [1-2]. Amongst them, a smaller number of field studies were conducted in hot-humid climates where two principal factors of high temperature and high humidity cause discomfort [3]. In that context, enhancing air movement is an effective strategy to retain indoor thermal comfort by increasing the rate of convective and evaporative heat losses from the body as a mechanism of physiological cooling [4-5]. The availability of sufficient airflow can restore occupant thermal neutrality at temperatures up to 3K warmer than the upper comfort limit [3,5-7]. Optimisation of natural ventilation in the building is a cost-effective solution to reduce cooling energy loads by mechanical systems.

In such comfort studies, together with identifying comfort conditions for occupants, researchers have also attempted to determine which indoor air velocities are undesirable or desirable. They have confirmed that in real environments, occupants’ air movement sensations bear no resemblance to the draught limit (0.2m/s) recommended by the international standards [8-9]. People not only desire more air movement but are satisfied with higher airspeeds than the ASHRAE Standard limit (0.8m/s) suggested in free-running buildings [6,10-11]. The findings of previous work on comfortable indoor air movement have identified an acceptable range between 0.2-1.6m/s in naturally ventilated buildings in warm humid regions. However, most research has focused on the maximum acceptability of airspeed to expand the upper comfort limit. Meanwhile, for the adaptive approach, although air temperature is the principal factor to determine comfort temperatures, the overall thermal satisfaction of occupants is a function of other factors in given environments such as humidity, air movement, clothing insulation, and activity pattern [12-14]. For instance, in warm and hot regions, when a person is exposed to the environment within acceptable temperatures, elevated airspeeds simultaneously influence their comfort by removing sensible and latent heat from the body [3,11]. Only a few studies have researched the relationship between air movement and thermal acceptability, for example in laboratories [6] and the field for college students in Brazil [11].

This paper has been inspired by the above issues and an interest in the influences of context on human comfort perception. The work aims to understand the simultaneous correlation between airflow and thermal sensation, preference, and acceptability in naturally ventilated residences in Vietnam’s hot-humid climate. The authors studied buildings set in
the context of Ho Chi Minh City (HCMC) for analyses and discussion. Through on-site surveys in both hot and cool seasons, the paper addresses the airflow conditions for occupant thermal satisfaction derived from a combination of two variables of temperature and airspeed.

2. CLIMATE CHARACTERISTICS in HO CHI MINH CITY

Ho Chi Minh City is the most populous city in the south-central part of Vietnam. It is situated at latitude 10°48’N within the tropical climate zone; however, the operation of seasonal winds results in distinctive climatic characteristics for the city (and country). It is known as the tropical monsoon climate with two major seasons: ‘rainy’ between May and October; and ‘sunny’ between November and April [15]. Air temperature and humidity are uniformly high across much of the year. The monthly average temperature and humidity range between 25-30°C and 70-80% [16]. The average variation of daily temperature is below 10K. In warm months between March and June, the average maximum temperature fluctuates from 32 to 35°C. However, urban citizens must, and do, tolerate extreme heat with temperatures up to above 40°C around noon.

Significant outdoor winds frequently operate in HCMC over the year. There are three dominant monsoon winds: south and southeast winds in March-May with a typical maximum airspeed of 4.5m/s; west and southwest winds in June-October with the strongest wind reaching 5m/s in August; north and northeast winds in November-February with an average air velocity of 2.4m/s [15].

The average rainfall annually is 1950mm; additionally, in the rainy season, the monthly precipitation averages around 300mm. However, under the increasing impact of climate change, those amounts have risen by 20% [17].

Returning to the current study, the terraced houses investigated were surveyed in warm (April and May) and cool (January and February) months in HCMC. The average temperature over those periods was 33°C within the range of 29.5 and 38°C; and 30°C within the range of 26.5 and 33°C, respectively. In addition, the average humidity was similar 60% in both measuring periods; however, the variability of humid levels differed: 41-79% in summer and 45-73% in spring.

3. RESEARCH METHOD

The main research methods used for these comfort studies were repeated transverse field interviews by questionnaire and simultaneous measurements of physical variables. 65 terraced dwellings around HCMC were revisited in the hottest months (April and May) of 2017 and in the coolest months (January and February) of 2018. Most residences investigated were naturally ventilated, along with the use of air-conditioners at certain times on hot days. The characteristics of building samples were diverse, including as follows: eight common orientations (North, South, East, West, Southeast, Southwest, Northeast, and Northwest); the range of total floor area from 100 to 400 m²; building height up to the maximum of 6 storeys; and flexible use (only housing or a combination of housing and another function such as office and retail).

In the comfort survey conducted in the hot season, there were 117 subjects, who were revisited; supplemented by further 22 subjects in the cool season. Personal information related to gender, age, weight, clothing pattern, and activity level was recorded. The summary of those characteristics is an equal distribution of male and female groups, at the variation of age between 15 and 65, and bodyweight range from 40-80kg. In addition, due to the warm and humid climate, people usually prefer to wear light clothes; therefore, the pattern of clothing insulation was between 0.08 and 0.57clo. The metabolic rate reported ranged from 0.8 to 1.8MET. Table 1 shows a summary of occupant characteristics.

<table>
<thead>
<tr>
<th>Personal variables</th>
<th>Min.</th>
<th>Max.</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>15</td>
<td>65</td>
<td>37.8</td>
<td>12.72</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>40</td>
<td>80</td>
<td>58.5</td>
<td>9.2</td>
</tr>
<tr>
<td>Clothing pattern (clo)</td>
<td>0.08</td>
<td>0.57</td>
<td>0.3</td>
<td>0.11</td>
</tr>
<tr>
<td>Activity level (met)</td>
<td>0.8</td>
<td>1.8</td>
<td>1.1</td>
<td>0.24</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gender</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>69</td>
<td>70</td>
</tr>
</tbody>
</table>

All subjects were involved in responding to the questions asking for their thermal and air movement perceptions in given environments of their house in two field investigations. Meanwhile, environmental parameters of temperature, humidity, mean radiant temperature and air velocity were concurrently taken around the body. A total of 256 responses were recorded.

4. RESULTS & DISCUSSION

4.1 Indoor climate

The descriptive summary of the total of 256 datasets of indoor climates reported in the free-running houses is shown in Table 2. There was a similarity between the mean or minimum air temperature, radiant temperature, and operative temperature taken in those buildings around 30.6°C and 25.4°C, respectively. The maximum indoor air temperature, mean radiant temperature, and the operative temperature was 34.5°C, 35.5°C, and 35°C,
respectively. The higher value of MRT explained the impact of solar heat gain on the indoor thermal environment. Relative humidities indoors fluctuated within 45-77%, with a mean of 62% (SD 6.88).

Table 2 Indoor climate for the whole sample

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean</th>
<th>Min.</th>
<th>Max.</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature Tₐ (°C)</td>
<td>30.6</td>
<td>25.4</td>
<td>34.6</td>
<td>1.81</td>
</tr>
<tr>
<td>Mean radiant temp. MRT (°C)</td>
<td>30.7</td>
<td>25.5</td>
<td>35.5</td>
<td>1.86</td>
</tr>
<tr>
<td>Relative humidity RH (%)</td>
<td>62.3</td>
<td>45</td>
<td>77</td>
<td>6.88</td>
</tr>
<tr>
<td>Air velocity Vₐ (m/s)</td>
<td>0.2</td>
<td>0.0</td>
<td>0.8</td>
<td>0.14</td>
</tr>
<tr>
<td>Operative temp. Tₒ (°C)</td>
<td>30.6</td>
<td>25.4</td>
<td>34.8</td>
<td>1.82</td>
</tr>
</tbody>
</table>

The airflow environment inside the houses was calm during the investigations with a mean value of 0.2 m/s (SD 0.14); its variability was between 0.0 and 0.8 m/s. As shown in Figure 1, despite the wide range of air velocity, a larger proportion of values were lower than 0.2 m/s. Those findings are quite similar to the real airflow conditions measured by de Dear et al. in naturally ventilated apartments in Singapore [18] and higher than the air movements taken in non-air-conditioned detached houses in Indonesia [19]. These recorded air movement values for terraced houses in HCMC may not be adequate to restore thermal satisfaction of occupants in the warm climate, in particular, in hot months.

Alongside replying to the questionnaire of thermal cognition, people simultaneously recorded their air movement sensations for the immediate environments. A 5-point scale was suggested: ‘too still’, ‘still’, ‘just right’, ‘windy’, and ‘too windy’. Air movement sensations depend on not only airspeed but air temperature and personal variables [3]. In the real condition of low airspeeds reported, the majority of respondents sensed conditions as ‘too still’ and ‘still’ statements of natural airflow indoors, with 62% of the whole sample (Figure 3). 26% of subjects were satisfied with the air movement to which they were exposed. Meanwhile, a small percentage of people found the environments ‘windy’.

4.3 Correlation between thermal and air movement perceptions

Every person has different thermal responses [1-2]. Linking to the current work conducted in the dwelling buildings in HCMC, occupant thermal and airflow sensations varied when experiencing similar environments. Additionally, the air movement sensation of people was diverse, even when they expressed similar thermal perceptions.

Figure 4 shows the relationship between thermal and air movement sensation over two measuring periods. For each category of thermal sensation, different air movement perceptions were found. In the ‘warm’ and ‘hot’ categories, over 20% of subjects reported ‘too still’ and ‘still’ wind environments. There was a positive correlation of warm climate and
poor natural ventilation that resulted in discomfort, particularly in hot summer periods. 39% of subjects voted for low airflow within the acceptable thermal range from ‘slightly cool’ to ‘slightly warm’. Meanwhile, 21% found acceptability to both thermal and air movement conditions and approximately 10% complained of high air velocities. In a comparison between the sensation votes of occupants for the given environment in the two seasons, the cooler the air temperatures were, the greater the number of subjects satisfied with the airflow condition, even at low airspeeds.

![Figure 4 Overall thermal sensation and air movement sensation](image)

In considering the data recorded, air velocities inside buildings were skewed with a large percentage of low values. Thus, that context had significant influences on occupant air movement preferences. Over 80% of respondents asked for more airflow across all the thermal scales. Amongst these data, although 55% found the environment thermally comfortable, they desired more air movement in order to retain their thermal satisfaction, especially the highest percentage of ‘want more’ votes at thermal neutrality (Figure 5).

![Figure 5 Overall thermal sensation and air movement preference](image)

That proportion was 16% higher than the number of people who found the indoor air movement unacceptable. This explains the preference of more people to occupy environments of higher airspeeds, though they accepted the experienced climate in terms of temperature and airflow. A lower proportion wanted the existing air movement, and a small number of subjects preferred less airflow, particularly in the cooler outdoor climate. In environments of cool temperatures, even low natural ventilation, air flows could cause draught discomfort [7].

Corresponding to the 7-point scale of thermal sensation votes, a 7-point subjective thermal preference scale was also used. Its scale points were: ‘colder’, ‘cooler’, ‘little cooler’, ‘no change’, ‘little warmer’, ‘warmer’, and ‘hotter’. Following their exposure to accumulative warm temperatures in naturally ventilated residences in the tropics (such as Vietnam and HCMC), most people usually prefer a cooler thermal condition. The analysis of field data reported more than 85% of residents voting for three categories from ‘no change’ to ‘cooler’ for their thermal satisfaction (Figure 6).

![Figure 6 Overall thermal and air movement preference](image)

The comparison between the percentage of occupants, who voted for two articulated ranges: ‘slightly cool’ to ‘slightly warm’; and ‘little warmer’ to ‘little cooler’, revealed a difference of 20%. Although they accepted the prevailing environment in terms of sensation, they tended to want more air movement.

### 4.4 Air movement acceptability

Table 3 groups the percentage of occupant air movement preferences into two bins of air velocities: 0-0.2m/s and >0.2m/s in the relation of thermal sensation scales. The table shows that when people felt ‘neutral’ to ‘hot’, the percentages of ‘want more wind’ were much greater than the percentages of ‘no change’, particularly in the lower range of airspeeds (0-0.2m/s). The votes for more air movement gradually rose according to warmer thermal sensations and rise of temperatures. In thermal neutral and acceptable conditions, 67-82% of occupants preferred more airflow at airspeeds above 0.2m/s. When considering the group of people voting for the ‘slightly cool’ sensation, more of them wanted higher air movement in the airspeed range of 0-0.2m/s. Meanwhile, in the environment of airspeeds...
more than 0.2 m/s, the percentage of responses for no change was greater. It means that the increase in airflow in slightly cool thermal condition may be at the risk of draught discomfort for residents.

<table>
<thead>
<tr>
<th>Thermal sensation</th>
<th>Air velocity range</th>
<th>Air movement preference</th>
<th>Total</th>
<th>T_\text{op}</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>0-0.2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>&gt;0.2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cool</td>
<td>0-0.2</td>
<td>67%</td>
<td>3</td>
<td>27.3</td>
<td>1.76</td>
</tr>
<tr>
<td></td>
<td>&gt;0.2</td>
<td>100%</td>
<td>1</td>
<td>29.0</td>
<td>0.00</td>
</tr>
<tr>
<td>Slightly cool</td>
<td>0-0.2</td>
<td>67%</td>
<td>12</td>
<td>29.3</td>
<td>2.24</td>
</tr>
<tr>
<td></td>
<td>&gt;0.2</td>
<td>86%</td>
<td>7</td>
<td>30.4</td>
<td>2.26</td>
</tr>
<tr>
<td>Neutral</td>
<td>0-0.2</td>
<td>78%</td>
<td>68</td>
<td>29.9</td>
<td>1.21</td>
</tr>
<tr>
<td></td>
<td>&gt;0.2</td>
<td>30%</td>
<td>33</td>
<td>29.8</td>
<td>1.71</td>
</tr>
<tr>
<td>Slightly warm</td>
<td>0-0.2</td>
<td>93%</td>
<td>45</td>
<td>30.2</td>
<td>1.26</td>
</tr>
<tr>
<td></td>
<td>&gt;0.2</td>
<td>18%</td>
<td>17</td>
<td>31.1</td>
<td>2.00</td>
</tr>
<tr>
<td>Warm</td>
<td>0-0.2</td>
<td>95%</td>
<td>40</td>
<td>31.9</td>
<td>1.17</td>
</tr>
<tr>
<td></td>
<td>&gt;0.2</td>
<td>17%</td>
<td>23</td>
<td>32.5</td>
<td>1.12</td>
</tr>
<tr>
<td>Hot</td>
<td>0-0.2</td>
<td>100%</td>
<td>0</td>
<td>34.0</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>&gt;0.2</td>
<td>0%</td>
<td>5</td>
<td>33.6</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Table 3: Air movement preference for two airspeed groups

Another finding from the table is a variation of 1°C T_\text{op} between two air velocity ranges within each thermally sensational category, particularly ‘slightly cool’ and ‘slightly warm’. Whereas, the figures of T_\text{op} are similar at the thermal neutrality. In the room of warmer temperatures, the availability of higher airflow is necessary to moderate the room environment and provide equivalent comfort for occupants. In addition, with indoor climates above 29.5°C, higher airspeeds are preferable.

Based on those analyses, the air velocity of 0.5 m/s can be determined to be the minimum of air velocity for occupant acceptability, which is similar to the finding discovered by Candido and her team in naturally ventilated classrooms in Brazil [11]. Additionally, the neutral air movement found inside the free-running terraced houses in HCMC, Vietnam was 0.8 m/s. That value is equal to the maximum limit suggested by ASHRAE 55 [9] but it is lower by 0.1 m/s than the minimum comfortable airflow in the classrooms in Brazil [11] and the air movement satisfaction for 80% acceptability of college students in Thailand [10].

5. CONCLUSION

The research carried out used field questionnaire interviews and measurements for 65 terraced houses in HCMC, Vietnam. A total of 256 datasets of occupant thermal and air movement sensations in those buildings were recorded in the dry and rainy seasons. The paper reports the following significant results:

The residents voted acceptable conditions in the warm environment with average temperatures between 29.3 and 31.1°C. Most of the respondents desired ‘cooler’ thermal conditions under as represented by the compensation of elevated air velocities.

The real airflow data collected in the dwellings in HCMC indicated relatively ‘calm’ airflow conditions that were inadequate to restore the thermal comfort of occupants. Most indoor airspeeds were lower than 0.2 m/s. Within the range of indoor air velocities taken in the field, most people preferred higher airflow up to 0.8 m/s so as to provide thermal satisfaction, even when they were in thermal environments they deemed ‘acceptable’. This shows that a draught discomfort limit set at 0.8 m/s may be inappropriate for subjects in free-running buildings in the tropics.

The above analysis confirmed a close correlation between thermal and air movement sensation, preference, and acceptability of occupants in naturally ventilated residences in Vietnam. The occupant air movement perception was affected by thermal conditions of given environments. Higher airspeeds were the preference of a larger percentage of people in warmer conditions. The group of residents preferring cooler thermal conditions corresponded to the desire for more air movement.

Within the measured airflows in the residences, which were between 0.0—0.8 m/s, the value of 0.5 m/s can be determined to be a suitable reference point for airflow acceptability to restore human thermal comfort indoors. In addition, occupants found comfort at air velocities of 0.8 m/s.
There are variations of indoor air movement and air movement neutrality and acceptability between the current study and other previous work, even in the similar tropical climate, which might be due to the difference of local climate, building type, the principal design of physical building between types, and the social background and thermal history of people in different locations.

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REFERENCES
Temporary Dwelling for the High Altitude Andean Region of Puno, Peru
”Totora” reed as Insulation Material

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ABSTRACT: Peru is a seismic country. The impact of these events is significant in poor and rural regions, where people are most vulnerable and government emergency response takes time and reconstruction of housing and community buildings can take years. In addition to earthquakes, the high altitude areas of Puno, above 4000 meters above sea level, is inhabited by small rural communities with very poor living conditions, extreme cold weather, and few resources. There is a long tradition among the native families around the Titicaca Lake of working with “totora” to make mats and baskets; they even build islands on the lake where they live in their “totora” huts. The objective of this research is to design and evaluate the prototype of an appropriate temporary housing using “totora” as insulation material when disasters occur in these poor and harsh environments of southern Peru. Working with the Lake community of Chimu, a prototype of a temporary house made of “totora” panels was built in Puno. It was inhabited and monitored for three months to evaluate its thermal, structural and functional performance. Results showed that the prototype made of “totora” panels performed better than other temporary dwellings and typical houses of Andean high-altitude rural areas.

KEYWORDS: Totora insulation, Temporary housing, Andean region, Thermal Comfort

1. INTRODUCTION
Peru is a seismic country and earthquakes of important magnitude can occur at least once every year. The impact of these events is especially important in poor and rural regions, where people are most vulnerable and government emergency response takes time and reconstruction of housing and community buildings can take years and even never occur; therefore, affected people have to look for solutions by themselves and without professional support. In addition to earthquakes, the high altitude areas of Puno, at 15° Southern latitude and above 4000 meters above sea level, is inhabited by small rural communities with very poor living conditions, extreme cold weather, and few resources. Daytime solar radiation is of high intensity. At night, the exterior air temperature can be -10°C, while indoor air temperature of dwellings does not even reach 0°C. When catastrophic events occur in this region, emergency shelters are not appropriate to these cold conditions, are thermally uncomfortable for users, and soon are destroyed by strong winds and hailstorms, which are typical and frequent of this region year round.

The Titicaca Lake, at 3810 meters of altitude; has the “totora” reed (Schoenoplectus totora) growing on its shores up to four meters deep. Reeds have been used as building material in several regions of the world for centuries. This traditional building material is still being used in Puno, but just in the last years it is being studied as an adequate and natural building material to insulate houses in the region [1,2]. There is a long tradition among the native communities around the Titicaca Lake of working with “totora” to make houses, mats, baskets, furniture and other small objects; they even build islands on the lake, where they live in their “totora” huts (Fig. 1). However, many of these communities are leaving this tradition, and 100,000 tons of surplus “totora” have to be burnt every year for safety and renewal [3,4].

Figure 1: Houses made of totora reed at a Chimu totora island on the Titicaca Lake.

In 2016, after a 6.3 Ritcher scale seismic event in Lampa, Puno, most of the houses in the high altitude communities were destroyed and people made its own temporary shelters with metal tin walls and roofs supported by a simple wood structure. They
were economic and fast to install but too basic and inadequate to the climatic conditions of the region.

Figure 2: Temporary house in Orduna besides stone and mud house after earthquake. (Photograph: S.Onnis 2017)

The objective of this research is to design and evaluate a prototype of an appropriate temporary house using “tótora” as insulation material when disasters occur in the poor and harsh environments of high altitude communities of southern Peru.

2. METHODOLOGY

The first step was to collect information about guidelines and experiences of emergency shelters and temporary housing, especially in cold regions. This also included the experience of some members of the team on previous research projects on thermal performance and improvement of houses in high altitude communities of Puno [2,5]: the proposal for these adobe houses included a layer of “tótora” as insulation material for walls and roof. This was the most significant contribution to improve the thermal performance of the small houses of these communities. The second step was to learn how the families of the Titicaca Lake work the “tótora” and the possibilities of using it as a more standardized insulating material in the region. Currently, only the community of Chimu, out of the 16 native communities around the Lake, has the expertise and has continued working with “tótora” to build the typical “tótora” mats (q’esanas) and other objects [4].

Figure 3: Chimu people sewing “tótora q’esanas”

The third step was to define the characteristics of the temporary house by a better understanding of the needs, practices, life style and routine of the local people of this harsh environment; basically, they need three separate areas: sleeping, cooking/eating, and storage of tools and food. The fourth step was to study the “tótora”, to learn how Chimu people collect, select and work the “tótora” reed, and to experiment with different combinations of “tótora” with other materials to define the better way to use it as insulation material for building purposes. At the end of this phase, it was confirmed that the common “tótora” mat (q’esana) was the fastest to prefabricate, lightweight and provide adequate insulation. For the construction and insulation purposes of this research, the “tótora” panel selected was made of double mats, with closer seams than traditional ones, 0.60 m wide by 1.80 long, 0.08 thick and weight 7.9 Kg. The panels have to be protected from humidity, sun, and rain. When protected “tótora” can last for more than 10 years, otherwise it has to be replaced every one to two years.

Figure 4: Panels of double totora mats (samples and actual size)

Thermal conductivity essays of the panel of “tótora” double-mats were made at the Laboratory of Energy of the section of Mechanical Engineering of the “Pontificia Universidad Católica del Perú”. It was made with the HFM-436 Lambda equipment and according to ASTM_C 518, ISO 8301, JIS_A1412 and DIN EN 12667 standards.

Three samples of the double “tótora” mat panel, 0.30 by 0.30 meters, were tested. The average conductivity result was 0.047W/m-K, which is within the range of other common insulation materials.
The fifth step was the design and construction of a prototype of the temporary house in Puno. Since the use of “totora” panels was already defined, the next decision was to use wood prefabricated elements not only as structure but also to keep in place the “totora” panels and to allow users to assemble and disassemble the house with few and simple tools.

The sixth step was to monitor the constructive and thermal performance of the prototype for three months, and also how functional it was for users.

The final step was to disassemble the prototype, adjust some details according to the results of the monitoring, and to reassemble it by local people of a high altitude community. This final step was to define how difficult it would be and how long it would take to reassemble it by untrained users, following the instructions of the “Manual de Ensamblaje de la Vivienda Temporal” (Manual to Assemble the Temporary House). This manual had to be mainly graphic, so that Spanish, Quechua, and Aymara-speaking people of the region could easily understand and use.

3. DESIGN OF THE TEMPORARY HOUSE PROTOTYPE

The following criteria defined the design of the temporary house:

It is an intermediate dwelling following a seismic event in between an emergency shelter and the construction of the new permanent house. The lifespan of the temporary house is 1 to 3 years, which is the estimated time to finance and build the new permanent house.

It must be an appropriate response to the physical and climatic conditions of the high altitude regions of southern Peru and resistant to seismic events.

It provides spaces for sleeping, cooking-eating, cleaning and storage appropriate for 4-6 family members; it also contributes to improve the quality of life of the high altitude Andean population.

Thermal comfort is achieved with passive bioclimatic design strategies, especially related to solar gain, heat conservation, air tightness, insulation and humidity control.

The materials are available in the region, quick to prefabricate, low cost, and easy to transport to remote locations of the high altitude Andean region.

“Totora” is used as insulation material, to re-value the availability of this material and the traditional craft of the communities around Titicaca Lake.

It is possible to be assembled and disassembled by 2-3 people. Assembly should take less than a week.

Most of the elements of the temporary house can be reused, either to move it to another location or to build the permanent house.

The proposed solutions comply with building regulations, are practical and low cost so that the local people can replicate them when building their permanent house.

A prototype of the temporary house was built in Juliaca, Puno in July 2019. Pre-fabricated elements were made in Puno and Lima.

The prototype is 20 m² and has three rooms: entry thermal airlock which also includes a cleaning area and storage; cooking/eating room; and bedroom.
The structure is made of prefabricated wood elements, including 12 “foundation boxes”, which rests on the ground, so that the temporary house floor is 0.50m above ground. This is important to avoid humidity from the floor and to prevent the need of excavating the hard soil of high altitude Andean regions. The columns and beams have I and C profiles to keep the “totora” panels in place.

The walls are made of panels of “totora” double mats pre-fabricated by a family of the Chimú community of the Titicaca Lake. These mats are also used as insulation of the floor and the roof. The modular “totora” panel is made of two q’esanas (“totora” mats), one has the fibres horizontally, the other has them vertically and both are sewn together according to the Chimú craft tradition but with closer seams. This makes the panel rigid and lightweight; one person can easily handle it. The insulation of doors, windows and skylights shutters are made of single “totora” mats. Wood planks are used for the floor and the exterior finish of walls; this is to prevent rain and sun damage of the “totora” panels. The interior side of the walls and roof exposes the texture of the “totora” panels. Only the cooking area has the walls covered with metal tin sheets to prevent a fire hazard. The roof has metal tin sheets over the “totora” panels, two skylights to allow solar gains and a photovoltaic solar panel to provide electricity for lighting and small appliances. Total cost of prefabrication and construction of the prototype was US$ 6500, however, if doing in more quantity this cost can be reduced.

4. MONITORING OF THE PROTOTYPE

The prototype was built on an open area with no other buildings around, to be exposed to winds, rain and sun without obstructions, as is usual for rural dwellings in the high altitude Andean region.

Figure 8: Temporary house prototype in Juliaca, southwest corner. Data logger on south façade.

Seven data loggers HOBO H08-003-02 of ONSET Computer Corporation registered air temperature and relative humidity: two outside the prototype and five within it:
- HOBO 3 – Entry thermal airlock
- HOBO 4 – Exterior, North facade
- HOBO 5 – Exterior, South facade
- HOBO 6 – Kitchen
- HOBO 8 – Dining room
- HOBO 9 – Bedroom 2, Northwest
- HOBO 10 – Bedroom 1, Southwest

Data loggers were located 1.80m above floor level. Data were collected and analyzed for 3 months: August to October. During this time, the prototype was occupied by two students. Cooking was made on a gas stove. The students had laptops and mobile phones.

During these months the prototype was impacted by intense solar radiation, strong winds, rainstorms and hail.

5. RESULTS AND DISCUSSION

From the three months analysed, August represents a typical winter month of the high altitude Andean region. The other two months correspond to transition months from the dry-winter season to the rainy spring one. The range of the daily exterior air
temperature was 25-30°C; night temperature in August was below 0°C; some nights it was even below -10°C, while daytime temperatures reach 20°C.

Figure 10: Outdoor air temperature in Juliaca

The most critical situation in high altitude communities is extreme cold at night. As an example, in Orduna at 4800 meters above sea level, data from a previous research project [2] showed that June and July are the coldest months, with average minimum temperature that can reach -10°C. The typical house includes separate volumes made of stone walls and metal tin roofs; the interior temperature in the bedroom not even reach -2°C. The goal for bedrooms in the prototype was 10°C, which is an adequate comfort temperature for these Andean high altitude regions, applying Nicol and Humphreys [6] adaptive comfort temperature equation to the coldest months in Orduna. Despite being below international standards, this is adequate to the clothing of the Andean people and to their living practices.

Figure 11: Monthly mean outdoor air temperature of high altitude Andean community of Orduna. Confort temperature and temperature range [2,6]

Although 70% of the registered indoor temperature is above 10°C, at night the temperature of the bedrooms and cooking/eating areas decreased up to 2°C (Fig. 12). These two areas have almost similar temperature because they are integrated as one thermal zone: the partitions had no door in between them. The entry thermal airlock has the lowest indoor temperature, which remains about 2°C below the temperature of the other rooms.

The “totora” panels prevented conduction heat transfer: during daytime, the indoor air temperature of the North bedroom and cooking area were only 2°C over the outdoor air temperature despite the North wall received direct solar radiation and the average temperature of the exterior side of this wall reached up to 28°C in August (Fig.13). At night, the “totora” panels reduced heat loss by conduction and prevented the indoor air temperature to go below 0°C, despite the following issues: few internal gains; lack of thermal mass to collect and store the intense solar radiation of daytime hours; partitions with no door in between the bedroom area and the cooking/eating area; and more important, the union of the “totora” panels with the wood structure was not tight enough and it allowed for cold air infiltration, especially on windy nights. This last issue was identified when the prototype was disassembled and from interviews with the users.

Figure 12: Average daily air temperature of temporary house prototype in Juliaca.

Figure 13: Comparison of average daily temperature of exterior of North wall and indoor air temperature of North bedroom and cooking area.

Although the interior air temperature of the prototype did not maintain the expected 10°C at
night, when compared with the registered temperature in Orduna houses, it is an improvement of the thermal sensation at night: it is 4°C higher when outdoors is -10°C.

![Graph](image1.png)

The prototype was disassembled in December in just two days. The “totora” panels and wood structure were in good conditions, just some damages on the windows paint and the varnish of the exterior wood planks, especially on the facades impacted by the wind.

The prototype was reassembled in Orduna in February 2020 during the rainy season. The three owners of the site with the help of another person from Orduna assembled it in 7 days, following the instructions of the manual prepared for users. Members of the family are living in the temporary house and the new thermal monitoring period will be from May to July, the coldest months of the year.

6. CONCLUSIONS

The proposed temporary house built mostly with natural materials of the southern Andean Mountains of Peru is a better solution to the climate conditions and harsh environment of the high altitude Andean region, in comparison to other temporary dwellings and to the typical houses of the rural areas.

Despite few heat gains sources at night and the infiltration of cold air due to the problem of the fit of the “totora” panels with the wood structure of the prototype, the interior temperature was maintained above 0°C.

There are still some construction details and passive design strategies that can be improved to make the assembly process easier and faster for the user and to have a better thermal performance.

It might even be necessary to include some additional bioclimatic design strategies, especially to provide thermal mass to collect and store the intense solar radiation of daytime to be released at night in the bedroom area.

With more research on the insulating properties of the “totora” panels, they could be brought to international standards, and become an accessible building material for insulation of rural and urban houses of the Southern Andean region of Peru.

The results of the temporary house assembled in Orduna, with some of the improvements identified from the prototype in Juliaca, will provide more useful information of its thermal performance in a whole winter season.

ACKNOWLEDGEMENTS

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REFERENCES

Overheating risk in social collective housing in the Basque Country and Navarre built under the Passivhaus standard
Monitoring campaign and comfort analysis of a 171-dwelling building in Bilbao, Spain.

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ABSTRACT: The regulatory trend in building in Europe has evolved towards the construction of very low energy consumption buildings developed under the Nearly Zero Energy Buildings concept. In order to achieve these objectives, high insulation and airtightness construction standards developed over the years by central and northern European countries are being followed. However, the use of these standards in climates with greater solar radiation, different typologies and user behaviour has not been comprehensively evaluated. This study assesses the levels of comfort reached in collective housing designed according to the regulations of the Basque Country and built under the Passivhaus standard, according to different European comfort models. Both dynamic simulations and monitoring of certified collective housing have been carried out. The results of the monitoring of four dwellings and the occupants’ comfort surveys of another 54 units in a building of 171 Passivhaus-certified dwellings are analysed.

KEYWORDS: Thermal Comfort, Passivhaus, Collective Housing, Overheating

1. INTRODUCTION
The improvement of energy efficiency in Europe, regulated by the European Directive EU 2010/31 [1] proposes as an objective the construction of buildings with almost zero energy consumption (NZEB), developed in EC 2016/1318 [2, 3]. Some aspects outlined in the document [3] are the use as models the very low energy consumption buildings developed in Europe with conservative solutions built in the cold climates of Central and Northern Europe. The benchmark are the Passivhaus and Minergie standards, which have a long tradition in Central Europe. The simulations are carried out with very broad reference climates. This methodology has some disadvantages such as the use as a model of single-family houses with a significantly different behaviour to collective housing, predominant in Spain. The real occupation in collective housing in Spain are higher than the Central European average and internal gains very influential in buildings with very low energy demand. At the same time, local climatic variations also have a decisive influence on the internal contribution of solar radiation. Some countries and regions have incorporated objectives very similar to those set by the Passivhaus standards into their national regulations [4]. The objective of this study is to verify the behaviour of collective dwellings built under energy-conserving standards such as Passivhaus in the climate of the Basque Country and the degree of interior comfort according to different regulations focused on the detection of overheating.

2. STATE OF THE ART
Overheating is a known problem in highly airtight and insulated buildings with numerous studies confirming it [5-9]. As a summary, a study of the first Passivhaus houses in Denmark [10], states that "the great interest in energy efficiency has reduced the interest in interior comfort. This has led to problems in overheating of buildings, among others", and concludes that there is an emerging conflict between the implementation of energy efficiency standards and the recommendations of Article 4 of the EU Directive 2010/31: "These requirements shall take into account the general conditions of the indoor climate, avoiding possible negative consequences such as inadequate ventilation, as well as the particular conditions, use and age of the building" [1]. Many of the studies add overheating mitigation measures [11-15].

3. METODOLOGY
This study has been developed in two phases. In the first phase, the most common typologies in social housing in the different climates of the Basque Country and Navarre were analysed by means of dynamic simulations. In a second phase, a monitoring campaign was carried out on a Passivhaus-certified collective social housing project built in Bilbao by the regional government of the Basque Country. In the...
spirit of a complete Post Occupancy Evaluation (POE), the study also included a comfort survey handed out to the occupants.

3.1. Thermal comfort models and standards

The choice of comfort models is a fundamental aspect in assessing the quality of the interior climate. The two most adopted models are the Thermal Balance Model or empirical model (EN ISO 7730:2006 and EN 15251:2008) based on studies with climatic chambers, and the Adaptive Models based on field studies, that account for subjective aspects of comfort and are in permanent revision [16]. Thermal Balance Models like EN ISO 7730 [17] best apply to indoor environments where steady-state thermal comfort or mild deviations from comfort occur. In Spain, the technical standard in effect (RITE) [18] is based on EN ISO 7730. EN 15251 [19] suggests the use of Fanger’s model for mechanically heated and/or cooled buildings and Humphrey’s and Nicol’s adaptative model for buildings without a mechanical cooling system [16]. Some more advanced national standards, that of CIBSE in the United Kingdom, for instance, combine both approaches. CIBSE Guide A [20] follows an empirical model, while CIBSE TM:52 [21] follows an adaptative model. These documents also define several criteria for overheating assessment. TM:52 is used primarily in commercial buildings and should only be applied when the occupants are able to act on their environment to regulate indoor climate conditions, while TM:59 [22] was developed for housing. The comfort range in the Passivhaus standard is based on a steady-state equation that predicts average monthly values without taking into account the effects of thermal inertia [23].

3.2. User comfort surveys

Surveys are deemed the most reliable method to detect overheating in buildings already in use [21], they provide direct information of the occupants’ degree of comfort needless of a model. A comprehensive POE survey was designed with a holistic approach that accounted not only for Building Performance (BPE), but was also oriented at knowing the perceived comfort, habits and opinions of the occupants and considered non-technical factors as well, in the spirit of a Universal Design Evaluation (UDE). The 28-item survey was made available online for all occupants of the building in the late summer of 2019.

3.3. Analysed case

The analysed building is located in Bilbao. The coastal line of the Basque Country contains the most populated cities in the mentioned territory (more than 1.4 million inhabitants, 60% of total population), the metropolitan area of Bilbao being the densest (45% of total). It is a public promotion of between 9 and 27 floors that houses 171 homes, 63 of which are destined to subsidized rental and 108 to fixed-price sale. The homes have been occupied as of March 2019. The building obtains the Passivhaus certificate in March 2018 with a heating demand of 6 kWh/m²y, a design heating load of 7 W/m² and an airtightness of 0.4 h⁻¹ in the n₅₀ test. The expected overheating periods (hours where T> 25°C) are 7%, less than the maximum 10% allowed in the PH standard. The building is located in an urban area of the city of Bilbao, in a noisy environment. It is protected from direct solar radiation by opaque reflective blinds located inside the windows. It lacks balconies or any other kind of sun protection. All façades are covered with a black finish aluminium composite façade panel (Fig.1).

![Figure 1: View of the analysed building (foreground, left) and the 2nd phase tower currently under construction, with similar characteristics (background, right).](image)

Four units are monitored for representativeness of the typological variety and average occupancy of the dwellings. A house is launched on March 13, 2019 while the other three are monitored since August 30, 2019. The selected dwellings are also in different floors and have different orientations, and users report different degrees of operation on blinds and windows (Table 1).

<table>
<thead>
<tr>
<th>Dwelling</th>
<th>1</th>
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<tr>
<td>Windows</td>
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*Table 1. Summarized characteristics of the monitored dwellings.*

3.4. Data collection

T&D RTR-576 equipment with 3 channels, CO2 Concentration, Temperature and Humidity have been used for monitoring. The measuring range of CO2 is 0 to 9999ppm, Temperature: 0 to 55°C (accuracy ±0.5 °C) and Humidity: 10 to 95%RH (accuracy 5 %RH at 25
The reading is transmitted remotely by a T&D RTR-500 unit and allows remote reading through the manufacturer’s own T&D Web Storage service.

3.5. Exterior climate data
Outdoor weather data are obtained from the nearby weather station of Abusu-La Peña (<500 m) that belongs to the Basque Meteorological Agency, Euskalmet. The analysis of the weather data shows that the monitoring period is within the historical average, not being a particularly hot summer.

4. RESULTS

4.1. Phase I: energetic simulation
The risk of overheating in public collective housing buildings constructed with the PH standard in different locations in the Basque Country and Navarra is analysed, based on the definition of overheating of the standards EN ISO 7730, EN 15251, CIBSE GUIDE A and Passivhaus’ own. The territory is characterized by a climate with a strong variability in solar radiation (3.55-5.40 kWh/m²day) and temperature (warmest month average ranges 15 to 25°C). The most common dwelling typology in public housing (75 m²) is studied through an energy simulation with EnergyPlus in its different combinations and orientations (22 models), located in the most populated cities of each climatic area (7 in total). The cases are designed to meet the PH standard in the winter period. It is concluded that in spite of the relatively milder climate compared to Central Europe, cool periods generate high daily demands and heating load (200-230 Wh/m²) that require considerable insulation (at least 10 cm in the Atlantic coast and South of the territory and up to of 20-25 cm in the Plains of Alava and pre-Pyrenees). The analysis of the different overheating control systems yields the following conclusions:

1. Sun protection is necessary throughout the year, especially in the period from mid-April to the end of October. These protection means must combine fixed and mobile protections to have precise control of the radiation incident in the homes.

2. The homes can stay within the comfort ranges using a pattern of intensive natural ventilation in the coolest moments of the day, but this measure requires significant attention from the user. The mitigating effect of night ventilation is not as strong in the coast, due to the narrower temperature range and high external relative humidity.

3. The use of mechanical ventilation with an automatic bypass and with a maximum capacity of 4 r/h is necessary to stay within the comfort limits of the PHI. Buildings in urban heat islands would need somewhat higher.

4. Climate change models further accentuate overheating hours.

4.2. Phase II: case study analysis

Results of the user comfort survey
A survey campaign is carried out to assess interior comfort and user satisfaction. The response to the questionnaire is high, being carried out by 84 occupants of 54 different dwellings. The survey provides information on the real occupation of the dwellings: 14% have one occupant, 50% have 2 inhabitants, 14% have 3 inhabitants and 32% 4 inhabitants or more.

The survey highlights discomfort during the summer. 100% of men and 78.9% of women report having sleep-related issues during the summer on a regular basis, either difficulty falling asleep or regarding the quality of said sleep. The most common answer to the general thermal sensation in the summer was "It’s too hot" (95%). The reported clothing index in summer is, on average, 0.27 CLO, equivalent to wearing underwear only, confirming the perception of overheating. Long format comments submitted by the survey-takers depict the problems that excess heat generates in daily life, even if they claim to have permanently ventilated the rooms (20%) and to be very active with the use of the blinds.

Results of the monitoring campaign
The results of the monitoring of the four dwellings are presented graphically for dwelling no. 1 and in summary form for dwellings no. 2, 3 and 4.

Dwelling no. 1: According to the comfort chart of the EN ISO 7730 standard, the T/RH pairs are analysed in the period from 1 May to 30 Sep 2020 (Fig. 2) for the summer. There are a number of T/RH pairs that fall above the recommended maximums of 25°C, although the RH does not exceed the maximum values of 70%. The maximum recorded temperatures are up to 29°C.

Figure 2: Dwelling 1. Graph depicting thermal comfort according to EN ISO 7730, during summer.

The analysis of the winter period (Fig. 3), October-April, shows that the month of October and part of November have problems of overheating. This aspect had already been predicted in the simulation phase, and is mainly due to the fact that Bilbao’s climate is highly influenced by the proximity of the sea, which is still at a very high temperature at this time of year.
Of the 3672 hours of the period, 1790 were >25°C (48.7%). The hottest and most humid month is July (83.6% h>25°C) and then August and September with similar values (70-74%). RHs fall in the range 40-75%.

Analysis according to the adaptive model EN 15251 shows that the limit marked for Category I in said standard is exceeded by a considerable number; the limit for Category II is never exceeded.

The following graph of the evolution of temperatures in summer (Fig. 5), shows the previously mentioned problem, plotted against the adaptive limits marked by CIBSE TM:52.

In the analysis according to CIBSE TM:59, two variants are studied: dwellings with possible natural ventilation and dwellings with predominant mechanical ventilation. The degree to which these dwellings are naturally ventilated depends on proximity to traffic, proximity to the train tracks, insect nuisance due to the proximity of the river. In addition, the shading system on the inside prevents the opening of the windows when the interior sun protection is lowered. In the first case (natural ventilation), criterion 2 is not met, night hours (22-07 h) where T > 26°C were 297, when the maximum allowed is 32 hours. If it is assumed, as it can be, that mechanical ventilation predominates, total annual hours exceeding 26°C are limited to 3% (263 h), while the monitoring campaign recorded 1123 hours above that limit.

The analysis of night-time comfort made with the hourly chart (Fig. 6) shows the periods with excess of night temperature in summer (May-Oct). Night-time hours in summer > 24°C are 61.1%; while night-time hours in summer > 26°C are 16.1%. The maximum temperature recorded at night was 27.8°C.

### Dwellings no. 2, 3 and 4:

The following table (Table 2) compiles the % hours T > 25°C broken down by month from the monitored readings.

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<td>DEC</td>
<td>0,0</td>
<td>0,0</td>
<td>0,4</td>
<td>6,72</td>
</tr>
<tr>
<td>YEAR</td>
<td>24,7</td>
<td>13,3*</td>
<td>5,8*</td>
<td>7,3*</td>
</tr>
</tbody>
</table>

Table 2. Percentage of hours of exceedance (T>25°C) in the monitored dwellings (* dwellings with incomplete data).
The figures marked with an asterisk (Table 2), are calculated with respect to a whole year (8760 hours) and not with respect to the monitored hours only. It is remarkable how some of the dwellings can exceed the 7% stated on the Certificate or even the yearly limit of 10% set by the PHI with data from September and October only.

The data from the dwelling monitored throughout the whole year (Dwelling No. 1) serve as a projection to the rest of the summer not monitored of the other three dwellings (Fig. 7). This allows us to predict what degree of comfort will be achieved in dwellings 2, 3 and 4. Three out of four of these dwellings would not comply with the Passivhaus standards’ limit of hours >25°C. It can be said, however, that although dwelling No. 4 complies with the set limit, it probably would not if it were not for its occupants extremely active role in solar control and night ventilation, as we learned in an interview, where they reported the constant attention demanded by their home to maintain a comfortable temperature made their daily life difficult.

Figure 7: Percentage of hours with T > 25 ºC for the full year and summertime (May-Oct). Projected data for dwellings 2, 3 and 4, based on full period monitorization of dwelling 1.

The projection of data in the night hours with T>26ºC, confirmed by the inhabitants’ surveys. (Fig. 8) shows an excess of night-time hours above 26ºC, the limit set by CIBSE TM:59 for naturally ventilated dwellings being 1% (32 hours) for the whole year.

Figure 8: Percentage and absolute count of yearly night-time (22-07 h) hours where T > 26 ºC (TM:59 max: 1% or 32h).

Considering the limits for mechanically ventilated dwellings marked by CIBSE TM:59 (3% of occupied hours T>26ºC or 263 h) would be exceeded in the 4 monitored dwellings. At night, 10% of those surveyed stated that they had problems falling asleep because of the noise, which suggests that they do not sleep with the windows open. The summary of compliance with different comfort models is summarized in the following table (Table 3).

<table>
<thead>
<tr>
<th>Dwelling</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHI</td>
<td>NO</td>
<td>NO*</td>
<td>NO*</td>
<td>NO*</td>
</tr>
<tr>
<td>EN 15251</td>
<td>YES*</td>
<td>YES*</td>
<td>YES*</td>
<td>YES*</td>
</tr>
<tr>
<td>CIBSE TM:52 Criterion 1</td>
<td>YES</td>
<td>YES*</td>
<td>YES*</td>
<td>YES*</td>
</tr>
<tr>
<td>CIBSE TM:52 Criterion 2</td>
<td>YES</td>
<td>YES*</td>
<td>YES*</td>
<td>YES*</td>
</tr>
<tr>
<td>CIBSE TM:52 Criterion 3</td>
<td>YES</td>
<td>YES*</td>
<td>YES*</td>
<td>YES*</td>
</tr>
<tr>
<td>CIBSE TM:59 -predominantly naturally ventilated Criterion 1</td>
<td>NO</td>
<td>NO*</td>
<td>NO*</td>
<td>NO*</td>
</tr>
<tr>
<td>CIBSE TM:59 -predominantly mechanically ventilated Criterion 1</td>
<td>NO</td>
<td>NO*</td>
<td>NO*</td>
<td>NO*</td>
</tr>
</tbody>
</table>

Table 3. Compliance with the analysed comfort standards. (* dwellings with incomplete data in the summer period)

5. DISCUSSION

Quantitative analysis: in dwelling nº1, the h >25ºC add up to 2162 h, 24.7% h of the year (1790 from May to September), higher than the maximum allowed of 10% by the PHI and the 7% declared in the certificate. However, hours above 28ºC are very rare, 22 h, with a maximum indoor temperature of 28.2ºC. The rest of the dwellings follow this trend. Although it is a basic method, it seems that it corresponds to the perception of the users.

The quantitative criteria of the CIBSE standards are also not met in any of the cases, the limits set for night time in particular being exceeded regularly. CIBSE recommend limiting night temperature values to 23ºC in bedrooms and dormitories since temperatures above 24ºC are considered to be detrimental to sleep, and define overheating when the operative temperature exceeds 28ºC during 1% of the annual hours occupied in the rooms without air conditioning, and when it exceeds 26ºC 1% of the annual hours occupied in the bedrooms (32 hours) [20], none of these limits are met.

Adaptive analysis: the adaptive models derived from EN 15251 standard and the more refined ones from the CIBSE standards are fulfilled for Category II, being surpassed in some moments in Category I. These more refined methods do not seem to be in line with the declared perception of the users in the POE survey.

6. CONCLUSION

The scientific literature has predicted in numerous occasions the issues of overheating in Passivhaus certified housing, this study further develops these predictions and presents recorded data from monitoring of a built project that shows real world results can be worse than predictions, due to wrong design decisions taken in this project, namely the interior solar protection and the lack of true cross ventilation. The analysis of overheating periods has been carried out both in quantitative terms, hours T>25ºC and night hours >26ºC, and by means of adaptive models. Confrontation against less demanding adaptive models has shown a higher
degree of compliance, however the occupants’ responses to the POE surveys they may indicate that they are inadequate. As the British standards show, the combination of both models sets the regulatory trend. The compactness of the houses and the impossibility of avoiding direct radiation and ventilating at the same time, are the aspects that generate greater difficulties. The discomfort that occurs during the hours of sleep is remarkable, so it is necessary to pay attention to the problems of overheating during these hours of the day. In light of the European regulatory trend in the search for energy savings, this discomfort will not only occur in Passivhaus certified homes but will be a widespread problem in buildings built in this climate in the coming years without adequate mitigation measures, better solar protection and adequate natural ventilation.

7. ACKNOWLEDGEMENTS
This study has been financed by the Territorial Planning and Housing Department of the Basque Government and the Department of Architecture of the University of The Basque Country (EHU). The authors would also like to thank the Municipal Housing Agency of Bilbao and the inhabitants of the Bolueta Tower that have participated in the study, as well as Rubén Llanera from SAFER Instrument.

REFERENCES
Energy saving by adapting Passive House buildings in warm climates: A case study of Vietnamese housing

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Centre for Urban Design, Architecture and Sustainability, University of Huddersfield, UK.

ABSTRACT: The residential sector is responsible for approximately one third of total energy consumption in Vietnam. This is partly due to the poor thermal performance of the existing housing stock, which is often constructed using poorly insulating materials such as: concrete or corrugated iron roofs; clay brick walls; and single-glazed windows. This leads to the use of much energy to meet cooling demand. To improve thermal performance and the sustainability of housing in Vietnam and in other warm regions, Passive House techniques can be used as an advanced solution. Proposed here is a completely new approach replacing the common techniques of natural ventilation or hybrid methods in current housing in warm climates. However, the specification of temperature set-points of 20 and 25°C in Passive House calculations for all climate zones should be carefully considered. The hypothesis is that adopting a higher thermal comfort range for warm climates would be more appropriate for indigenous residents whilst saving more energy compared to using the 20 - 25°C range. In addition, the Passive House standard could be achieved using simpler and more affordable materials. This research helps to establish the theoretical foundation for the arrival and development of the Passive House approach in Vietnam.

KEYWORDS: Passive House, energy saving, thermal comfort, warm climates, Vietnamese housing

1. INTRODUCTION

The residential sector is responsible for approximately one third of total energy consumption in Vietnam. This is due to the poor thermal performance of the existing housing stock, which is often constructed using poorly insulating materials. These materials include: concrete or corrugated iron roofs; clay brick walls; and single-glazed windows. This leads to the increased use of energy to meet cooling demand, the main contributor to energy consumption in the warm climate of Vietnam [1]. A natural ventilation approach combined with passive cooling design techniques can significantly reduce discomfort hours. However, it is a fact that natural wind is an uncontrollable factor, along with the impact of global warming, urban heat island effect, and air pollution, which makes natural ventilation in many cases not an effective solution. Therefore, in order to improve thermal performance and the sustainability of housing in Vietnam, and in other warm regions, Passive House techniques can be used as an advanced solution.

Generally, a Passive House is characterised by: a high level of thermal insulation; air tightness for the building fabric; thermal bridge free design; and an energy recovery ventilation system for fresh air supply. These principles maintain the indoor temperature at a comfortable year-round state of 20 - 25°C while saving up to 90% of energy consumption compared to conventional buildings in Central Europe. Indoor air quality is ensured by consistent fresh air supply. Compared to a conventional home, construction costs of a Passive House are 3% to 8% higher (in Germany), but the Passive House is more affordable in the longer term [2]. With such advantages, Passive House construction is growing rapidly in temperate climates, and gradually spreading to warmer regions. There are now examples in hot climates such as in Dubai, Qatar and Indonesia.

Passive House involves a completely new approach replacing the common techniques of natural ventilation or hybrid methods in current housing in warm climates. However, the specification of temperature set-points of 20 and 25°C in Passive House calculations for all climate zones in general [3], and for Vietnam in particular, should be carefully considered. Using the 25°C limit, the first Passive House project in Qatar was unable to meet the Passive House standard because it consumed more primary energy than the criterion of 120 kWh/m² annually. Khalfan (2015) reckoned that the limit of 25°C might be a little low for the Qatar climate [4]. Meanwhile, the only Passive House building in Indonesia, the office of Austrian embassy, passed the standard by adopting many additional design techniques including the use of high-quality windows, a well-insulated envelope and a concrete core temperature control system [5]. The use of such expensive materials could be a barrier for the
development of Passive House concept in developing countries. Therefore, the hypothesis of this study is that adopting a higher thermal comfort range for warm climates would be more appropriate for indigenous residents whilst saving more energy compared to using the 20 - 25°C range. In addition, the Passive House standard could be achieved using simpler and more affordable materials. This research helps to establish the theoretical foundation for the arrival and development of the Passive House approach in Vietnam and other warm countries.

2. METHODOLOGY AND METHODS

This study firstly conducted a survey of the thermal comfort range for Vietnamese people. Secondly, simulations using the Passive House Planning Package (PHPP) were carried out to investigate the energy saving accrued by using a higher thermal comfort range.

2.1 Thermal comfort survey method

An experiment method in a controlled room was used to investigate thermal acceptability of Vietnamese people. The details are as follows:

Subjects
There were 128 college-age participants involving 73 males and 55 females. All of them were born and raised in the hot humid climate of Vietnam. The subjects were clothed in underpants, and bra for women, short-sleeve shirts or T-shirts, thin long trousers and sandals. This clothing ensemble could be specified as light summer clothing, for which the thermal resistance value is 0.5 clo.

<table>
<thead>
<tr>
<th>Sex</th>
<th>Age (±)</th>
<th>Height (m) ±0.05</th>
<th>Weight (kg) ±9.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male (73)</td>
<td>21.9 ± 1.8</td>
<td>1.69</td>
<td>60.9 ± 9.1</td>
</tr>
<tr>
<td>Female (55)</td>
<td>21.5 ± 1.5</td>
<td>1.57</td>
<td>47.9 ± 5.2</td>
</tr>
<tr>
<td>All (128)</td>
<td>21.7 ± 1.7</td>
<td>1.64</td>
<td>55.2 ± 10</td>
</tr>
</tbody>
</table>

Experimental facilities
An air-conditioned classroom in MienTrung University of Civil Engineering, which is situated in Tuy Hoa City, South Central Coast of Vietnam was employed and retrofitted for the experiments. The dimensions of the classroom are 6m wide, 8m long and 3.8m high. The windows face North and South. The wide surrounding corridors of the upper floor and the inside curtains ensure the participants were not exposed to direct sunlight. Four environmental parameters, which are air temperature, globe temperature, relative humidity and wind velocity, were carefully measured during the experiments.

In a pilot test, wind velocities were measured at three levels of height, 0.1m, 0.6m and 1.1m above the floor, at 27 sample points in the room. The result showed that mean air velocity was 0.08 m/s with standard deviation of ±0.04 m/s. The maximum air velocity did not exceed 0.2 m/s (a value which can cause draught sensations).

Air temperature, globe temperature and relative humidity were also measured at 4 sample points in the chamber in order to investigate the differences of these environmental variables at three levels of height. The data indicated that there was no significant difference since the standard deviations were only ±0.1°C and ±2% for temperature and humidity respectively. Therefore, the measured data were collected at 0.6m above the floor, which is suitable for seated occupants, throughout the experiments.

2.2 Simulation method

Modelling existing houses
Two typical models of terraced and detached house (Fig. 2, 3), the dominant housing types in Vietnam, were created using designPH and the PHPP.
(these are essential tools developed by the Passive House Institute for planning Passive House buildings).

Both houses were oriented South. The terraced house measurement is 5m by 18m with a back yard 5m by 2m. It has 3 storeys and 220m² treated floor area. Window-to-wall ratio (WWR) is 30%. The detached house, located on a land plot of 13m by 19m, has 3 storeys, 223m² treated floor area, and WWR of 17%. Materials of the building elements are shown in tables 2 and 3. Air infiltration for both houses was 0.7 air changes per hour (ACH) at normal air pressure. According to the PHPP calculation, this value is approximately equal to 9.5 ACH and 9.7 ACH at 50 Pascal differential pressure (n50) for the terraced house and the detached house respectively. Absorption coefficient of external walls, roofs is 0.7 for both houses. Total value of the internal heat gains was set at 2.3 W/m² complying with the standard value for residential buildings. The building properties proposed here were based on a field study on existing housing in Vietnam conducted by the authors in 2018.

Figure 2: Terraced house model and floor plans

Figure 3: Detached house model and floor plans

Table 2: Building elements properties of the existing terraced house.

<table>
<thead>
<tr>
<th>Element</th>
<th>Construction layers and thickness</th>
<th>U-value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior walls</td>
<td>15mm cement plaster + 190 mm hollow clay brick + 15mm cement plaster</td>
<td>1.93</td>
</tr>
<tr>
<td>Walls to neighbour</td>
<td>15mm cement plaster + 80 mm hollow clay brick + 15mm cement plaster</td>
<td>2.97</td>
</tr>
<tr>
<td>Flat concrete roof</td>
<td>20mm cement screed + 100mm concrete slab + 15mm cement plaster</td>
<td>3.18</td>
</tr>
<tr>
<td>Ground floor</td>
<td>8mm ceramic tile + 20mm cement screed + 100mm lining concrete + 100mm levelled sand + natural soil layer</td>
<td>2.60</td>
</tr>
<tr>
<td>Window glazing</td>
<td>Single layer of 6mm ordinary glass</td>
<td>5.59</td>
</tr>
</tbody>
</table>

Table 3: Building elements properties of the existing detached house.

<table>
<thead>
<tr>
<th>Element</th>
<th>Construction layers and thickness</th>
<th>U-value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior walls</td>
<td>15mm cement plaster + 190 mm hollow clay brick + 15mm cement plaster</td>
<td>1.93</td>
</tr>
<tr>
<td>Flat concrete roof</td>
<td>20mm cement screed + 100mm concrete slab + 15mm cement plaster</td>
<td>3.18</td>
</tr>
<tr>
<td>Pitched concrete roof</td>
<td>30mm cement roof tile + 30mm air layer with 10% batten wood + 100mm concrete slab + 15mm cement plaster</td>
<td>1.84</td>
</tr>
<tr>
<td>Ground floor</td>
<td>8mm ceramic tile + 20mm cement screed + 100mm lining concrete + 300mm levelled sand + natural soil layer</td>
<td>1.37</td>
</tr>
<tr>
<td>Window glazing</td>
<td>Single layer of 6mm ordinary glass</td>
<td>5.59</td>
</tr>
</tbody>
</table>
**Weather data and the Passive House standard**

Weather data of Tuy Hoa city, an example for the hot humid climate of Vietnam, was obtained from Meteonorm software and shown in Fig. 4.

![Figure 4: Monthly temperature and relative humidity of Tuy Hoa city, Vietnam.](https://doi.org/10.17979/spudc.9788497497947)

According to climate and building characteristics, the Passive House criterion for cooling will be adapted and automatically calculated in the PHPP. The calculation method and formulae are described in the Certification criteria for residential Passive House buildings [9]. Accordingly, energy requirements for cooling and dehumidification for Tuy Hoa city is less than 40 kWh/(m²a). Alternatively, cooling and dehumidification demand is less than 76 kWh/(m²a) and cooling load does not exceed 10 W/m². Criteria for heating and primary energy demand remain the same for every location at 15 and 120 kWh/(m²a) respectively.

**Simulation step**

Firstly, energy consumption of the existing housing models were adjusted and the cooling demand addressed by conventional air conditioners. Secondly, the houses were simulated to the Passive House standard. Each house was equipped with a mechanical ventilation system (75% cooling recovery and 77% humidity recovery). Air tightness complied with the Passive House requirement of 0.6 ACH at 50 Pascal differential pressure. To improve thermal performance, the existing building envelope was amended with a layer of extruded polystyrene (XPS), and the exterior absorptivity of walls, roofs was reduced to 0.3. Two thermal comfort ranges, 20 - 25°C and a revised version, were set respectively in the PHPP to compare the energy consumption and the materials required to meet the Passive House standard; these indicated substantial energy saving.

### 3. RESULTS AND DISCUSSION

#### 3.1 Thermal comfort range for the Vietnamese

A total of 640 responses were collected from the experiments. However, only the last three thermal sensation ballots per subject, corresponding with 384 ballots for 8 experiments, were used for the following analysis. This is based on the assumption that the subject had achieved thermal equilibrium after an exposure of one hour. The time period needed for acclimatising to the room temperature is a controversial issue since it has been applied differently across 147 experiment studies with the average time of 26.9 ± 11.8 minutes [10]. Table 4 shows the frequency distribution of thermal sensation votes in each of 8 experiments.

<table>
<thead>
<tr>
<th>Season</th>
<th>Air temperature (°C)</th>
<th>Operative temperature (°C)</th>
<th>Relative humidity (%)</th>
<th>Thermal Sensation Vote</th>
<th>Mean Vote</th>
<th>Percent of -1 to 1 Votes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cool</td>
<td>23 ± 0.2</td>
<td>22.7 - 23.0</td>
<td>58.1 - 66.1</td>
<td>1</td>
<td>25</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>24 ± 0.2</td>
<td>23.7 - 24.0</td>
<td>76.3 - 79.3</td>
<td>0</td>
<td>7</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>25 ± 0.4</td>
<td>24.4 - 25.0</td>
<td>75.1 - 78.6</td>
<td>0</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>Warm</td>
<td>26 ± 0.4</td>
<td>25.9 - 26.4</td>
<td>45.2 - 48.8</td>
<td>1</td>
<td>11</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>27 ± 0.2</td>
<td>26.9 - 27.2</td>
<td>48.0 - 52.5</td>
<td>0</td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>28 ± 0.4</td>
<td>27.6 - 28.3</td>
<td>48.3 - 50.7</td>
<td>0</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>29 ± 0.3</td>
<td>28.9 - 29.3</td>
<td>47.5 - 54.4</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>30 ± 0.3</td>
<td>29.9 - 30.4</td>
<td>60.5 - 64.2</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

According to Fanger (1970), it is very difficult to set thermal conditions that can satisfy everyone: there is always a minimum of 5% of people who feel dissatisfied [7]. In this study the boundaries were extended to a criterion of 80% of people satisfied in order to determine the ‘thermal acceptability’ of the group of people. The percentages of subjects who felt satisfied in this experiment, (i.e. voting from -1 to +1), were then plotted against the operative temperature.

In the warm season, the upper temperature for 80% satisfaction was found at 29.6°C. In the cool season, thermal acceptability to low temperatures was calculated at 23.7°C. These values for 90% satisfaction criterion are 24.8 and 28.8°C. These results are in line with Vietnam’s thermal comfort standards and the results of other studies. However, it is noted that Vietnam currently has some inconsistent standards of thermal comfort. While TCVN 7438:2004 based on ISO 7730:1994 shows the comfort range of 20 - 26°C, the values in TCVN 9411:2012 and TCXDVN 306:2004 are 20 - 29°C and 21.5 - 29.5°C respectively [11-13]. An experiment by Nguyen, M.H. et al. (2003) in Hanoi, Vietnam showed a comfort range of 24 - 29°C (90% satisfaction) [14]. Zhang et al. (2016) also found a similar range of 24.5 - 29°C (90% satisfaction) for people in Guangzhou, a
city in the warm humid region of China [15]. Therefore, 23.7°C and 29.6°C were chosen for the lower and upper temperature set-points in the next simulation step.

3.2 Energy and construction cost saving from applying higher temperature set-points

Table 5 shows the energy demand needed to maintain 20 - 25°C indoor temperature of the existing houses and the improved houses built to the Passive House standard. For the detached house, compared to the existing condition, Passive House approach reduced 80% cooling and dehumidification demand, 85% max cooling load and 66% primary energy demand. These values for the terraced house were 73%, 85% and 66% respectively. This result indicated the poor energy efficiency of existing housing in Vietnam and revealed the great potential of Passive House application to the hot humid climate of this country.

Table 5: Energy demand for 20 - 25°C comfort range of existing houses and Passive House models.

<table>
<thead>
<tr>
<th>Energy demand</th>
<th>Detached house</th>
<th>Terraced house</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Existing house</td>
<td>Passive House</td>
</tr>
<tr>
<td>Cooling and dehumidification demand (kWh/m²a)</td>
<td>372.2</td>
<td>74.5</td>
</tr>
<tr>
<td>Max cooling load (W/m²)</td>
<td>71</td>
<td>10.4</td>
</tr>
<tr>
<td>Primary energy (kWh/m²a)</td>
<td>374</td>
<td>118</td>
</tr>
</tbody>
</table>

However, the adoption of the original 25°C upper limit in warm climates could waste energy for cooling since the indigenous residents can adapt to a higher temperature. Therefore, to investigate the potential of energy saving in Vietnamese housing from applying a higher temperature set-point, the revised comfort range, 23.7 - 29.6°C, was used to replace the original 20 - 25°C while preserving the same building properties. As a result, cooling and dehumidification demand of the detached house significantly reduced by 49%; maximum cooling load also reduced by 49% and total primary energy demand reduced by 27.1% (Fig. 5). For the terraced house, cooling and dehumidification demand reduced by 44.4%; maximum cooling load reduced by 63.5% and total primary energy demand reduced by 14.7% (Fig. 6).

It is noted that the above energy demands for the 23.7 - 29.6°C set-point are much lower than the Passive House requirement for the climate of Vietnam. It means that it is possible to use cheaper building materials as well as simpler design solutions for these models to meet the Passive House standard when the upper temperature set-point is 29.6°C.

Table 6 and 7 show building characteristics of the terraced house and the detached house that satisfied the Passive House energy criteria for the warm climate of Vietnam. By using 23.7 - 29.6°C set-point, those energy criteria can be met with higher thermal-transmittance materials and a lower level of airtightness compared to the use of the 20 - 25°C set-point. For example, in the detached house, insulation layer thickness for external walls was cut down two thirds, from 180 mm to 60 mm. Window quality only required double layers of ordinary clear glass instead of low-E window with argon filling and solar protection. Air infiltration of the envelope was 3 ACH (n50) rather than a strict value of 0.6 ACH.

The use of simpler windows and thinner insulation layers for external walls, roofs and ground floor can save much in construction costs. In addition, the lower requirement for airtightness would be appropriate to the construction techniques of many countries especially of developing ones. In short, the benefits of energy saving and affordable construction cost can be achieved by adopting Passive House approach with higher temperature set-points in warm climate regions.

![Figure 5: Energy demand for two different temperature set-points in the detached house model.](image)

![Figure 6: Energy demand for two different temperature set-points in the terraced house model.](image)
Table 6: Detached Passive House building properties for two different temperature set-points.

<table>
<thead>
<tr>
<th>Building element</th>
<th>20-25°C Material, insulation layer</th>
<th>U-value (W/m²K)</th>
<th>23.7-29.6°C Material, insulation layer</th>
<th>U-value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior walls</td>
<td>180 mm</td>
<td>0.18</td>
<td>60 mm</td>
<td>0.45</td>
</tr>
<tr>
<td>Flat roof</td>
<td>150 mm</td>
<td>0.22</td>
<td>50 mm</td>
<td>0.57</td>
</tr>
<tr>
<td>Pitched roof</td>
<td>150 mm</td>
<td>0.21</td>
<td>50 mm</td>
<td>0.51</td>
</tr>
<tr>
<td>Ground floor</td>
<td>100 mm</td>
<td>0.28</td>
<td>0 mm</td>
<td>1.23</td>
</tr>
<tr>
<td>Window glazing</td>
<td>Double low-E + Argon filling + solar protection</td>
<td>1.1</td>
<td>Ordinary double, clear glass</td>
<td>2.8</td>
</tr>
<tr>
<td>Airtightness (n50)</td>
<td></td>
<td>0.6 ACH</td>
<td></td>
<td>3 ACH</td>
</tr>
</tbody>
</table>

Table 7: Terraced Passive House building properties for two different temperature set-points.

<table>
<thead>
<tr>
<th>Building element</th>
<th>20-25°C Material, insulation layer</th>
<th>U-value (W/m²K)</th>
<th>23.7-29.6°C Material, insulation layer</th>
<th>U-value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior walls</td>
<td>100 mm</td>
<td>0.3</td>
<td>20 mm</td>
<td>0.92</td>
</tr>
<tr>
<td>Walls to neighbour</td>
<td>100 mm</td>
<td>0.31</td>
<td>20 mm</td>
<td>1.1</td>
</tr>
<tr>
<td>Flat roof</td>
<td>100 mm</td>
<td>0.32</td>
<td>30 mm</td>
<td>0.85</td>
</tr>
<tr>
<td>Ground floor</td>
<td>50 mm</td>
<td>0.55</td>
<td>0 mm</td>
<td>2.6</td>
</tr>
<tr>
<td>Window glazing</td>
<td>Double low-E + Argon filling + solar protection</td>
<td>1.1</td>
<td>Ordinary double, clear glass</td>
<td>2.8</td>
</tr>
<tr>
<td>Airtightness (n50)</td>
<td></td>
<td>0.6 ACH</td>
<td></td>
<td>4 ACH</td>
</tr>
</tbody>
</table>

4. CONCLUSION
This study carried out a thermal comfort experiment in a semi-controlled room and identified a new and more appropriate thermal comfort range of 23.7 - 29.6°C for Vietnamese housing. Using these to replace the 20 - 25°C set-points of the Passive House standard can significantly reduce the energy demand and construction cost of the buildings. Therefore, this study facilitates the expansion of the Passive House approach to warm and hot climates, including Vietnam.

ACKNOWLEDGEMENTS
This study is part of a research project funded by the Ministry of Education and Training, Vietnam. Thanks to University of Huddersfield for the financial support for this conference attendance.

REFERENCES
ABSTRACT: The construction industry is changing rapidly where sustainability has become the key word, driving all innovations. Every new material is graded for its environmental impact and the most commonly used technique for this is the Life Cycle Assessment (LCA). This paper attempts to look at the LCA of a specific Magnesium Oxide Structural Insulated Panel (MgO SIP) used for a home in North England – the focus is on embodied CO2 and not operational CO2. The LCA compares the environmental impact across six indicators - Global warming, Acidification, Eutrophication, Formation of ozone, Depletion of Ozone and Primary energy. This is right across the life cycle phases of raw material extraction, manufacturing, on-site construction, transportation, use and end of life/disposal. The result showed that this specific MgO SIP does not score higher than the conventional SIPs as it is manufactured in China and assembled in UK thus nullifying the sustainable impact. In fact, these MgO panels present negative environmental impact. However these MgO SIPs can score over the conventional SIPs and emerge environmentally friendlier if these MgO SIPs are manufactured domestically. Although this is a context-driven conclusion, the paper does highlight the potential of this MgO SIP for attaining the nearly Zero Energy Building (nZEB) objective set by UK.

KEYWORDS: Zero Energy Building (nZEB), Magnesium Oxide (MgO), Structural insulated panels (SIPs), Life Cycle Assessment (LCA), embodied CO2

1. INTRODUCTION

Globally, buildings and construction account for 36% of global final energy use and 39% of energy-related carbon dioxide (CO2) emissions, [1][11]. Under the climate change act 2008 UK has been committed to reduce the greenhouse gas emission by 80% in 2050 [2][15], currently UK has around 27 million homes and the number is on the rise. The building sector is the largest energy consumer in comparison to all other sectors with CO2 emissions rising to 9.6Gt in 2018 from 7.7Gt in 2000[10]. There are two main factors that play major role in greenhouse gas emission reduction, first is the envelope, the thermal efficiency of the building and second the operation carbon [15]. The European 2050 roadmap aims to reduce energy use, As a result, the European Performance of Buildings Directive (EPBD) policy requires all new building to be nearly Zero Energy Building (nZEB) by 2021, now the nZEB requires commercial and residential to be high energy efficient performance and to be supplied with renewable technologies on site or nearby [11][13]. To achieve nZEB a building should not exceed energy consumption per unit area per year (kWh/m2/year). Ofcourse the targets differ by country, for example Austria have set their target as 160 kWh/m2/year, France 40-65 kWh/m2/year and the UK 44 kWh/m2/year [13]. First, the most feasible approach is the selection of the right building materials, where all the walls, windows and door have high thermal resistance and airtight. Secondly, reduce the primary energy use in the building through advance mechanical systems, and thirdly on-site renewables should be used as the primary source of energy or nearby stations. In the UK, the Committee on Climate Change (CCC) [13] has recently reported that energy-inefficient and high-carbon housing is jeopardizing the UK’s chances of meeting its energy reduction targets [14][17][18]. These types of buildings necessitate the need for very high energy performance and will commonly require renewable technologies, however the embodied carbon impact is usually not considered. Over the years prefabricated construction has been promoted as a strategy to reduce building carbon emission, prefabrication is the process of manufacturing building materials and delivering to the site to reduce construction waste and time [14].
In this study, a new type of a prefabricated SIPs system the (MgOSIP) that is capable of possibly meeting nZEB standards has been tested on a real-world case study in the North West of England. The SIPs system offers several improvements over conventional construction and, in this paper, the embodied CO\textsubscript{2} impact is considered using life cycle assessment (LCA) techniques. This paper reports, for the first time, the LCA of a specific Magnesium Oxide (MgO) SIPs system, sold under the brand name of Dragonboard. The panels are assembled in the UK, with the (MgOSIP) boards themselves manufactured in China and shipped to the UK. Using LCA techniques, this specific SIPs homes embodied CO\textsubscript{2}e is 18 kg CO\textsubscript{2}e/m\textsuperscript{2}/year. Similar results were found in the study by Peixian Li et al [6] in 2018, who quoted a much lower figure of 13.3 kg CO\textsubscript{2}e/m\textsuperscript{2}/year. To the best knowledge of the author, this paper provides the first LCA of this specific type of MgO SIPs panel for a home in the UK.

1.1 Preference for MgO SIPs

Magnesium Oxide Structural Insulated Panels (MgO SIPs) are gaining preference as it has the potential to outperform the conventional materials of construction like cement, gypsum, plywood, plastics and Oriented Strand Board (OSB) as it is resistant to flame, water, mold and even insects [6]. These SIPs are emerging as one of the good methods for envelope system of sustainable housing. In this case study of the house in Heswall North England, the external walls, the floor and the roof used the DragonBoard MgO SIPs.

![Figure 1: Section of the external wall/ground floor/roof](image)

MgO SIP panels are the most advanced contemporary method of construction in the field of prefabrication construction, to reduce the impact of CO\textsubscript{2} emissions and the closest approach to achieve nZEB agenda. The prefabricated SIPs, DragonBoards, are made of Magnesium oxide composition that has a cement texture which acts as a durable insulation material. These sandwich MgO panels are energy efficient and composed of 3 main layers: MgO materials on both side and EPS foam in the middle.

The measurement of the prototype External MgOSIP panel:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. MgO boards of 24mm</td>
<td></td>
</tr>
<tr>
<td>2. MgO boards of 24mm</td>
<td></td>
</tr>
<tr>
<td>3. Fibre cement 100mm</td>
<td></td>
</tr>
<tr>
<td>4. Silicon 80mm</td>
<td></td>
</tr>
<tr>
<td>5. Plaster 150mm</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. MgOSIP external wall measurements. (The U-Value of the external wall was measured at 0.16 (Passive Houses U-Value ranges from 0.10 to 0.15 W/(m\textsuperscript{2}K)).

All the required MgO SIPs were bought from the local supplier of DragonBoard in UK, who in turn said that the MgO itself comes from China. Thus the embodied CO\textsubscript{2}e takes a huge jump the moment this import cost is added, subduing the overall score.

2. METHODOLOGY

To study the embodied CO\textsubscript{2}e of the MgO SIPs system, a single-family house was selected in Heswall North England of a total built area of 92m\textsuperscript{2}. The house consists of one Master-bedroom (6m x 4m), bathroom (2.6m x 3.3m), living room (7m x 6.7m), office (3m x 3m) and utility room (2m x 3m). This LCA software and related datasets are compliant with ISO 14040/14044 or EN 15804 [7]. This LCA software covers life cycle stages from cradle-to-grave with separate reporting to the extraction of raw material, manufacturing, transportation, onsite construction, operation and disposal/reuse, but our study area will focus on the embodied carbon. There are multiple LCA tools available in the market such as OneClickLCA, Gabi6, SIMAPro, and Athena.

2.1 System boundary.

For this study, OneClickLCA has been selected because the University of Liverpool has obtained the license of the software [7]. More importantly, most of the software lack the wall assembly in their database, since the MgO boards are fairly new in the market and they have limited information about them. However, OneClickLCA, at our request, allowed modification of the MgOSIP wall assembly in the program, making calculation much easier.

The program breaks down the calculation into five main criteria:

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Foundations and substructure</td>
<td></td>
</tr>
<tr>
<td>2. Vertical structures and façade</td>
<td></td>
</tr>
</tbody>
</table>

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DOI: https://doi.org/10.17979/spudc.9788497497947
3. Horizontal structures: beams, floors and roofs (Sven Schimschar, Michelle Bosquet, Nesen Surmeli, Andreas, 2013)
4. Other structures and materials
5. Building technology

Table 2. OneClickLCA’s calculation criteria.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>SIP House</th>
</tr>
</thead>
<tbody>
<tr>
<td>No of floor</td>
<td>1 Floor</td>
</tr>
<tr>
<td>Total area</td>
<td>92m2</td>
</tr>
<tr>
<td>External</td>
<td></td>
</tr>
<tr>
<td>Dragon Board Sip</td>
<td></td>
</tr>
<tr>
<td>Fiber cement 0.10m</td>
<td></td>
</tr>
<tr>
<td>Silicon 0.08m</td>
<td></td>
</tr>
<tr>
<td>SIP</td>
<td></td>
</tr>
<tr>
<td>Expanded Polyvinylchloride 0.0120m</td>
<td></td>
</tr>
<tr>
<td>SIP ESP Expanded polystyrene 0.1270</td>
<td></td>
</tr>
<tr>
<td>Polyvinylchloride 0.0120m</td>
<td></td>
</tr>
<tr>
<td>Plasterboard 0.01250</td>
<td></td>
</tr>
<tr>
<td>Ground floor</td>
<td></td>
</tr>
<tr>
<td>Dragon Board Sip</td>
<td></td>
</tr>
<tr>
<td>Aerated concrete slap 0.40m</td>
<td></td>
</tr>
<tr>
<td>Sand and gravel 0.20m</td>
<td></td>
</tr>
<tr>
<td>SIP ESP Expanded polystyrene 0.150m</td>
<td></td>
</tr>
<tr>
<td>Underlay rubber 0.010m</td>
<td></td>
</tr>
<tr>
<td>Roof</td>
<td></td>
</tr>
<tr>
<td>Dragon Board Roof</td>
<td></td>
</tr>
<tr>
<td>Roof tile 0.020m</td>
<td></td>
</tr>
<tr>
<td>Roofing felt 0.020m</td>
<td></td>
</tr>
<tr>
<td>SIP</td>
<td></td>
</tr>
<tr>
<td>Expanded Polyvinylchloride 0.0120m</td>
<td></td>
</tr>
<tr>
<td>SIP ESP Expanded polystyrene 0.150m</td>
<td></td>
</tr>
<tr>
<td>Polyvinylchloride 0.0120m</td>
<td></td>
</tr>
<tr>
<td>Plasterboard 0.01250</td>
<td></td>
</tr>
<tr>
<td>Window glazing</td>
<td>Triple Glazed</td>
</tr>
<tr>
<td>Infiltration rate</td>
<td>0.8 ac/h estimated</td>
</tr>
<tr>
<td>HVAC system</td>
<td>Thermal store used for heating and DHW</td>
</tr>
<tr>
<td>MVHR</td>
<td>Air source heat pump</td>
</tr>
<tr>
<td>Occupancy rate</td>
<td>46 (m2/person)</td>
</tr>
</tbody>
</table>

Table 3. Characteristics of the SIP house in Wirral UK

3.1 Power
The house is powered by 100% grid connected electricity with no gas supply. The electricity powers all M&E systems inclusive of plug loads, appliances, lighting, thermal storage heating, an immersion heater, an Air Source Heat Pump (ASHP) and a Mechanical Ventilation with Heat Recovery (MVHR) system, external CCTV cameras and WiFi. No renewable solar, thermal energy technologies or battery storage systems are currently in place.

4. RESULT
It was found that the total embodied Co2e of the MgOSIP house is 18 kg CO2e/m2/year, when
compared to nZEP target for the UK the MgOSIP house has relatively small amount of carbon emission CO2e/m2/year. However, the number could have been nearly zero if the transportation for MgO was sourced locally. The mode of transportation plays a major role in calculating the embodied carbon because its related to the consumption of fossil fuel, specially when the MgO SIPs panels are transported from China’s warehouse to England where the assembly for the MgOSIP takes a place. Based on the calculation of the embodied carbon it is assumed that the MgO transportation has the highest impact to Global warming potential (GWP) by 20.2%, acidification 10.3%, Eutrophication 9.2%, primary energy 16.6%.

Table 4: LCA result of the environmental impact of the envelop system.

Even though the panels partially were manufactured in the UK but the MgO panels imported from china the system will add the transportation in the total CO2e calculation, which will spike the environmental indicators resulting a negative impact on the overall environment. Nonetheless, this could be prevented if a substitute to MgO was sourced locally.

As a result, MgO panels present negative environmental impact mainly due to long distance transportation from factory to manufacturing site and if we compare them to the other method of construction Dragonboards are in fact not sustainable at this stage. Similar results were also found in [6][7]. In addition, the use of OneclickLca was beneficial because it provides details analysis of each materials in accordance with environmental indicators and provides suggestion for a substitute materials.

5. CONCLUSION.

The study of the prototype clearly shows that MgO panels do present a negative environmental impact and this is mainly assumed to be the long-distance transportation from factory to manufacturing site. And this study shows conclusively that when compare the MgO SIP system to the other methods of construction, DragonBoards technology used in the SIP house do not show optimum solution until now. However, DragonBoards SIPs panel have a great potential in meeting net zero building by 2050 if the prefabricated MgO panels were manufactured locally using local materials. If the substitute to MgO was sourced locally the embodied Co2e of the SIPs can be subsided significantly resulting very low or nearly zero embodied carbon emission, also MgOSIP construction has the ability to save energy due to insulation quality when paired with renewable energy off the grid like the photovoltaics solar panels and/or battery storage.

As a result, SIP systems could be the potential government investment to the road nZEP 2050.

Therefore, further research is required to optimize the Dragonboard potential. This research aims to develop alternatives strategies to modify the environmental impact of the MgO SIP panels to minimize the effect of embodied carbon to meet the passiveHaus standards and (nZEB) 2050 plan.

6. LIMITATION

As the prototype used MgOSIP system, there is currently no knowledge whether MgO can be substituted with some other metal or biodegradable chemical compound. The MgO is mined and transported from China and it is not known whether it would be viable to get the same from other Magnesium ore mining countries. It is also not known why MgO is preferred and not any other material. There are limited research and data around the use of MgO as a durable material in the prefabrication industry and why the country is unable to manufacture a similar or even original substitute locally since the panel sandwich is assembled domestically, sourcing an alternative material to MgO will subside the greenhouse gas emission significantly. Thus, more research is required to find out an alternate for MgO, which could be sourced.
within UK or nearby, thereby bringing down the embodied Co\textsuperscript{2e} drastically. And if we can reduce the embodied carbon to nearly zero and source our energy the operational carbon from the renewable’s technologies then nZEB agenda would be achievable in the near future.

6. REFERENCE


ABSTRACT: In the UK, schools alone are responsible for 15% of the public and commercial buildings total energy consumption. The recent studies showed that new school buildings are failing to meet the essential standards of performance criteria in terms of indoor environmental quality (IEQ) and energy consumption. The provision of good indoor air quality and thermal comfort for schools can be challenging, particularly in UK school, which do not have mechanical ventilation and air conditioning in summer months. It is predicted that the UK climate will see a significant rise in temperatures and in internal gain such as ICT (Information Communication Technology). This paper highlights the existing situation of school buildings in the UK in terms of indoor environmental quality and energy consumption. Field measurements of the indoor environmental quality of 16 classrooms were examined both in winter and in summer. The results show that 41% and 68% of monitored classroom globe and air temperature were above 25°C. The results also showed that the indoor CO₂ level was 62% above 1000 ppm during the occupied school hours. The findings of this study indicate that new build schools in the UK faces a significant risk of overheating under the current climate. Furthermore, most of these classes did not meet the UK school building for IEQ standards such as CIBSE and BB101. The authors conclude that the design of school buildings in the UK will have to adapt to the changing climate and future proof solutions should be developed.

KEYWORDS: Overheating, indoor air quality, thermal comfort, new build school buildings.

1. INTRODUCTION

UK schools house nearly ten million pupils, who spend almost 30 percent of their life in school and 70% of their time inside a classroom during their school hours. Consequently, the classroom’s indoor environmental quality (IEQ) does not only affects pupils’ health and thermal comfort [1], but can also lead to other consequences, such as impaired learning performance and decreased school attendance. School buildings are complex spaces to design, deliver and operate, as they need to achieve and perform following all aspects of national parameters set for IEQ. IEQ includes thermal comfort conditions, indoor air quality (IAQ), noise comfort, and light comfort. Achieving an adequate IEQ while accommodating specific periods that are characterised by very high occupant densities can be particularly challenging, as these high-occupancy classroom densities can cause high internal gains, high carbon dioxide (CO₂) levels, the concentration of several indoor pollutants and dust (i.e. PM2.5 and PM10), and overheating. Previous studies [2, 3] show that the internal environment of classrooms, both in terms of the level of overheating and carbon dioxide concentrations, can have a noticeable effect on occupants’ performance and comfort.

Furthermore, targets for carbon and energy emissions reduction will most certainly become more demanding, as IEQ standards are typically stricter for such buildings. In general, schools and spaces for learning have more demanding and complex environmental requirements than other buildings. Meeting these standards is often challenging; however, the design requirements are fundamental for occupants’ – mostly pupils – overall wellbeing and educational attainment. The UK was the first country to adopt and introduce a long-term legally-binding framework to reduce climate change crises, to reduce carbon emissions by 80% by 2050 through the Climate Change Act (2008). The building sector has responded to this initiative, aiming to improve buildings’ performances through new standards and regulations that result in highly insulated and airtight building envelopes. However, there is still scarcityness regarding data on air and global temperatures for new school buildings during the summer months, due to that period’s open schedule. Therefore, it is not easy to define the occupants’ behaviour in designs in which clustered learning takes place.

Therefore, this study will carry out field measurements to investigate the indoor environmental parameters of the classrooms in newly constructed schools and compare the findings to the BB101 and CIBSE School Building Standards, identifying the conflicts and problems that exist when implementing a holistic system of combined technological and design solutions. In this paper, results obtained from monitoring studies in a selection of schools have been compared with school guidelines.
to determine how effectively the schools performed and to introduce a potential solution.

2. ENVIRONMENTAL PERFORMANCE OF NEWLY BUILT SCHOOLS

Can low-carbon schools provide a comfortable teaching environment in the future?

Several studies have investigated and focused on the operational and environmental performance of newly built low-energy schools. They have shown that new schools are failing to meet even the basic criteria for the provision of IAQ [1, 4] and energy consumption [5].

The first study by [1] looks into the IEQ performance of 18 classrooms in nine newly constructed schools. The investigation was monitored by the authors during the winter (heating season), to assess IAQ and thermal comfort and the influence of the ventilation system (ASHRAE, 1992). Most of the classrooms in the case studies exceeded the regulation limit of 1000ppm of CO2 over the occupancy time, and only a few classrooms met the need of providing 8 l/s per person required by BB101. The study showed that the high CO2 level was caused by natural ventilation design being just sufficient to provide the minimum level of 3 l/s per person. This can be due to the design of the building with too few windows and the use of windows with restricted opening, consequently not allowing enough natural airflow to come in.

Another study [4] utilised case studies to investigate and evaluate the post-occupancy conditions in the design environment of the school. This is believed to be the first study that successfully attempted to analyse the difference between the predicted and the actual energy performance in five low-energy schools. Four of the schools that were evaluated showed that they exceeded the allowable median carbon emission rate, while the fifth school seemed to perform only “marginally” better [5]. The UK government set energy benchmarks aiming for school buildings to have a median of 150 KWh/m² and 40 KWh/m² for fossil fuel use and electricity consumption respectively [6]. The study by [5] indicated that the introduction of information communication technology (ICT) in classrooms further accelerated overheating, while the fossil fuel required was measured between 5-15 KWh/m² during the cooling period. These conditions are important to pay attention to, taking into consideration that, to date, the majority of classrooms are fitted with a projector, while also dealing with frequent use of laptops and iPads.

The Royal Institute of British Architects (RIBA) and the UK Chartered Institute of Building Services Engineers (CIBSE) carried out a study to develop and produce an online platform intended to compare designed energy use with actual energy required during the operation of recently completed projects. The database was created and designed to enable researchers and designers to more accurately carry out a process of design estimate and actual energy performance of a building while comparing the actual energy use against the energy benchmark of CIBSE TM46 [6].

3. IMPACT OF CHANGING CLIMATE ON OVERHEATING AND IAQ IN SCHOOLS

Buildings are becoming more cost-effective to run, and the built environment is playing an important part in the transition to a low-carbon economy. As a result, the building sector is making progress in tackling the problem of heating in domestic and non-domestic buildings, such as schools, but there is still much work to be done. However, as the construction sector becomes better at building and retrofitting construction, to prevent heat loss during winter, there is a phenomenon, of unintentionally increasing the risk of overheating during the warmer months of the year, particularly in homes [7]. An increase in the frequency and intensity of heatwaves and hot summers has been predicted worldwide [7]. Some research has even suggested that this increase will be higher than initially estimated [8]. According to the UK Climate Change Projection 2009 (UKCP09), all UK regions are projected to become warmer, particularly during summer [4].

The building sector has responded to this initiative, aiming to improve the performance of buildings through new standards and regulations that result in highly insulated and airtight building envelopes. This ultimately avoids the threat of overheated buildings that are not appropriately designed [9, 10].

To reduce high indoor air temperatures and building energy consumption, several works have suggested and studied the use of passive cooling strategies. Strategies such as the use of night ventilation techniques, ventilated walls, and Phase Change Material (PCM) can be suitable for the UK climate.

The UK’s building standards and regulations have historically aimed to reduce energy consumption for school heating. However, the standard has not addressed buildings’ summer thermal performance [1]. In 2018, BB101 was revised for adoption by the UK government, offering a set of criteria to prevent overheating in schools [11]. These criteria needed to meet the building regulations that prevent overheated designs during the summer season.

In response to the issues outlined above, a significant amount of policy and research has assessed the risk of indoor overheating in UK school buildings. Several reports carried out by private and government bodies have highlighted the need to enhance understanding of the risks of overheating in school buildings, in pursuit of the optimal realisable solution [12]. However, most academic research that has
attempted to quantify the extent and concern of overheating risks in UK classrooms has relied on modelling [4]. There is a clear lack of monitored data regarding global air temperatures in new school buildings, with most of the existing data dealing with schools constructed in previous periods. However, there is post-occupancy evidence that newly built constructions, or buildings that have been designed as highly energy-efficient, have been designed according to passive house standards, placing them at risk of overheating in summer [13]. Overheating and the consequence of heat-stress for the students in non-efficient classrooms is more severe in urban than rural areas. It is characteristic that, during the 2006 heatwave, dozens of schools closed when temperatures had hit more than 36°C (Moss, 2019).

However, there is still a lack of data on air and global temperatures for new school buildings during summer. Therefore, it is not easy to define occupant behaviour in designs where clustered learning takes place. Overheating occurs when too much heat builds up inside a classroom from external (e.g. the sun), and/or internal heat sources (e.g. occupants, appliances and ICT). All buildings should act as a physical buffer between the outside and inside to protect occupants, especially pupils, from the extremes of the external environment in the non-heating season. A school building’s location, orientation, ventilation, construction, heating and use all contribute to how well it achieves this.

A further risk is that overheating may encourage the increased use of mechanical cooling, which would ultimately lead to increased energy demand and diminish the opportunity for or effectiveness of non-mechanical alternatives. The high relative running cost of mechanical cooling also presents affordability issues and the associated greenhouse gas emissions problem.

4. METHODOLOGY

An in-situ method was adopted for the pilot study. Each school was monitored for five consecutive working days in the non-heating summer season of June-July. The first case study is a school in Mansfield and the was conducted between 17th and 21st June 2019. The second case study school, in Nottingham, conducted field measurements between 1st and 5th July 2019.

4.1 The purpose of field measurements in school case studies

- To observe the indoor performance of newly built classrooms in primary schools in terms of both IEQ and IAQ during summer. This will enable us to compare the actual data collected against the guidelines and regulations for ventilation, thermal comfort and IAQ for schools.

- To reveal how the classrooms’ thermal performance could best be studied for a more comprehensive monitoring programme.

- To identify the best system and solution, according to the experimental and field study data, to enhance the classrooms’ performance during both winter and summer seasons.

4.2 Equipment used for school field measurements

Outdoor temperature $T_{\text{out}}$, mean temperature, dew point and RH humidity were measured outside using a TinyTag data logging sensor. Furthermore, air temperatures and air velocity were measured outdoors using the PCE-009 with a data logger, which was placed in different locations approximately 1.6m and 1.8m above floor level. The indoor environmental analysis measurements in classrooms included global temperatures (GT), temperatures ($T_{\text{i}}$), air velocity (AV), air temperatures (AT), and CO$_2$ level. Moreover, for better representation of the temperatures in the classroom, the devices were placed in the middle of the classrooms whenever possible, close to the pupils’ working desks and at heights of 0.7m and 0.8m above floor level similar to [14]. Spot measurements included surface temperatures (ST) and thermal imaging. These were made using handheld instruments, as shown in table 1. Table (1) below presents the name, range and accuracy of the measurement instruments.

<table>
<thead>
<tr>
<th>TinyTag-4000 Outdoor and indoor environmental temperature and humidity</th>
<th>PCE-009 Hot Wire anemometers Indoor and outdoor measures of air temperature</th>
<th>PCE-WB-2050 Indoor and outdoor global temperatures</th>
<th>FLIR E40BX - Thermal imaging camera and CEM Dual Laser Infrared Thermometer</th>
<th>CO2 Analyzers PCE-AQD 20 infrared air quality metre: carbon dioxide (CO2) levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 devices</td>
<td>4 devices used</td>
<td>4 devices</td>
<td>2 devices</td>
<td></td>
</tr>
<tr>
<td>Reading</td>
<td>Accuracy ± 0.1°C</td>
<td>Accuracy ± 1.5% of 0-15°C</td>
<td>Measuring range; 0-10000 ppm</td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td>FT ± 1°C</td>
<td>Measurement: 0-1°C/°F</td>
<td>Resolution: 1ppm</td>
<td></td>
</tr>
<tr>
<td>Range 40°C to +85°C</td>
<td>0-1000 ppm</td>
<td>Accuracy ± 0.5%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.3 characteristics of the case study school buildings

The Mansfield school was selected because was newly constructed in 2014 as a low-energy building, using construction materials with energy values as low as 15w/m$^2$ in the school structure, the fabric of the floor, the wall and the roof. Furthermore, heating was provided using central gas and a local control system. A mixed-mode ventilation strategy was applied and...
installed to the rear at ceiling height, controlled through CO₂ measurements and occasionally operated in the classrooms. In addition to operable windows with Low–E double-glazing.

Figure 2: School case study 2. Defined classroom zone within a school building floor plan, indicating the location and disruption of the measurement equipment on each day of field study.

In the Nottingham school case study shown below, the main building is separated into two parts: KS1 and KS2. The newly build KS1 covers spaces from Reception to Year 2 classrooms. This case study school was selected because it was constructed in 2013 as low energy building. The school’s building uses natural ventilation. Figure 3 shows the floor plan and the classroom zone used in the field study.

Figure 3: Diagrammatic 3D model and Google Street View image of the second case study primary school.

5. RESULTS AND DISCUSSION
5.1 Overheating vs AT vs GT vs occupancy vs opening Schedule.

In case study 2, measurement of the classroom CS2YRF is shown in Figure 4 during school hours. The classroom faces south and has only single-sided ventilation, as the door and window would not open at the same time. The internal roller blind was up most of the time; however, the windows are covered with pupils’ drawings and work to prevent solar radiation. As can been seen in the results, the temperature recorded was 23.8°C at the start of the day. A possible explanation for this might be that the window and door were open when the classroom was unoccupied or before the start of the school day. Then the temperatures gradually increased to reach more than 26°C at 8:54 and started to slightly fall when the Reception class children went to play outdoors. GT and AT rose to a high point and peaked at 13:30, which was the end of the school day. Recorded temperatures ranged from 26.5°C to more than 27°C when the windows were open and the door was closed.

Figure 4: GT and AT in classroom code CS2YRF (case study 2).

Figure 5 illustrates the minimum, maximum and average temperature for every hour during the typical school day in two classrooms. Figure 4 shows that the recorded temperatures are significantly higher than the benchmark temperatures recommended by CIBSE.

Figure 6 shows the percentages of monitored classroom temperatures that were above benchmark levels. The respective values for GT and AT above 25°C were 42.76% and 41.08% on 2nd July 2019. On 4th July 2019, GT and AT were 67.88% and 64.12%.

Figure 5: The minimum, maximum and average (a) AT and (b) GT recorded through the typical school day in two classrooms.
5.2. Air quality vs CO2 level vs temperatures vs occupancy

CO2 concentration was measured for each day of the working week between the hours of 8:10 and 15:30. The results showed that CO2 levels increased rapidly from the start of the day, reaching three to four peaks during a typical school day. Figure (7) shows a typical correlation of CO2 concentration with relevant temperatures and AV. The CO2 concentration rose from the start of the day, reaching 1800 ppm, and peaked when the children came into the classroom. When the window was opened, the CO2 concentration decreased and stabilised between 1200 ppm and 1000 ppm. It decreased during morning break and when the classroom was empty during the physical education lesson. CO2 increased again when the classroom was occupied after the break, reaching another peak of more than 1500 ppm for a 20-minute interval. CO2 concentration decreased again in the afternoon break, followed by two other peaks of 1800-2000 ppm in the afternoon before afternoon break, and before the end of the school day. The large variations in CO2 concentration over the different days relate to large variations in both the occupancy level and the way in which windows and doors were left open. However, as this is an airtight newly built school, constructed in 2014, the CO2 level did not dramatically dilute during the breaks when the classroom was unoccupied.

In terms of the overheating assessment of the selected classroom, the external weather condition during the field’s measurement on 4/7/2019 was observed in the figure (7) and (8). The variation in the recorded air temperatures between internal classroom and external was observed to reach up to 5°C-6°C. Which fall below the BB101 (Building Bulletin) and CIBCE (Charted Institute of Building Services Engineers) standards. As the figure, show the air temperatures for the whole periods against the corresponding outdoor air temperatures for every 30-second intervals. Indoor air temperatures rose a respond of the outdoor temperatures steadily and respond to the occupant density as well as the window and door schedule. A steeper increased in the air temperatures between 27.3°C-27.5°C inside the classroom between 9:30 – 10.11. Then followed a slight fall in the temperatures between 26.4°to 26.2°C.

The slight decline may be due to window opening by the occupant. The figure demonstrates the air temperatures profile of the classroom monitored in the typical fields study was reveals that the classroom experience overheating as the temperatures vary between 25°C and 27°C which the temperature exceeding the Cibce fixed thresholds - dashed lines.
It is clear that both classrooms had poor IAQ. The proportion of time that the CO₂ level exceeded 1000ppm was 62.19% and 64.52% in classroom year_2 and classroom year_1 respectively. The results show that monitored classrooms are overheated more than 60% of the occupied time. The internal air condition and temperatures every year and at least a 7°C increase by the end of the century. The internal environment in one of the new schools is too “lenient” [8]. In particular, for low-carbon schools to be produced there should be greater consideration of insulation and airtightness, causing more heat to be retained in the classrooms. Classrooms’ IAQ was affected by the existing ventilation design strategies or lack of them, as a result of an adjoining corridor design. Therefore, it is apparent that the existing designs did not consider the implementation of openings or windows to improve cross-ventilation. The design of singular corridors/classrooms/cluster-learning spaces will prevent cross-ventilation. The results in this paper indicate that the next step, therefore, is to discuss how future designs of schools can adapt to the changing UK climate. The potential solution such as will be presented in our future works.

Acknowledgment

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REFERENCES

The Overheating Risks in Myanmar Vernacular Dwellings: Indoor Thermal Environment Study from Measured and Simulated Data

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ABSTRACT: Despite Myanmar’s alarming Climate Change Risk Index, no regard is given to the possible impacts of climate change in vernacular housing. Using empirical and simulated data sets, this paper investigates whether free-running dwellings in Myanmar can provide thermal comfort in the present and future climate scenarios based on wet-bulb and heat-index analysis. Warmer hours above the outdoor dry bulb temperature of 36°C increased eight times in 2018 compared to the baseline typical weather year. The results reveal that the monitored dwelling could achieve a 12.5% yearly reduction in warmer hours above 36°C compared to outdoor weather with optimised modifications. The importance of occupant behaviour for adaptive thermal comfort in the free-running dwelling was notable. Regarding the wet-bulb temperature for the outdoor condition, the historical outdoor data for 2018 showed that 7.6% of the annual hours had a wet-bulb temperature between 30°C to 35°C, and 0.7% of the annual hours was above 35°C. In the monitored data set, the monitored dwelling maintained indoor wet-bulb temperature below 30°C. However, the monitored dwelling had a close relation to the outdoor, similar vernacular houses in Myanmar might face overheating risk and have high vulnerability to extreme events in the future due to the long-term Climate Risk Index.

KEYWORDS: Indoor thermal environment monitoring; Building thermal performance; Wet-bulb and heat-index temperature; Climate change; Myanmar vernacular dwellings.

1. INTRODUCTION

Myanmar’s 2014 Census data reported that 38% of dwellings are made of timber, 34% of bamboo, and 33% have thatched roofs [1]; all of these are considered vernacular architecture strategies. Only 16% of dwellings are made of brick and concrete, while 62% have corrugated metal roofs [1]. The practices of vernacular housing seem to have remained remarkably resilient in Myanmar, but no regard is given how the customs in vernacular housing affect thermal comfort and whether they can cope with future climates.

Located an outlying subrange of the Greater Himalayan mountain range, northern Myanmar historically (1926-1950) featured a warm temperate climate with winter dry and warm summer (Koppen climate Cwa). The climate shift depicted by Köppen-Geiger climate classification predicts that the climate Cwa of northern Myanmar is likely to be replaced by an equatorial winter dry climate (Koppen climate Aw) in 2076-2100, due to global trends in observed climate and projected climate change scenarios [2]. Furthermore, Myanmar has been ranked second out of 183 countries in the long-term Climate Risk Index for the period 1990-2018 [3], and it continues to be at high risk. As the current climate change trends are expected to continue throughout the remainder of the 21st century and beyond, the built environment of Myanmar should be prepared for the adaptability of buildings to perform in changing climatic conditions.

However, there is no empirical research that accounts on the effect of climate change on Myanmar housing.

This study attempts to fill the knowledge gap by presenting: (a) the analysis of the indoor thermal environment data sets from the monitored dwelling compared to the weather outdoor from the historic stations; (b) the validation between the indoor thermal environment data of the monitored dwelling and simulation models to undertake the simulation experiments for the predicted future weather scenario. This study will be the first study to investigate the indoor thermal performance of a vernacular dwelling in Myanmar using a one-year monitored data set.

2. METHODOLOGY

2.1 Monitoring process

The monitored dwelling (Figure 1) was selected from a rural area of Myitkyina - a northern highland city in Myanmar. The naturally ventilated brick-nogging dwelling faces almost due north and is adjacent to similar detached houses. The whole building covers an area of about 63 m², with a maximum length of 8.4 m and a maximum width of 8.4 m; the total floor area is about 126 m². A private office is located at the ground level where the dwelling envelope is built with brick walls, timber posts, and a concrete floor. Residents live at the first-floor level, where the dwelling envelope is built with timber floor, timber walls (at the front) and bamboo
woven walls (at the side and back). The timber-framed Dutch gable roof is covered with zinc sheets, and small gable vents on the pediments of the Dutch roof allow the removal of hot air from the first-floor level rooms.

The monitored room, which is the living room on the first-floor level, has bamboo woven partitions, a timber ceiling (at the first half of the room) and a bamboo woven ceiling (at the second half of the room), from which the roof ventilation uses high air permeable ceilings and gable vents. The windows at the front of the dwelling consist of timber-framed glass and louvre windows. The other windows consist of timber-framed glass panels and timber panels. Portals are timber-panelled, double-leaved doors. The indoor air temperature and indoor relative humidity were continuously monitored from 01/01/2018 to 31/12/2018 at 30-minute intervals using a Tinytag TGU-4500-Ultra-2 Gemini data logger.

Figure 1. Location of the monitored dwelling in Myitkyina, instruments for measurement, location of a monitored room, and elevations views of the dwelling.

2.2 Simulation and analysis methods

The simulations were performed using the Integrated Environmental Solution software (IES) [4]. The simulation model had a low thermal capacity and insulation in walls and floors, and poor insulation and low solar absorptance value in the roof. Table 1 and Table 2 show the characteristics of the simulated dwelling, including material properties, occupant activities, internal gains, and window and door operation time. In this work, outdoor dry bulb temperature (DBT), indoor air temperature (AT), relative humidity (RH), wet-bulb temperature (WBT) [5] and heat index temperatures (HT) [6] were utilised to analyse the data. The WBT is widely used in the heat-stress index to assess health risks in physical work situations based on the heat-humidity threshold. In order to analyse the heat stress risk through the humidity effect, the HT was calculated based on the heat index value, in which the relative humidity was factored in with air temperature. A similar analysis was used in the study [7]. The typical and historical weather files used in this paper were accepted as standard data for simulation for ASHRAE [8]. The typical weather data set was created with data collected from 2003 to 2013. The future weather file was based on the standard typical weather year, also used in the study [9].

Table 1. Internal gains and schedules used in simulations

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupant activities</td>
<td>Three occupants (90 W/person for maximum sensible gain; 60 W/person for maximum latent gain)</td>
</tr>
<tr>
<td></td>
<td>06:00-09:00 am and 16:00-22:00 pm in living room; 22:00 pm to 06:00 am in bedrooms; 09:00 am - 16:00 pm in office.</td>
</tr>
<tr>
<td>Internal gains</td>
<td>Lighting: 8 W/m² for sensible gain and 8 W/m² for maximum power consumption. Equipment: 5 W/m² for sensible gain and 5 W/m² for maximum power consumption.</td>
</tr>
<tr>
<td></td>
<td>Lighting: 18:00-22:00 pm. Equipment: 24 hours.</td>
</tr>
<tr>
<td>Window and door</td>
<td>Front windows (80% openable area). Side windows (80% openable area). Louvre windows (30% openable area). Doors (90% openable area).</td>
</tr>
<tr>
<td></td>
<td>Windows: 06:00 am - 22:00 pm. Doors: closed continuously. Louvers: opened continuously.</td>
</tr>
</tbody>
</table>

Table 2. Material assumption of the monitored dwelling and simulations [10]

<table>
<thead>
<tr>
<th>Components</th>
<th>U Value, W/(m²K)</th>
<th>Thermal Capacity kJ/(m²K)</th>
<th>Solar Absorptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case (as per monitored dwelling)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roof</td>
<td>2.6778</td>
<td>4.0176</td>
<td>0.2</td>
</tr>
<tr>
<td>Ground floor wall</td>
<td>1.7205</td>
<td>83</td>
<td>0.3</td>
</tr>
<tr>
<td>Upper fl. wall</td>
<td>3.0165</td>
<td>15.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Ground floor</td>
<td>0.7957</td>
<td>174.72</td>
<td></td>
</tr>
<tr>
<td>Upper floor</td>
<td>1.9977</td>
<td>15.6</td>
<td></td>
</tr>
<tr>
<td>Ceiling</td>
<td>1.9977</td>
<td>15.6</td>
<td></td>
</tr>
<tr>
<td>Windows</td>
<td>Opague glazing windows with timber frame. Solar heat gain coefficient = 0.292; Visible transmittance = 0.76; U = 5.6890.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doors</td>
<td>Timber door both for external and internal doors. U=2.1863.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infiltration</td>
<td>A rough assumption for air infiltration = 15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. RESULTS

3.1 Air Temperatures

The comparative analysis of the monitored indoor thermal environment data set and the outdoor weather used historical weather file data for the year 2018 and the typical weather file. As shown in Figure
2, small temperature differences between the indoor and outdoor indicate that the indoor thermal environment of the monitored dwelling had a close relation to the outdoor weather, but maintained lower mean air temperature throughout the year. For the outdoor data for the historical weather year 2018 in Myitkyina, 22.8% of the annual hours was above the DBT of 30°C, and 4% of the annual hours was above the DBT of 36°C. For the indoor data set of the monitored dwelling in 2018, 13% of the annual hours was above the air temperature of 30°C and 0.5% of the annual hours was above the air temperature of 36°C. On the contrary, for the outdoor data for the typical weather year of Myitkyina, 12.6% of the annual hours was above the dry-bulb temperature of 30°C, and 0.5% of the annual hours was above the dry-bulb temperature of 36°C. Comparison between outdoor weather data sets revealed that, compared to the baseline typical weather year, the warmer hours above 30°C increased 1.8 times and the warmer hours above 36°C increased 8 times in 2018. Furthermore, the outdoor monthly temperatures above 36°C were significantly increased in the hot and wet season of 2018 (from April to August) compared to the typical weather year. Comparison between indoor and outdoor data sets for the year 2018 revealed reductions in the monitored dwellings compared against the outdoor weather, including 9.8% fewer warmer hours above 30°C, and 12.5% fewer warmer hours above 36°C during the year.

3.2. Wet-bulb and heat index temperatures

Figure 3 presents the proportion of WBT and HT for a year. The indoor monitored data set showed that 41.1% of the annual hours in 2018 was below the WBT of 20°C, compared to 27.7% of the annual hours in outdoors. The typical weather year maintained for 37% of the annual hours a wet-bulb temperature below 20°C. In the outdoor weather of 2018, a total of 8.3% of the annual hours was above the WBT of 30°C, but the monitored dwelling maintained a total of 0.02% of the annual hours above WBT of 30°C. The indoor monitored data set showed that 59.2% of the annual hours comprised a ‘no heat stress’ time, but 51.5% of the annual hours was found outdoors. Conversely, the typical weather file showed that 63.72% of the annual hours comprised ‘no heat stress’ time. There was no ‘extreme danger’ stage in the typical weather year and monitored indoor data set for the year 2018; however, 4.84% of the annual hours was found to be an ‘extreme danger’ stage in the historical outdoor weather in 2018.

In the monitored indoor data set, the highest AT of 34.5°C was found on the 23rd of April and the 18th of August. However, their HT on those days was significantly different due to a combined effect of air temperature and relative humidity. The HT reached 39.8°C on 23rd of April and reached 51.8°C on the 18th of June. Although the RH of December was as high as that of August, the HT of the 1st of December was as low as its air temperatures. The WBT reached 25.3°C on 23rd of April, 30.3°C on the 18th of June, and 19.6°C on the 1st of December.

3.3. Simulation for weather scenarios

The outdoor temperatures for 2018 annual (O2018), the indoor temperatures for the monitored dwelling in 2018 (M2018) and simulation model based on historical weather year 2018 (S2018), the outdoor temperatures of future weather scenario (O-F), and the indoor temperatures of the simulated model for future weather scenario (S-F) were firstly compared in Figure 5. Lower values for mean temperatures, upper quartiles, and upper whiskers were found in the monitored dwelling compared to the outdoor weather and simulated model; that showed discrepancies between the monitored indoor data set and the results of the simulation model. For instance, the annual mean temperature was 25.4°C in the monitored indoor data set, but 26.8°C in the simulation model. On the 23rd of April, the maximum outdoor DBT reached above 45.1°C but the maximum indoor AT reached above 36.9°C in the monitored dwelling, and the maximum indoor AT reached above 45.7°C in the simulation model. The monitored room contained several openings at the front, right and back, and the opening time of the doors and windows could be varied by the occupants throughout the year, depending on the seasons; that could be the causes of discrepancies. Those discrepancies highlighted the importance of occupant behaviour for adaptive thermal comfort in the monitored dwelling. Beside these discrepancies, it can be considered that the simulation model had a reasonably good agreement with the monitored indoor data set.

Similar analyses were undertaken to compare the impacts of the different weather scenarios including the historical weather year 2018, typical weather year and future weather year on the simulation model. As the future weather file was created by adding the predicted temperature increment based on the typical weather year, consideration for the extreme temperatures was excluded in creating future weather file. Despite these limitations, using the same model, the simulation results predicted that the percentage of a year below air temperature 30°C will be decreased in the future weather scenario. Without considering the extreme temperatures benchmark, in the future weather file, it was found that 32.2% of the annual hours was above AT 30°C in the simulation model for the future weather scenario, but there was 25.6% of the annual hours in the simulation model for the historical weather year 2018.
Figure 2. Historical outdoor dry bulb temperature and monitored indoor air temperatures in 2018, Myitkyina dwelling

Figure 3. Proportion of wet-bulb temperatures and heat index temperature in a year for a typical and historical weather year data sets and monitored indoor data set, Myitkyina dwelling

Figure 4. Monitored indoor hourly air temperature, wet-bulb temperature, heat-index temperature and relative humidity in April, August and December, Myitkyina dwelling
4. DISCUSSION

Using a years’ worth of monitored, empirical data with quantitative and analytical simulation experiments, the evidence-based results presented above are vital for a comprehensive knowledge of the local context, and translating theory into real practical applications.

Regarding the DBT for the outdoor condition, the warmer hours increased in 2018 compared to the baseline typical weather year, although there were no extreme heatwave events and considerable high temperatures in the monitored year of 2018; it should be remembered that particularly extreme highs are possible and probable. On the other hand, the hot and cold seasons in the year 2018 were drier than in the typical weather year. Changes in outdoor DBT and RH affect the health risk of the occupants in all free-running Myanmar dwellings due to their dependence on the heat-humidity threshold according to the outdoor weather.

Regarding the WBT for the outdoor condition, the historical outdoor weather of Myitkyina for the year 2018 showed that 7.6% of the annual hours had a WBT between 30°C to 35°C, and 0.7% of the annual hours had a WBT above 35°C. However, the monitored dwelling maintained indoor WBT below 30°C. The outdoor WBT rarely exceeds 31°C worldwide [11].

The indoor thermal environment of the monitored dwelling did not reach the ‘extreme danger’ stage in the year 2018, although 4.84% of the annual hours did in the outdoor weather. As the heat index is a measure of how hot it feels when RH is factored in with the actual AT, the quality of indoor thermal environment depends on the combined effect of AT and RH, the air exchange between the outdoor and indoor, and also how quickly humid, hot air is removed through ventilation. The results of monitored indoor data set showed that the indoor thermal environments of the dwelling maintained lower temperatures and relative humidity than the weather year outdoor throughout the year, due to the use of natural ventilation and building envelope material properties.

The simulation model, a model contained a material assumption of the monitored dwelling, represented the use of vernacular materials such as timber walls and floors but poor roof insulation in the metal roof. Regarding the maximum temperatures of the year 2018, the maximum outdoor dry bulb temperature reached above 45.1°C on the 23rd of April, the maximum indoor air temperatures reached above 36.9°C in the monitored dwelling, and the maximum indoor air temperatures reached above 45.7°C in the simulation model. The results presented here are in agreement with the study [12]: if buildings have poor insulation characteristics or are lightweight, with low thermal capacity, they are likely to produce uncomfortable indoor temperatures during hot summers; the results could be worse in the extremely high-temperature events.

Whilst the monitored dwelling may not be representative of all vernacular dwellings in Myanmar, it does represent passive design strategies, the fundamental construction materials used, and the building envelope performance for the studied climate. However, it is necessary to note some limitations of this study.

1) The importance of operative temperatures and the threshold for thermal neutrality for free-running buildings like the monitored dwelling were excluded in this work.

2) The heat index equations are generated from a heat balance condition with a list of 20 fixed assumption factors. One should not forget that the airflow rate in the heat index equations is a fixed assumption; therefore, the heat index equation is not directly applicable to a free-running condition. The analysis undertaken in this work was only aimed to calculate the degree of heat stress based on the humidity effect rather than the occupant’s thermal comfort.

3) The results of simulations were limited due to assumption for the boundary conditions, air infiltrations, internal gains, occupant behaviours for door and window opening times; therefore, act situations in real-world scenarios could be different.
5. CONCLUSION

Using empirical data sets and simulations, the building thermal performance study in this paper pieced together an understanding of how the climate affected the performance of the observed dwelling. Comparison between different weather data sets showed a 1.8 times increase in warmer hours above outdoor dry bulb temperature of 30°C, and an eightfold increase in warmer hours above the outdoor dry bulb temperature of 36°C in 2018 compared to the baseline typical weather year. In the indoor data set of the monitored dwelling in 2018, 26.64% of the annual hours was above the air temperature of 28°C, 13% of the annual hours was above the air temperature of 30°C, and 0.5% of the annual hours was above the air temperature of 36°C. Against the outdoor weather, the monitored dwelling maintained indoor WBT below 30°C and also showed the capability to maintain low heat index temperatures, below the ‘extreme danger’ stage, against the outdoor weather (which reached this stage for 4.84% of the annual hours). Therefore, it can be predicted that the monitored dwelling has some degree of thermal and ventilation performance to respond to the outdoor weather (with a 12.5% reduction in yearly warmer hours above 36°C in the monitored dwelling against the outdoor weather).

Although the indoor thermal environment of the monitored dwelling maintained lower temperatures and relative humidity than the outdoor weather throughout the year, as it also had a close relation to the outdoor weather, a prediction can be made that the monitored dwelling (and similar vernacular houses in Myanmar) might face overheating risk and have high vulnerability to extreme events in the future due to the long-term climate risk index. Further studies are necessary to investigate applications to achieve greater thermal comfort for future climate scenarios.

All results obtained from this work were generated from the living room of the monitored dwelling, which is from a single sample. In order to identify what impacts climate change may have on Myanmar vernacular building, a large monitoring data set including bedrooms is necessary.

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REFERENCES


Are nZEBs Nearly near Zero Enough? 
Considerations of nZEB Housing and Standards as a Solution to Building Associated Climate Change

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ABSTRACT
All new dwellings in the European Union are to abide by the near Zero Energy Building (nZEB) Standard from 2020. According to this standard will result in a much improved next generation of residential buildings, over buildings built even ten years ago. This study, however, investigates if considering the urgent matter of climate change, buildings built to this standard are even efficient enough. Or more pertinently it asks even if we build these new buildings to these high standards, are we building too many buildings? Is there enough of our ‘carbon budget’ remaining, or might the construction and operation of a new cohort of buildings push us beyond boundary limits? This paper evaluates nZEB in the context of the above narrative. It places nZEB as the optimum build solution for that which will be built and then questions if the nZEB standard is stringent enough. Does it stipulate a performance that is near enough to zero? And can it capture the full range of performance in and across nZEB homes. Are broader or stricter regulations required to ensure these buildings are nearly zero in operation. Or as previously questioned, is building a folly when considered in light of the greater climate crisis context?

The paper outlines a thought experiment based on construction projections until 2060. Phenomena of building usage are identified using some real data from case study buildings of the nZEB101 project.

1. INTRODUCTION
The answers to the questions are not simple, and boundaries are difficult to clearly define. The solutions also are not clear and certain. In the general field of construction, building science is given relatively little attention. It is caught in a space between the fields of architecture that is disinterested in sustainability and a construction industry that often sees sustainability as a promotional tag. Further the construction industry is a pillar of economic growth in any capitalist society, and as such real change is unlikely as systems and structures remain the same. Even as these systems and structures fail completely to deliver for the basic needs of people, they remain inert. For example in many countries there is an urgent need for housing and this is driving calls for an increase in construction activity and house building. Righting of societal failings in the short term has cause over consideration of long term, less certain, projections. In that case when we do build, however, at the very least we should build with the lowest impact, and to the highest standard of operation. Contemporarily that standard in Europe is the nZEB standard – a standard for ‘low’ energy operation (but not for low impact construction).

The nZEB101 project [1] is interrogating nZEB housing in operation, by evaluating a proposed 101 homes, and comparing performance across this set of homes of variable design, construction typology, heating and ventilation methodologies.

Results and data from this project are used in this paper to show the performance benefits of adapting buildings to nZEB. Results, however, also exhibit a wide variability in performance for housing retrofit to the same high standard. These results are used to present the central role of the occupant’s personal living habits in shaping the energy usage within the home. The presented results are discussed with reference to retrofit but are also assumed as a proxy for new build to enable discussion of housing in the round. Much is claimed for nZEB, by proponents and players within the energy efficient housing sector. However, to measure the real and relative benefit of nZEB, we must look at the impact of the housing industry as a whole, the possible gains that can result from designing to a higher (nZEB) standard but also the carbon cost of construction activity. Any reductions, or predicted reductions, in carbon intensity deriving from designing to an nZEB standard have to be placed in the context of total housing production – which is rising, housing size – which is rising, building design life – which is falling and...
the actions of people – which are only ever certainly uncertain.

It is important from the outset to be clear and upfront about the limitations of this study. This paper does not pretend to be a rigorous scientific study of some houses and some data. It is an explorative analysis of the future impact of building even to an nZEB standard. It uses results from other studies to project future possible energy housing related carbon impact. It then evaluates the significance of these in the context of climate change, by evaluating them relative to remaining carbon budgets.

2. CLIMATE, CARBON BUDGETS AND BUILDINGS IN USE

Eminent climate scientists predict imminent risk and call for urgent response. Reduced order, approximation models predict global warming will cross dangerous thresholds as soon as 2036 [2]. A recently released United in Science report by the World Meteorological Organisation predicts current plans would lead to a rise in average global temperatures of between 2.9°C and 3.4°C by 2100, a shift likely to bring catastrophic change across the globe [3]. These are just two examples of the many studies that now abound reporting frightening prospects for climate change. A recent study reported that in worst case scenarios areas currently home to a third of the world’s population will be as hot as the hottest parts of the Sahara Desert within 50 years. Even in their most optimistic outlook, 1.2 billion people will fall outside the “climate niche” of human comfort in which humans have lived over the previous 6000 years [4]. Air conditioning usage is expected to grow considerably and is already increasing at an alarming rate globally [5]. The IEA projects that as the rest of the world reaches similar levels of usage to the USA, air conditioning will be associated with about 13% of all electricity worldwide, and produce 2 billion tonnes of CO₂ a year.

Looking further into the climate change science, and particularly the remarkable work of the climate modellers, offers opportunity to put current and possible future building related emissions in an understandable context. Model prediction results from mid-2019 estimate a remaining carbon budget of 480 GtCO₂ for a 50% chance of remaining below 1.5°C, with other models reporting uncertainty bounds that drop the total to as low as 100GtCO₂ [6,7]. Numbers in the trillions (giga) of tonnes are difficult to grasp, and a general hinderance to wider understanding of the climate crisis, and in this case construction’s association with it. Their impact is lost due to their very scale. In fact, the carbon totals listed in themselves are not particularly insightful, when aiming to understand the impact of buildings. Evaluating with respect of the emissions of the current building stock offers more insight. This paper further looks to the future stock, and assumes an nZEB standard of operation to evaluate performance of the full cohort into the future.

The operation of buildings in existence globally resulted in the release of more than 3 trillion kgCO₂ (or 3GtCO₂) in 2018. There was a brief period of decrease in recent years but the total increased again last year, and has generally been on an upward trajectory [8]. This is even though environmental awareness, and cognizance of the factors that cause this high total, have increased in recent years. When direct and indirect emissions from electricity generation and commercial heating are taken into account this number is more than tripled. The International Energy Agency report over 10 trillion kgCO₂ (or 10GtCO₂) in 2019 related to buildings, the highest level ever recorded. Although definite proportional breakdown is not easy come by, it is generally assumed that energy/ emissions related to buildings are split near evenly between commercial and residential buildings.

Assuming these numbers the impact of running all our buildings in existence today until 2060 equates to 380GtCO₂. However, 380GtCO₂ does not account for the carbon emissions from the operation (or construction) of new buildings that will be added between now and 2060. The need to ensure all future construction is limited in its impact is obvious. Perhaps even much of construction - which has so often been flippantly undertaken, even celebrated as a boon to national and global economy - should be reconsidered into the future. Housing is one sector of construction that has better credentials of necessity. However, with so many countries in crises of limited supply, and an urgent need to meet demand to house the homeless, considerable increase in house construction is essential.

The need to construct this housing to high standards, ensuring minimal impact in construction and in operation is obvious. The nZEB definition in Ireland is described in the Irish Building regulations as a building that achieves an energy performance coefficient of at most 0.30 and a carbon performance coefficient of at most 0.35 – parameters that refer to improvements in performance over a reference building of last decade’s regulations. The original nZEB definition of 2016 for oceanic regions more clearly proposed; 15-30kWh/m²/yr of net primary energy with, typically, 50-65kWh/m²/yr of primary energy use covered by 35kWh/m²/yr of on-site renewable sources [9]. A more straightforward definition even (and the one used in this study for simplicity and clarity) [10] proposes a regulated load of 45Wh/m²/yr with “significant proportion” to be covered by renewables. This energy consumption profile represents a stringent standard
(although no account is taken for embodied energy of construction). By comparison to comply with the Passive House standard, dwellings must consume less than 120 kWh/m²/yr of primary energy. It also represents a considerable reduction in consumption relative to the current level in homes. In Ireland this is documented as 18,000 kWh/yr for an average home but these can vary in size from average of 171m² for a house to 90 m², for an apartment (105-200kWh/m²/yr) [11]. Hence buildings built to a 30kWh/m²/yr nZEB standard can achieve improvements of up to 84-192kWh/yr over the average, per m² of building constructed (when on-site renewables are integrated).

3. CONSTRUCTION AND CONSTRUCTION TO NZEB

Projections for increased global construction are remarkable. Globally it is expected that we will double our current built floor area by 2060 [12].

The following extrapolation uses the referenced values published by the IEA as the basis for calculation of the carbon impact of operation of the buildings that are to be built by 2060. If we assume the same construction growth rate of 2.5% /year to reach that total is maintained, the total amount of carbon that will be added by 2060 will total 572 trillion kgCO₂. This number is remarkable and concerning as it alone exceeds the remaining carbon budgets for a 50% chance of staying within 1.5°C.

If instead all these buildings are built to an nZEB standard and a value of 45kWh/m²/yr is assumed, their impact could be reduced to less than 300 trillion kgCO₂.

The majority of construction growth is expected in developing countries. In Europe - where it is commonly assumed that much of our buildings are built - it is expected that an additional 25 billion m² of floor area will be added [3]. Approximately 75% of floor area in the EU27 is residential [13]. Working with these numbers; >18,750 billion m² of housing will be developed in Europe alone.

Looking at the Irish context in isolation: the National Development Plan for Ireland outlines plans to construct 550,000 nZEB dwellings by 2040. The carbon intensity of electricity in Ireland is 437gCO₂/kWh [14] - a vast improvement on the carbon intensity of only 15 years ago. There are plans to further decarbonise the electricity supply in Ireland and this will improve the carbon intensity further. However, for the purpose of this thought experiment a value of 437gCO₂/kWh is assumed as static. The addition of a single nZEB, of 130m², operating at 45 kWh/m²/yr would add 2556kgCO₂/yr. The addition of 550,000 nZEBs will result in an operational impact of approximately 1.4 billion additional kgCO₂e each year of the full cohorts lifetime operation (130m² (avg. 171 & 90 m²)). Appropriating, a value of 1200kWh/m², in line with the embodied energy of nZEB dwellings in Ireland calculated by Goggins et al. (2016) [15], the energy required to build all houses would approximate 35.5 billion kgCO₂e.

These Irish numbers alone may seem trivial when thought of in the context of the remaining carbon budget (they are in the low billions after all). However, Ireland is a small country with a small, and aging population.

4. NZEB PERFORMANCE AND PERFORMANCE GAP

Further interrogation of nZEB gives insight into the houses in operation. The nZEB101 project aims to uncover design and in-use insights of nZEB in operation through extensive monitoring and performance analysis of a large set of nZEBs. The initial study by Colclough et al [16] documented the energy performance of a selection of nZEB housing in Ireland. Case study housing reported an energy load of 52kWh/m²/yr, with 23% (12 kWh/m²/yr) of the energy load delivered by renewables. This increases to 54% if the heat pump is assumed as a renewable source of energy, i.e. supplied from renewable energy supplies.

In the Irish context the heat pump is a common, although not mandatory, element of the nZEB. It is categorised as a renewable energy source, although the electricity it consumes remains in the majority generated using fossil fuels, including low efficiency peat and coal. In the context of the residences in this study the heat pump accounts for space heating, domestic hot water, and mechanical ventilation system its load is assumed as indicative of the general efficiency of occupant energy usage, although it is recognised that this is a subset of the ‘regulated load’ only. Figure 1 shows the cumulative energy consumption for an integrated heat pump within 8 nZEB dwellings. Each home is small with floor space 40m² and retrofit to the nZEB standard. The data is taken directly from the heat pump unit.
Figure 1. Energy consumption of heat pumps in Irish homes shown as cumulative energy consumption (kWh) against time.

Pertinent to this study, the image shows a wide variation in use performance in these homes. The energy consumption of all homes remain below 800kWh through Spring and Summer but increase considerably during the heating season to reach two and three times that total by end of monitored year (March to March). Two houses in particular – those associated with high internal temperatures – report the highest energy consumption. These results are reported in another paper at this conference by these authors where the actual energy consumption for four of these houses and the internal temperatures are shown to be correlated [17] (Colclough et al, ‘Recorded energy consumption of NZEB dwellings – and corresponding interior temperatures’ PLEA 2020).

Winter data for the same set of houses is shown in Figure 2.

Figure 2. Energy consumption of heat pumps in Irish homes shown as cumulative energy consumption (kWh) against time.

These images show that over the course of a year, or even over the course of a heating period, the variable comfort requirements of occupants result in a widely varying energy consumption. In fact the range of temperatures in which people inhabit in the same climate is remarkable. The interested reader is directed to the other paper by these authors at this conference which reports some remarkable average temperatures for the whole house.

The results are included here as evidence that even in small homes, that receive the same energy efficiency treatment, results can vary widely depending on the living patterns of the occupant.

The corollary to the above results might be assumed to be the same for occupants living in cooling dominant climates. This is particularly concerning in light of the afore mentioned Xu et al study [4] that reports over 1.2 billion people could be living in uncomfortable temperatures by 2060. Certainly some migration flows will result, but if the people who choose to stay, use air conditioning to maintain comfortable temperatures, the impact will be considerable.

5. BETTER, BUT BIGGER AND MORE BOUNTEOUS

This year is the 50th anniversary of the first Earth Day. The number of buildings we have on this planet has grown hugely in that time period. And the energy related to buildings has increased hugely.

To add a positive note to the above narrative there has certainly been a reduction in the amount of energy per m² of floor area. Colclough et al 2020 report values that are a considerable improvement on values for housing previously.

There have also been other gains, we have managed to dematerialise quiet successfully. So things including building products contain less natural resources today than they did 50 years ago. And the energy related to the processing of those materials has decreased. Steel and concrete for example can now be produced with about 60% of the energy used in 1970. Steel for example has gone from between 30-40 GJ/tonne in 1970 to < 20GJ/tonne today [18]. Additionally the carbon intensity of our electricity has reduced considerably and that reduces the impact of producing construction materials for building and the operation of buildings itself.

A tonne of cement today produces about 900kg of CO₂. In the early 1970s it was somewhere closer to 1400 kgCO₂ for the same tonne. However, when one works through the numbers as done in this paper it becomes increasingly obvious that these improvement are swamped by other factors that have increased dramatically in that time.

Primarily the population is more than double today what it was on the first Earth Day in 1970. All of those people have required, and continue to require buildings. Not just housing, but also workplaces factories, offices, and increasingly, sports and leisure spaces. Of course with huge variation depending on which country you’re born in. However, the key point is that the floor area that we build today has increased hugely.

The seminal text Growth [19] by the eminent scholar Vaclav Smil outlines, with reference to national statistics, the huge increase in resource consumption generally, but pertinently for this study built floor area. It has increased by approximately 33% in Europe since the early 1970s. The single-family American house has gone from 150m² 1970 to over 250m² today. And in China the floor area per capita has increased almost 10-fold.

The embodied carbon impact is huge, but even more significant is the operational energy required to run these buildings.
And as people in the developing world demand better standards of comfort like they have in Europe and the US since the early 70s energy related to comfort including space heating and air conditioning as examples are increasing dramatically.

We have much work to do to reduce energy related to buildings. While nZEB is a move in the right direction but it seems that without some curb on the amount of building that we plan to undertake, even these high standards will fail to ensure a sustainable built environment, or avoidance of certain climate change.

5. CONCLUSIONS

This paper evaluates the impact of a reduction in carbon intensity of housing operation through the stipulation of the nZEB standard for new build. Using projection numbers, it also aims to ascertain the overall impact of projected total housing production - even if built to high energy standards - with regard to climate change predictions and particularly so-called 'carbon budgets' to avoid >1.5°C warming.

With regard to nZEB it is evident that high standards are being set for new housing. Compliance is less obvious, and irrespective of the standard designed to, the occupant can still have considerable impact on final building performance.

The efficiency of housing is improving but the quantity of construction that is projected is swamping all such improvements.

ACKNOWLEDGEMENTS

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Severity of Overheating Risk Across the UK Under a Warming Climate

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ABSTRACT: Spatial variability of climate across a country’s landscape needs to be considered when assessing building thermal performance. However, few studies have investigated the impact of the spatial variability of climate on buildings at a national level. This study aims to assess severity of overheating risk at a high spatial resolution. Dynamic thermal simulation for a typical UK house was carried out for each 5km × 5km grid location across the UK for the 1990s and 2080s, i.e., baseline and future climates respectively. It was found that overheating in the typical house was unlikely to exceed 1% of annual occupied hours in the 1990s but longer than 1% in the 2080s across 89% of the country. Furthermore, the bedroom of the typical house would be overheated longer than 10% of occupied hours in south England accounting for 23% of the country. The severity of overheating was measured by Weighted Cooling Degree Hours (WCDH). The mean and standard deviation of WCDH were 3142 and 2418 in the 2080s, indicating a significantly high spatial variation across the country. It is hoped that the overheating maps presented in this study would help the government make an appropriate building adaptation strategy at a national level.

KEYWORDS: Overheating risk, Spatial variability, Climate change, Weather generator, High resolution mapping

1. INTRODUCTION

It was projected that the likely range of increase in global mean surface temperature is between 2.6°C and 4.8°C under RCP8.5 greenhouse gas emission scenario by the end of the 21st century relative to 1986-2005 [1]. Heat-related mortality and morbidity [2-4] would occur if buildings fail to adapt to warming climate. Domestic buildings in the UK are typically non-air-conditioned. Warming climate therefore would cause a high risk of overheating in the English housing stocks if without sustainable building adaptations. Previous modelling based studies [4-10] predicted that overheating risk in the UK would significantly increase due to warming climate. Unfortunately, optimal combination of various structural adaptations, for instance, installing insulation, thermal mass, shading device and increasing surface albedo could not eliminate the risk of overheating completely in the 2080s [5]. Looking into the future, UK domestic buildings require air-conditioning to keep indoor thermal comfort and avoid heat-related mortality and morbidity. This would largely increase the carbon emission from the UK residential sector which accounted for 17% of the national carbon emission in 2017 [11]. Thus, it is imperative to assess thermal performance of domestic buildings at a national level to help governments to make a sustainable building adaptation plan. In addition, countries with spatially unbalanced development and great topographic variability would see non-uniform regional climate change. It has been found that overheating risk in non-air-conditioned buildings was projected to be highly variable due to the spatial variability of external climate [4, 12]. Therefore, spatial variation in the severity of overheating under a changing climate should be taken into account when making a nationwide cost-effective and sustainable building adaptations strategy. However, it has been difficult to assess overheating risk across a national due to lack of reliable weather data at a high spatial resolution. This study aimed to investigate the the severity of overheating risk at a 5km by 5km spatial resolution across a country for the 1990s and 2080s, i.e., baseline and future climates respectively. Overheating maps would be created at a high resolution for the 1990s and 2080s in this study. It is hoped that these maps would be highly useful for policy makers in identifying the area with greatest concern regarding severity of overheating against warming climate by the 2080s. By doing so, cost-effective building adaptations strategies could be provided to reduce cooling demand in housing stocks at a regional or national level and contribute to build a low carbon nation.

2. METHODOLOGY

2.1 The Spatial Urban Weather Generator

The Spatial Urban Weather Generator (SUWG) [13] can provide synthetic daily and hourly weather data at a 5km by 5km spatial resolution across the UK for the 1990s and 2080s (i.e., future climates under medium
emission scenario). The probabilistic Hot Summer Years (pHSYs) [7] for use in the assessment of the severity of overheating in buildings could be created based on the synthetic weather data generated by the SUWG.

2.2 Thermal model of a typical UK house

Thermal model of a typical UK domestic building was created for assessing the impact of regional climate changes on overheating risk across the country. As shown in Figure 1 and Table 2, the typical building is a south facing detached house with insulated cavity wall (U-value = 1.5 W·m⁻²K) and single glazed windows (U-value = 4.8 W·m⁻²K and SHGC = 0.85). Infiltration rate of the house is 0.7 ach. As presented in Table 1 the maximum air change rate was set to 4 ach. More details for construction, fenestration, internal gains of the thermal model can be found in [14]. Windows were open when internal temperature was higher than 24°C whilst the internal temperature was lower than the external temperature, and during occupied hours (07:00 to 23:00 for the living room while 23:00 to 07:00 for the bedroom).

Table 1 Natural ventilation rates

<table>
<thead>
<tr>
<th>Zones</th>
<th>The maximum ventilation rate (ach)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living room</td>
<td>4</td>
</tr>
<tr>
<td>Bedroom</td>
<td>2.5 (cross ventilation is not possible for security issue)</td>
</tr>
</tbody>
</table>

Table 2. External wall and window construction

<table>
<thead>
<tr>
<th>Construction</th>
<th>U-value (W·m⁻²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External wall</td>
<td>1.5</td>
</tr>
<tr>
<td>105 mm, brickwork outer leaf</td>
<td></td>
</tr>
<tr>
<td>100 mm, cavity ventilated</td>
<td></td>
</tr>
<tr>
<td>105 mm, brick, inner leaf</td>
<td></td>
</tr>
<tr>
<td>13 mm, plaster</td>
<td></td>
</tr>
<tr>
<td>Ground floor</td>
<td>1.1</td>
</tr>
<tr>
<td>500 mm, clay underfloor</td>
<td></td>
</tr>
<tr>
<td>150 mm, concrete floor slab</td>
<td></td>
</tr>
<tr>
<td>50 mm, flooring screed</td>
<td></td>
</tr>
<tr>
<td>Pitched roof</td>
<td>2.0</td>
</tr>
<tr>
<td>10 mm, concrete roof tiles</td>
<td></td>
</tr>
<tr>
<td>- - roof space</td>
<td></td>
</tr>
<tr>
<td>12.5 mm, plasterboard (ceiling)</td>
<td></td>
</tr>
<tr>
<td>Window</td>
<td>4.8</td>
</tr>
<tr>
<td>6 mm, generic clear glass</td>
<td>SHGC=0.85</td>
</tr>
</tbody>
</table>

2.3 Assessment of overheating severity at a national scale

The pHSYs were created for each 5km by 5km grid in the UK (11326 grids) for two time slices: the 1990s and 2080s. Then, 22652 runs of EnergyPlus simulations (= 1 detached house model × 11326 grids × 2 time slices) were carried out using the Balena High Performance Computing system. The QGIS Geographic Information System was used to create high resolution maps of overheating severity for the 1990s and 2080s respectively. Equal interval data classification method was used to present spatial variation in overheating severity across the country. Static overheating criteria (i.e., internal temperatures exceed 28°C for living rooms while 26°C for bedrooms for longer than 1% of annual occupied hours) suggested by CIBSE Guide A [15] as well as Weighted Cooling Degree Hours (WCDH) defined in CIBSE TM49 were used to measure the overheating risk (i.e., percentage of overheated hours to annual occupied hours) and severity in the typical UK house.

3. RESULTS AND DISCUSSION

3.1 Overheating risk in London under changing climates

Figure 2 shows the cumulative hours above the high temperatures for the 50th percentile HSYs for the 1990s (i.e., baseline) and 2080s in London. For instance, the external temperatures warmer than 26°C would occur 593 hours in the 2080s, which is over four times of that shown in the 1990s. The significant differences between the 2080s and the 1990s indicated that there would be a dramatic increase in overheating risk if without any building adaptations.
Figure 2: Cumulative hours above high temperatures for the 50th percentile Hot Summer Years (HSY) of the 1990s and 2080s in London

Figure 3: Cumulative hours above high temperatures for the living room and bedroom of the typical UK house in the 1990s and 2080s in London

Figure 3 presents hours above high temperatures for the living room and bedroom of the typical UK house. Similarly, substantial differences in the internal temperatures between the 2080s and 1990s were presented. For the living room, overheating hours above 28°C were 443 in the 2080s while 38 in the 1990s; for the bedroom, overheating hours above 26°C were 568 and 125 for the 2080s and 1990s respectively (see Table 3). Percentage of overheated hours to annual occupied hours, i.e., overheating risk for the living room and bedroom can be found in Table 3. The living room shows 0.7% in the 1990s which is slightly below the overheating criteria suggested by CIBSE Guide A [15]. However, the living room of the house would exceed the overheating criteria significantly in the 2080s. In particular, the bedroom would be overheated for 17.3% of its occupied hours in the 2080s, indicating an increased occurrence of sleep impairment.

Table 3: Overheating in the typical UK house in London for the 1990s and the 2080s

<table>
<thead>
<tr>
<th>Time slices</th>
<th>Living room</th>
<th>Bedroom</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1990s</td>
<td>2080s</td>
</tr>
<tr>
<td>Annual occupied hours</td>
<td>5475</td>
<td>3285</td>
</tr>
<tr>
<td>Overheated hours</td>
<td>38</td>
<td>443</td>
</tr>
<tr>
<td>Overheating risk</td>
<td>0.7%</td>
<td>8.1%</td>
</tr>
</tbody>
</table>

3.2 Spatial variation in the severity of overheating risk

Looking into other major UK cities shown in Figure 4, differences in overheating risk between them were highly variable. In addition, it was found that the climate change resulted in significant increase in overheating risk, which was in line with previous findings [4-10]. In particular, both the living room and bedroom of the typical house, if located in Glasgow, showed less than 1% in the 1990s which was below the static criteria; however, the overheating risk in the bedroom would increase to 7.8% by the 2080s. Thus, it is imperative to make thermal adaptations for housing stocks in Glasgow and those warmer than Glasgow such as Manchester, London and Plymouth.

Figure 5 shows the maps of overheating risk in the living room and bedroom of the typical house for the 1990s and 2080s respectively. The spatial variation in overheating risk was high across the landscape. For instance, overheating risk for the living room would be less than 1% for the north region in the 2080s while greater than 5% for the south England, and approximately two times of greater overheating risk in the bedroom for the south England compared to other regions in the UK. In the 1990s, overheating risk for the living room was unlikely to exceed 1% (CIBSE Guide A criteria [15]) across the UK while most of the south England exceeded 1% and with some regions up to 5%. For the 2080s, significantly increased overheating risk compared to the 1990s could be found on the maps.
presented in Figure 5. For instance, the living room and bedroom of the typical house would face at least 5% and 10% of overheating risk in the south England for the 2080s.

As shown in Table 4, overheating risk in the living room and bedroom would exceed 1% (i.e., overheating risk criteria defined in CIBSE Guide A [15] ) across the 47% and 89% of the country respectively for the 2080s. Furthermore, 23% of the country showed the bedroom of the typical house would experience overheating risk greater than 10% in the 2080s.

Weighted Cooling Degree Hours (WCDH) [16] was used for measuring severity of overheating risk in the typical house. Table 5 shows WCDH for the living room and bedroom of the typical house for the 1990s and 2080s in four UK cities. The differences between the cities were significant. For instance, London showed WCDH in the living room and bedroom approximately 2.7 times greater than Manchester respectively in the 2080s. In addition, substantial differences in WCDH between the 2080s and 1990s were found. WCDH would be approximately 10 times greater in the 2080s for Manchester, London and Plymouth while Glasgow would see approximately 20 times more WCDH in the 2080s compared to the 1990.

<table>
<thead>
<tr>
<th>Overheating risk</th>
<th>1990s</th>
<th>2080s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living room</td>
<td>&gt;1%</td>
<td>&gt;5%</td>
</tr>
<tr>
<td>Bedroom</td>
<td>1990s</td>
<td>2080s</td>
</tr>
<tr>
<td></td>
<td>0%</td>
<td>21%</td>
</tr>
<tr>
<td></td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Figure 4: Percentage of overheated hours to occupied hours for the living room and bedroom of the typical house.

Table 4: Percentage of the UK areas above the risk of overheating.
Figure 6 shows WCDH across the UK at a spatial resolution of 5km × 5km for the 1990s and 2080s respectively. WCDH was lower than 2000 across the country and unlikely to exceed 1000 for most areas (93%) of the country in the 1990s. However, WCDH would exceed 2000 for 55% of the country while 4000 for 31%, i.e., most South England region. The mean and standard deviation of WCDH for the country were 3142 and 2418 for the 2080s. As the spatial variability of WCDH was highly variable, localised building adaptations should be considered when implementing a cost-effective building adaptation strategy.

Table 5: Weighted Cooling Degree Hours in a typical UK house for the 1990s and the 2080s

<table>
<thead>
<tr>
<th>Location</th>
<th>1990s Living room</th>
<th>2080s Living room</th>
<th>1990s Bedroom</th>
<th>2080s Bedroom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glasgow</td>
<td>37</td>
<td>79</td>
<td>79</td>
<td>1421</td>
</tr>
<tr>
<td>Manchester</td>
<td>190</td>
<td>1813</td>
<td>340</td>
<td>3818</td>
</tr>
<tr>
<td>London</td>
<td>547</td>
<td>4910</td>
<td>1100</td>
<td>10087</td>
</tr>
<tr>
<td>Plymouth</td>
<td>96</td>
<td>1083</td>
<td>298</td>
<td>2709</td>
</tr>
</tbody>
</table>

4. CONCLUSION

Global warming would lead to an increase in overheating risk, hence future climate should be considered when assessing building thermal performance during the lifecycle of buildings. In addition, topographic variation and regional climate change would make a high spatial variation in future climate across a nation’s landscape. This would have a significant influence on thermal performance of buildings. This study carried out dynamic thermal simulation using a model of a typical UK house for each 5km × 5km grid location in the whole UK for the 1990s and 2080s to understand the spatial variation in overheating risk across the country. It was found that overheating risk in the living room of the typical house would be less than 1% (i.e., static overheating risk criteria defined in CIBSE Guide A) in the northern region while greater than 5% in the southern region in the 2080s. For the bedroom, overheating risk would be approximately two times higher in the south England compared to the rest of the country. Glasgow which was less likely experience overheating risk in the 1990s would face a high overheating risk in the 2080s. Therefore it is urgent to make appropriate building adaptations for the cities warmer than Glasgow to avoid the risk of internal heat-related mortality and morbidity. Regarding the severity of overheating, mean and standard deviation of WCDH for the country would be 3142 and 2418 for the 2080s, indicating a high spatial variation in the severity of overheating and cooling load in the English housing stocks across the country. In addition, regional climate change would have a significant influence on overheating risk. The country would be unlikely to experience overheating in the 1990s. However, the bedroom of the typical house would show overheating risk exceed 1% (i.e., the static criteria) across 89% of the country in the 2080s. Furthermore, the bedroom would be overheated less than 5% of annual occupied hours for the whole country in the 1990s but longer than 10% of annual occupied hours across 23% of the country in the 2080s. Also, it was found that differences in overheating between UK major cities would be significantly high due to localised climate. Thus, the maps of overheating risk...
and severity at a high spatial resolution predicted for future climate would be highly useful for building practitioners to identify the amount of differences caused by spatial variability of climate, and for governments in making sustainable and cost-effective building adaptations to avoid climate related disasters at a regional or national level.

Variability of localised building thermal characteristics, vernacular forms and population should be considered for comprehensive investigation into the spatial variability of overheating risk in the future work. By doing so, more appropriate and specific building adaptation strategy could be provided for the region with great concern on overheating risk under a changing climate.

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ABSTRACT: Neonatal mortality rate is unequally distributed across the globe with higher numbers especially in underserved locations such as counties of the Sub-Saharan Africa and specifically in Uganda. One of the biggest contributors is lack of proper infrastructure including neonatal care facilities that can respond to the high demand in the area. The New Neonatal Unit in the rural city of Mbale in Uganda attempts to address this problem by designing to passive low energy architecture standards and is analysed using advanced daylight and thermal simulations in order to meet daylight and thermal comfort during the year. Passive design strategies were evaluated and informed design decisions. The main building ward is reported to achieve high useful daylight distribution and high ventilation rates solely with passive means. Active Photovoltaic Panels offer independence from the grid in the case of power supply failure and water tanks distributed on the site supply the water network with collected rainwater. The facility is aspiring to act as a replicable example of best performing buildings in the healthcare sector in the area and beyond.

KEYWORDS: underserved location, low source energy, early design, healthcare, Uganda, passive design

1. INTRODUCTION

Despite the global progress in reducing child mortality over the past few decades (Table 1), an estimated 5.3 million children under age five died in 2018 – roughly half of those deaths occurred in sub-Saharan Africa. The first 28 days of life – the neonatal period – is the most vulnerable time for a child’s survival. The average global neonatal mortality rate was at 18 deaths per 1,000 live births in 2018. Globally, 2.5 million children died in the first month of life in 2018 – approximately 7,000 neonatal deaths every day. [1].

Table 1: Comparative statistical data for children in Uganda, the UK and the US. Created with data from: UNICEF [2]

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Year</th>
<th>Uganda</th>
<th>United Kingdom</th>
<th>United States</th>
</tr>
</thead>
<tbody>
<tr>
<td>Under-5 mortality rate (deaths per 1,000 live births)</td>
<td>1990</td>
<td>185</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>168</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Infant mortality rate (under 1) (deaths per 1,000 live births)</td>
<td>1990</td>
<td>109</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>2018</td>
<td>34</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Neonatal mortality rate (deaths per 1,000 live births)</td>
<td>1990</td>
<td>39</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>32</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>2018</td>
<td>29</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Neonatal deaths as proportion of all-under-5 deaths (%)</td>
<td>2018</td>
<td>44</td>
<td>60</td>
<td>54</td>
</tr>
</tbody>
</table>

The purpose of this project is to contribute to the reduction of the neonatal mortality rate to the lowest possible level within the region of east Uganda and beyond. The new neonatal unit is designed for the Regional Referral Hospital of Mbale, a small rural underserved city in eastern Uganda with approximately 100,000 inhabitants. At the moment, the existing neonatal facility provides a space that is designed to serve 10 neonates, when in reality the facility may be serving 50 patients together with their mothers at a time.

The new neonatal facility for the Mbale Regional Referral Hospital in Uganda is designed upon the principles of passive architecture. A very low source-energy building maintains a high level of thermal and visual comfort while also maintaining independence form the grid when needed. The building is designed in a way that sensibly addresses the significant challenges of low resource settings, while also contributing to the refinement of related neonatal research, knowledge and skills, and serving as a potential model for the design of similar facilities in other low resource settings.

The building does not utilize any mechanical systems to regulate temperature and humidity, it is solely relying on passive design strategies to enhance thermal comfort and provide adequate daylight. Renewable energy systems are designed to make up for critical times, like regular power outages. Along with the low source energy requirement, the building complex design also responds to additional challenges, such as the requirement to limit construction methods to simple, low maintenance solutions; understand and respect local cultural composition; programmatically and spatially address the extremely low nurse-to-patient ratio (2:50) by facilitating high visibility from one central nurse station to all patient beds and to the entrance; engage hygienic habits (i.e. hand wash, use of
window screens), and provide daylight with multiple user options (adequate levels required for medical examinations and dimmer spaces appropriate for neonates).

2. CLIMATE AND CONSTRUCTION METHODS

Mbale (1.08N, 34.158E, elev. 1,143m) is a city found in Eastern Region, Uganda. The Köppen Climate Classification subtype for this climate is "Am". (Tropical Monsoon Climate) [3]. The climate of Mbale is influenced by its proximity to the equator and its position at the rainy windward foot of Mount Elgon, that is 40 kilometres directly east of the city and rises to 4,320 meters.

Despite its moderate tropical climate, overheating and thermal discomfort have been transformed into a major issue in Uganda. This can be partially attributed to the replacement of traditional construction materials and methods with modern ones, and partially to climate change and global warming [4].

2.1 Climate Analysis and TMY file

Analysis of local climate conditions and building performance modelling presented as challenge to the design team due to lack of reliable recorded weather data in the area. Collection of field data was the only possible way to successfully create a functional typical weather file (Typical Meteorological Weather – TMY file) that could be used for building simulation purposes [5].

The climate of Mbale is warm and humid without extremes and with almost no seasonal variations in temperature throughout the year. On a diurnal basis, large temperature differentials that regularly exceed 10K present a good potential for night purge ventilation (Figure 1).

![Temperature graph](image1)

**Figure 1:** Monthly diurnal Temperature averages throughout the year. Comfort band is plotted as adaptive range for naturally ventilated buildings. Data derived from reanalysis data that was calibrated from summary onsite measured data [6].

Seasonal differences are primarily attributed to rainfall patterns and therefore the year is typically divided into wet and dry period (Figure 2). Year to year variations in annual rainfall can be considerable, and the onset of seasons can shift by 15 to 30 days (earlier or later) [6]. The wetter season lasts from March 24 to November 20, and the drier season lasts from November 20 to March 24 (Figure 3) [7].

![Relative Humidity graph](image2)

**Figure 2:** Monthly diurnal Relative Humidity averages throughout the year. Data derived from reanalysis data that was calibrated from summary onsite measured data [6].

![Precipitation graph](image3)

**Figure 3:** Monthly rainfall averages [8]

2.2 Climate change

Uganda ranks 155 out of 181 countries in the ND-GAIN index (2017). It ranks 166th on vulnerability and 143rd on readiness – meaning that it is very vulnerable, yet very unready to combat climate change effects [8]. The warming trend is projected to continue with some models projecting temperature increase of more than 2°C by 2030 in Uganda [7]. The temperatures in East Africa may rise between 3-4°C in the next 70 years [9]. The magnitude of observed warming in Uganda, especially since the early 1980s, is large and unprecedented within the past 110 years, representing a large deviation from the climate norm, increasing the potential in the frequency of extreme events [6]. Global projections downscaled to Uganda for the 2015-2045 period indicate that there may be an increase in precipitation during December, January and February, which has historically been the dry season across the country. While it is projected that precipitation will increase in some parts of East Africa, warmer temperatures will accelerate evapotranspiration, reducing the benefits of increased rainfall [6].

2.3 Construction Trends

In recent years, globalization and urbanization have challenged the vernacular building traditions and urban forms of East Africa. A similar phenomenon is occurring with building materials, where “modern” materials, such as Concrete Masonry Units (CMUs), are considered to be a sign of higher social rank and financial standing in comparison to traditional, local materials, mud and
timber [10]. This has in part resulted in loss of skilled builders in traditional methods that mostly specialize in modern techniques.

Despite their expensive production and their relative impracticability in construction, concrete block buildings, once completed, require comparatively less maintenance than their wattle and daub counterparts [10]. CMU’s are widely believed to provide a healthier and safer living environment, especially for healthcare facilities.

3. BUILDING LAYOUT AND MASSING

Given the nearly equatorial location, it is recommended that buildings are located on an east-west axis where possible to avoid unnecessary glare and overheating from lower sun angles. Windows are minimized on the east and west elevations and large overhangs provided to the north and south to generate mid-day shade. The roof form is used to create large overhangs to shade walkways and outdoor seating areas [9].

The building complex is developed around two structural grids, one optimally oriented along the east-west axis and one 35° from east-west, following the campus dominant grid (Figure 4). Over 2/3 of patient beds are optimally oriented facing north or south. The layout of the building is organized around four wings. This arrangement is dictated largely by orientation that promotes passive strategies as well as by high visibility demand from the centrally located nursing station. Programmatic requirements called for an additional building that accommodates mothers’ dormitory (intensive cases or babies in isolation), as well as administrative spaces for staff and an educational space for training. The building complex forms two courtyards creating microclimates that favour outdoor thermal comfort and further mitigate solar penetration. The focus of this study is the main building and specifically the single-spaced bed area that houses all beds and the nursing station.

The massing of the building initially adhered to performance-driven rules of thumb that were later optimized based on simulation analysis: tall structure, narrow wings, big openings and ample shading. After quantifying basic rules of thumb as outlined in [9] and using manual calculations, the authors used ray-tracing Radiance based daylight simulations [11], dynamic envelope thermal simulations and static CFD analysis [12] in order to evaluate the effectiveness of envelope building components and appropriately size building elements.

Figure 4: Programmatic plan of the New Neonatal Unit. Highlighted is the study focus: the single space bed area

4. PERFORMANCE DESIGN STRATEGIES

Environmental strategies are divided between those that contribute to thermal performance, to daylight, to water management and to energy generation. (Figure 5)

4.1 Daylight

Windows are to be located in such a way that they provide ample natural light to every space in the building to reduce power consumption as well as the dependency on the irregular electric power supply. Adequate solar protection eliminates the potential of glare and blocks any unnecessary direct sunlight that contributes to overheating. Elongated building profiles with shallow floor depths help with daylight as well as ventilation when orientated on an east-west axis. Light-coloured ceilings help reflect diffused light deeper into a room [10].

Different window sizes and configurations were tested against Spatial Daylight Autonomy (sDA), Annual Sunlight Exposure (ASE) and Useful Daylight Illuminance (UDI) as metrics [13, 14]. DIVA plugged into Grasshopper in Rhinoceros [15] was used in

Figure 5: Environmental Concepts and Synergies
order to parametrically evaluate different configurations for the optimal solution to be chosen. DIVA uses Daysim [16], a Radiance-based daylighting analysis software that models the annual amount of daylight in and around buildings. For south and north orientated windows, overhangs extending from the roof at an angle of 64° from the window sill – the minimum solar altitude angle at noon - blocks most direct sunlight and eliminates glare potential. Openings that face campus dominant direction rely on additional horizontal shading directly positioned above the window head. Movable exterior shutters on all windows allow custom adjustments of lighting conditions per individual requirement (Figure 6).

![Figure 6: Window configuration (below) and three dimensional perspective (above).](image)

Although narrow ward wings assisted in optimizing daylight penetration, the centre of the plan remained a much deeper space leaving the nurse stations considerably underlit. Daylight penetration in such deep space was addressed with a central single-sided, well shaded clerestory.

The simulated study of the final configuration resulted in 76% sDA and 7% ASE. Figure 7 illustrates the Useful Daylight Illuminance (UDI) [17] distribution in the space after implementing all optimization strategies.

![Figure 7: Useful Daylight Illuminance mapping on plan](image)

The key to design in a tropical climate is the roof. Large roof overhangs cover the exterior walls, providing protection from driving rains, and shade from the sun that blocks heat and glare while allowing large openings for daylighting, good ventilation and temperature control [9]. Roof insulation is the most effective strategy to improve thermal comfort and reduce overheating, while insulation on walls and floor may be harmful if not well thought through [4]. The massing of the building accounted for a well-shaded structure with the implementation of a double roof system. In addition, the second roof layer is extended following solar geometry to guarantee elimination of direct sunlight from openings. Thermal and CFD analysis, for thermal mass and natural ventilation studies respectively, was performed in IESVE [18].

4.2.1 Natural Ventilation

Passive ventilation is best created through cross ventilation. This is normally achieved through open windows on opposite sides of the room and via vents (opening at a higher level) above windows and/or doors. Vents enable air-flow to occur even when windows are closed and the room is uninhabited [9].

Natural ventilation on this project acts both as a cooling strategy and as a source of fresh air. Wind in this location is minimal, and the little wind there is comes from all direction throughout the year. While the cross-ventilation strategy works well for the wings as they have relatively shallow depths, the central deeper area where the nursing station is situated was shown to be low in air changes per the initial CFD analysis. Creating pressure differentials through massing and incorporating the stack effect were shown to be beneficial as they do not depend on wind speed or direction to create air-flow. High ceilings and the addition of the clerestory right above the central area introduced stack effect and contributed to the rapid increase in the air change rate. Using wind speed and direction close to the measured average maximum as inputs, the CFD analysis indicates an increase in air changes per hour from almost 4 to more than 15, well above ASHRAE’s recommended values for a new-born nursery suite at 6ac/h [19] (Figure 8).

![Figure 8: Air Changes per Hour (ACH) for two weeks in the month of June. The pattern repeats itself throughout the year](image)

4.2.2 Thermal Mass

External temperature fluctuations that can create hot conditions during the day and cold conditions at
night inside the building within a 24-hour period during the day are mitigated with the use of exposed thermal mass, thus enhancing thermal comfort. A preliminary shoe-box energy model with bulk air-flow simulation was used in IESVE to evaluate the effectiveness of thermal mass. Results showed that on a typical hot day, using exposed thermal mass had the potential to flatten the extremes in the temperature curve for better thermal comfort and keep the indoors cooler by as much as 2.5°C (Figure 9). On an annual distribution level, thermal mass results in additional 10% of the time being within thermal comfort ranges.

4.3 Thermal model

Annual evaluation of the ward space was performed using Energy Plus in ClimateStudio [20]. Thermal comfort range using the adaptive comfort model for naturally ventilated buildings is estimated between 18 and 28°C. Generally, a NICU is kept to higher temperatures, closer to the upper band of the adaptive comfort zone to assist with thermal regulation of babies’ bodies. It is therefore more critical to avoid lower temperatures, since in the current setting, thermal regulation of premature neonates is typically achieved with clothing and kangaroo baby carrying by the mother. The simulated space shows that lowest temperatures never fall under 20°C and very rarely fall under 21°C. Although higher temperatures are common, they never exceed 28°C (Figure 10).

4.3 Onsite renewable energy

In an intensive medical environment power supply needs to be uninterrupted especially for the most vulnerable patients. Operational examples that require continuous power supply are CPAP equipment and ventilators. Complete independence from the grid will be achieved with the use of Photovoltaic (PV) Panels that are placed on top of the roof. The collected energy is stored in batteries and charges a back-up generator. During daytime (roughly 7am-7pm), the hospital shall be electrically supplied from the local district operator. In the event of an electrical failure the back-up generator will activate. During the day the PV array will be generating electricity and charging a battery for use at night. By night (roughly 7pm-7am), the hospital shall be electrically supplied from the energy stored within the PV batteries.

Energy demand calculations were performed based on anticipated use of lighting and equipment and the duration of average outages - up to 8 hours - and assisted in sizing the panels and the storage batteries. All systems were incorporated in the design from the beginning of the project. The active PV area covers the southern part of the main building roof which is less sloped and more optimally oriented for an equatorial location to serve all the year. The available area at this location is estimated at approximately 95m² with estimated energy output of circa 75kWh/day.

4.4 Water management

All roof area is utilized to direct rainwater to three water tanks that are connected to the buildings’ plumping system supplying all sinks, toilets, washing machines and showers. Like with the PV panels, water collection was treated as an integrated system and general massing accounted for its incorporation since the beginning of the design.

5. DISCUSSION

The New Neonatal Unit at the Mbole Regional Hospital adheres to passive building design guidelines suitable to the local climate. Narrow buildings, cross ventilation and well sized and shaded windows provided the baseline for a solar protected, naturally ventilated structure. Although relatively small in size, the programmatic requirements added a certain level of complexity that needed to be overcome with simple and clear solutions.

5.1 Challenges and limitation related to building performance

The biggest challenges related to building performance are associated to constructability, cost and maintenance.

Complex issues were solved with simple geometrical gestures both architecturally and operationally. However, because of the high visibility demand from the central nursing station to all patient beds, to the isolation room, to the high dependency room and to the entrance, the shape of the building resulted in a deep central area that highlighted the implementation of the skylight both from ventilation
—employing buoyance- and from daylight standpoint. The original proposal suggested a double sided skylight that provided useful daylight deep into the building. Structural limitations that collided with the “sacred” plan solution with optimum visibility downsized the skylight to a single sided solution that partially compromised daylight performance at the core of the building.

The roof shape and its function as solar energy collector and water collector needed to be simplified on various levels along the design process. The main driver for that were maintenance concerns that derive from simple lack of staff able to properly clean and maintain the building as well as inability to get access to replacement parts in case the system fails.

Performance studies showed from the early analysis that complete autonomy of the building could only be achieved with the use of photovoltaic panels and back-up generator. In several stages during the project, there was a level of uncertainty as to whether such investment was feasible due to the tight budget that is entirely relying on donations. It was only when a certain budget was secured that the PV panels became an integral part of the design.

5.2 Potential of the project

The building design is aspiring to become a model building for similar applications. The programmatic and operational specifics of the project called for a unique architectural solution to a complex problem. However, the overarching approach and guidelines relevant to building performance for an inpatient healthcare facility with extremely low staff-to-patient ratio in an underserved location in a tropical climate can be applicable in similar settings.

Bringing this design to a remote location away from the capital is setting a precedent for future applications, where human-centric, comfort-driven and sustainable solution can reinforce the application of autonomous buildings when it is mostly needed.

6. CONCLUSION

Daylight and thermal comfort analysis created the foundation for environmental building strategies and optimized building elements to minimize energy demand. The New Neonatal Unit for the Regional Hospital in Mbale is an exemplar design that provides design guidelines for a demanding healthcare building in an underserved location, both from uninterrupted energy demand and from programmatic requirements standpoint. With the aid of computational analysis, environmental strategies were evaluated, classified in importance and optimized. All restrictions of a low resource setting in eastern Uganda were taken into consideration and the design is aiming to act as an example for future structures in a similar context.

This initiative is just one part of the coalition of different disciplines that have come together in order to decrease neonatal mortality rate in Uganda and beyond.

REFERENCES

18. https://www.iesve.com/
ABSTRACT: This paper aims to analyze what was accomplished by the Brazilian academy concerning the environmental impact of the built buildings of the housing program Minha Casa Minha Vida (PMCMV), during its 10 years of implementation. Twelve master’s dissertations and 8 doctoral theses from the engineering and architecture areas were analyzed, seeking to understand the panorama of the buildings concerning the areas of sustainability, construction performance, and levels of energy efficiency. As a result of the analysis of the 20 selected studies, it was possible to verify the low architectural and constructive quality of the model executed throughout Brazil, as well as the great importance of reevaluating the bases of the program, adjusting its parameters to more sustainable initiatives.

KEYWORDS: Environmental Impact, Social Housing, Sustainability, Performance, and Energy Efficiency

1. INTRODUCTION
In 2019, the Brazilian Housing Program “My House My Life” (Programa Minha Casa Minha Vida – PMCMV) completed 10 years. It is the main program that subsidizes houses to families earning up to three minimum salaries and is related to almost 90% of the total deficit homes of the country [1].

During this period, more than 4 million homes were delivered throughout the country [2]. It became one of the largest programs in the sector, increasing the number of new construction jobs in the related working areas and fostering the Brazilian economy from 2010 to 2014. Due to its scope and relevance, 2,477 articles, master’s dissertations and doctoral thesis were written, during this period, to evaluate its implementation, considering both positive and negative aspects [3,4].

This paper aims to analyze the results obtained by doctoral thesis and master’s dissertations which focused on the environmental impact of the program, in search of the improvements that could be implemented in the MCMV.

2. BACKGROUND
Since the 60s, Brazil has been trying to implement social housing because of the high demand for housing in the country. It started with the National Housing Bank (Banco Nacional de Habitação – BNH), which was extinguished in 1986.

With the Real Plan, instituted in 1994, the country had a moment of economic stability, which encouraged the decentralization of housing policies to its federative states. In 2001, the Statute of Cities was created and, in 2004, the Ministry of Cities was established to analyze, study and evaluate how to improve and assist the growth of Brazilian cities [3,4].

These were the key points for the configuration of the PMCMV, introduced in 2009, which determined that the financial supports would be centralized in the Federal Government. At that year, Brazil had a housing deficit of over 9 million rising to about 12 million in 2010. Based on the research conducted by Fundação João Pinheiro (FJP), the home deficit in Brazil decreased from 2010 (at the beginning of the MCMV Program) until 2012 and had a small increase from 2013 to 2015, as shown in Figure 1 [5].

Figure 1: Relative housing deficit in %. (2015). Adapted by the author based on FJP.
The PMCMV is nationwide and is organized into 5 income target groups. It begins with target group 1 (families earning up to three minimum salaries, which also concentrate around 90% of the national housing deficit) to the target group 3 plus [2]. Table 1, presents the income requirements for the two target groups representing the population with fewer resources.

<table>
<thead>
<tr>
<th>T.G.</th>
<th>Income</th>
<th>Allowance and installations</th>
<th>Interest rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Until R$ 1.800,00</td>
<td>Up to 90% subsidy. Up to 120 months</td>
<td>Maximum R$ 270,00 monthly. Interest 0%.</td>
</tr>
<tr>
<td>1,5</td>
<td>From R$ 1.800,00 until R$ 2.600,00</td>
<td>Up to R$ 47.500,00 subsidy. Up to 360 months</td>
<td>5% interest year.</td>
</tr>
</tbody>
</table>

As for the project specifications, the program requires that the residences should be designed as follows: 1 double bedroom, 1 single bedroom (for two single beds), with kitchen, 1 bathroom and a laundry area. It allows a minimum area of 36 m² to 38 m² (if the service area is internal) for single-family buildings and 41 m² for multi-family buildings. For the items of comfort and energy efficiency, the recommendations are the night time cross ventilation and ceiling fans for bioclimatic zones 7 and 8 (the hottest). There are no recommendations for the others, only the obligation to comply with the performance requirements of NBR 15 575 [2].

Driven by the program, the country has experienced years of heating in the construction sector, generating countless jobs, delivering more than 3 million housing units and helping economic growth and our consolidation. Given this scenario, land value begins to rise exponentially, causing a reduction in the quality of the buildings in the interest of the enterprise’s profit.

This low quality will cause future problems, as can already be seen in the maintenance and repair of the buildings constructed for the program, plus the impact they generate on the environment. The construction industry is responsible for the consumption of approximately 50% of the world’s natural resources [6], for this reason, it is considered one of the least sustainable activities on the planet.

Regarding the quality of the houses delivered by the program, the results of the audits of the Tribunal de Contas da União (TCU) executed in November 2012 and January to March 2013 [7] and the Controladoria Geral da União (CGU) in 2016 [8] were presented.

The TCU report, evaluated 11 buildings with no more than 5 five years of use, of the target group 1, obtaining the following results: 31.9% had constructional defects; 23.2% have inadequate dimensions, with inadequate materials and facilities without leisure or common-use equipment; 21.7% have deficiencies in the asphalt pavement, paving, urban drainage and sanitary/sewage system and 13% do not have accessibility devices.

In 2016, the CGU report analyzed 195 constructions of target group 1, in 110 Brazilian municipalities between 2012 and 2014, representing a universe of 688 homes, found the outcome: 30.8% presented cracks or fissures, 29% had problems with infiltration, 17.6% with leaks and 12.3% with the roof.

These results were from a sample of buildings with less than 5 years of use and for the most needed owners and for those who are not able to afford repair.

Associated with these factors of low constructive quality, of which buildings that have not yet reached their useful life period, there are also pathologies or constructions defects, there is a pattern of monotony and architectural disqualification in the model currently used countrywide.

Due to the importance of the program and its dimension of construction, it is a topic of extreme relevance for the country, of which it was studied by several academics, in the sense of analyzing the good practices and learning from the mistakes made from the already consolidated experiences.

3. METHOD

According to the systematic literature review on the PMCMV, carried out between 2010 to 2016 in all knowledge areas [4], 750 papers such as dissertations and thesis were written. With that data, was conducted a bibliographic reviewing, focusing on dissertations and thesis on Engineering and Architecture areas, oriented to environmental improvements of the PMCMV, considering the period between 2009 to 2019, as part of the author’s doctoral thesis and were analyzed during April and May 2019.

The review had as main objective to understand the environmental panorama of the housing units which were delivered by the program, to analyze and understand the residences scenario. Originally were defined as the guidelines to the research pursuit determining the search keywords: environmental sustainability, energy efficiency, and performance.

According to the filters used a total of 183 dissertations and theses papers were found, of those 38 were doctoral level and 145 were master level. The data was researched using the search platform Thesis and Dissertation Catalogue of the Brazilian Ministry of Education.

This result was divided into three categories: sustainability, energetic efficiency, and performance. After the reading of the abstracts were chosen 20
investigations for analysis, as follows: 8 theses (5 of Architecture and 3 of Engineering) and 12 dissertations (6 of Architecture and 6 of Engineering). The result researchers were divided into three categories as follows:

Sustainability: 10 researches (3 Architecture Thesis and 3 Architecture Dissertations. 4 Engineering Dissertations).


4. RESULTS

As a quantitative result of the research, it is evident that the largest production year was 2017 and the region with more studies at this scope was the state of Rio Grande do Sul (RS), as can be seen in table 2.

Table 2: Thesis and Dissertations- year, location, method, and category.

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Method</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>SP</td>
<td>Interviews and visits</td>
<td>Performance</td>
</tr>
<tr>
<td></td>
<td>RS</td>
<td>LCAE</td>
<td>Sustainability</td>
</tr>
<tr>
<td></td>
<td>All country</td>
<td>LCAE</td>
<td>Sustainability</td>
</tr>
<tr>
<td>2013</td>
<td>MG</td>
<td>NBR 15 220, 15 575, 10 151 and 15 152.</td>
<td>Performance</td>
</tr>
<tr>
<td></td>
<td>SP</td>
<td>Simulation</td>
<td>Performance</td>
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<tr>
<td></td>
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<td>NBR 15 220 and 15 575. RTQ-R and Selo Azul</td>
<td>Energy Efficiency</td>
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<tr>
<td>2014</td>
<td>SC</td>
<td>“MASP – HIS”</td>
<td>Sustainability</td>
</tr>
<tr>
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<td>All country</td>
<td>Mathematical model</td>
<td>Energy Efficiency</td>
</tr>
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<td>2015</td>
<td>RS/RJ</td>
<td>Embodied energy and CO₂ emissions</td>
<td>Sustainability</td>
</tr>
<tr>
<td></td>
<td>MT</td>
<td>Simulation</td>
<td>Energy Efficiency</td>
</tr>
<tr>
<td></td>
<td>SC</td>
<td>Selo Azul</td>
<td>Sustainability</td>
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<td></td>
<td>SP/BH</td>
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<tr>
<td>2016</td>
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<td>Selo Azul</td>
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<td>Mathematical model</td>
<td>Energy Efficiency</td>
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<td>RS</td>
<td>LCA</td>
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<tr>
<td></td>
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<td></td>
<td>RJ</td>
<td>Analysis</td>
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<td>SP</td>
<td>Interviews and visits</td>
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<tr>
<td></td>
<td>RJ</td>
<td>Mathematical model</td>
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</table>

As for the study method, the computational simulation was the most used, as EnergyPlus the software used to measure the Energy Efficiency and CFX to measure the ventilation. Concerning the sustainability analysis, the Brazilian label Selo Azul da Caixa was used to analyze the cases and the validation of the tool itself into sustainability level on its three pillars (environmental, economic, and social).

From the analyzed researches, it was possible to verify that the PMCMV is relevant to the country, also generating employment and income. In other hand, it has also contributed to the rising in land value, social and spatial segregation, once the buildings are built, in the majority, in outlying areas, increasing residents’ commute to work, and even in accessing leisure facilities, supermarkets and schools [3, 4].

They are constructed on 5 floors, as the Brazilian normative permits this height without the need for elevators. Normally, the buildings are constructed without a good solar orientation, too close to each other and with the same architectural pattern all over national the territory.

These characteristics contribute to an architectural monotony, to the lack of privacy and the increase of energy consumption. It also contributed to the indebtedness of the poorer population, that have, now, higher condominium bills for water, electricity, and gas than they could afford, generated by the poor solar orientation and quality of the building materials used in the construction. Figure 2 reveals the reality of most of the MCMV buildings.

As a social housing program, the MCMV has not fulfilled its purpose. Unfortunately, many of the units were hindered to adapting to the family realities, the location is far from places of work and Essential Services. According to the Sustainability researches, it’s verifiable that the program has a lot to improve in this regard. Analyzing the energetic life cycle assessment of the Steel Frame construction systems, structural ceramic masonry, and concrete at a single-family residence with 39.57 m², the results of embodied energy to the three systems were: 3.9 GI/m²; 3.0 GI/m² e 6.6 GI/m². It can be verified that
the ceramic, commonly used in the country, is the one which causes less environmental impact [9].

To the Porto Alegre case, the energetic life cycle of 7 different construction typologies of the program was analysed: 5 single-family residences between 32 and 46 m² of ceramic masonry and reinforced concrete structure; 2 apartments in multi-family buildings, of 46 and 42 m², of structural ceramic masonry and concrete with prefabricated structure and 1 single-family residence with 30 m² constructed in Wood Frame System. The research has analyzed the total energy generated by each habitational unit in the 3 phases, pre-operational; operational and post-operational, concluding that the most of the energy used occur at the operational stage and the Wood Frame system is the one with more total energy generation, generating 31.83 GJ/m². It concludes that, for the pre-operational phase, the energetic average of the buildings studied was 129,88 GJ, if we calculated this value for the 2009 habitational demand, we would use the total of 10% of the energy consumed in Brazil or 27% of the oil consumed at the same period [10].

Regarding the analysis of the life cycle assessment, the research of the single-families houses of 40,29 m², constructed to the target group 1, built with concrete walls in Porto Alegre, RS, identified that replacing concrete by ceramic brick could potentially reduce from 5 tCO₂eq for the 700 residences and to 10,5 million tCO₂, considering the 2,3 million houses built until the moment of this research. [11].

On the national level, considering the target group 1 and 2, it was analyzed a single-family residence with 46 m², regarding the energetic, environmental, and social-economic impact caused by the materials employed on the building. If we use eco-efficient materials as cement-soil bricks, plant fiber tiles; ecologic cement and bamboo (in place of structural ironware), we could generate a reduction on the three eco-indicators studied: energetic (inputs energetic content – kWh/m²) of 12,560 kWh; environmental (CO₂ emission) of 3,7 tCO₂ and socio-economic (relation between the minimum salary and CUB/m²) of 0,61. Following through to the 250 million m² built by the Program, until the date of the publication of the thesis, if we would use these aforementioned materials, we would drop from emitting 22,629,862.26 tCO₂eq [12].

The studies which analysed buildings in accordance with the Selo Azul of Caixa presented the poorly service of the buildings regarding the Label requirements. In the city of Criciúma, at the moment of the presenting work, did not have any PMCMV certified buildings. Analyzing 3 buildings of the Program at the target group 2, according to the Label criteria, it has evidenced that none of the constructions complied with the mandatory criteria and reached the average 14 of the required criteria [13].

In Rio de Janeiro, the certification of one of the buildings from target group 1 also did not present the minimum level required by the Certification, evidencing the incorrect solar orientation, poor ventilation and the national constant regarding the great number of habitational units built at just one condominium [14].

The analysis of 6 buildings of the target group 1, at the metropolitan area of São Paulo, from visiting and interviewing the residents, presented the same result as the TCU and CGU audition reports, presenting issues relating to environmental and habitability comfort, like fissures and infiltration in one of the buildings [15].

In comparison with the 4 height buildings in of the PMCMV, to the habitational program of Montevideo, Uruguay, analyzing aspects as transports, services and infrastructure (city), surroundings (neighborhood) and the buildings organization and the construction themselves (implementation), as of rating evaluation from 0 to 78, it was verifiable the poor results of the Brazilian buildings, which reaches out just 10 points average, whereas the Uruguayan reaches 43 [16].

Applying the Sustainability Evaluation Methodology in Social Interest Projects (MASP - HIS), proposed by Carvalho (2009), in 6 single-family buildings projects that are until 50 m², it has shown that the residence with the best score has 47 m², along with accessibility and it is built with ceramic masonry, ceramic tiles, and wood framing windows [17].

In multi-family edifices of the states of RS and RJ, when analyzing the structural ceramic masonry, concrete masonry, and the concrete walls, trying to understand the project capacity index and the relation with the incorporated energy and the emission of greenhouse gases, it has been concluded that more compacter projects, needed around 20% less mass. In the analysis of the incorporated mass and CO₂ emission, the results show a difference of 16 to 20% considering the compactness of the project in an equal construction system [16].

The researches on energy efficiency were usually conducted by the Technical Regulation of Quality to the Energy Efficiency Level of Residential Buildings (RTQ-R), led by the Labelling Brazilian Program, contained on EDIFICA Procel Program.

For São Paulo and Salvador, the certification of the buildings was the following levels:

- Single-family ground-floor residence (the usable area between 36 and 38 m²): level E;
- Single-family semi-detached ground-floor residence (the usable area between 35 and 37 m²): level C and D;
- Multi-family residence (project floor in H format): level C and D;

Analyzing the certification results, São Paulo, for the year 2050 scenario, assumes that the increase of
discomfort hours will be by the heat is 129%, increasing in 140% the use of refrigeration, which on its turn the emissions of CO₂ goes from 0.98 kgCO₂/(m²/year) to 7.16kgCO₂/(m²/year) [17].

Using the computer simulation method by RTQ-R, with the Energy Plus software in the city of Cuiabá, certifying single-family residences with 40 m² maximum, in target group 1, and totalizing a sample of 13 thousand habitational units, it has been reached the result that these units have level D of energy efficiency.

Simulating the same habitational model, with air conditioning and orientation to the south, but with both the roof and walls painted white and alteration at the windows, those measures can raise the level from D to B [18].

Regarding the occupation metrics and the timetable stipulated by the RTQ – R, it was found some divergences between reality and what the Regulation stipulates. For the 4 buildings simulated, on the target group 3 the energy efficiency level reached was C in 2 of the buildings and D in the other 2, evidencing that even the constructions to the higher income target group don’t consider efficient solutions [19].

To the city of Rio de Janeiro, as evidence that the concrete walls in loco construction system are a method largely used in the accomplishment of the program, it has been analyzed the performance of a multi-family linear building with 4 floors, in the concrete walls system, conventional ceramic masonry, ceramic structural masonry, and concrete, demonstrating that the poorest energetic performance for all sun orientation was the concrete walls system. Doing some modifications on the wall structure, as EPS addition in its composition, has been shown improvement in the energetic performance, which could reduce the operation costs concerning the energetic demand [20].

Considering the energy efficiency of the domestic appliance used (refrigerator, freezers, air condition and electric showers) for 30 years, it can be established by a mathematical model, that improving these appliances’ energy efficiency we could reach an energetic reduction of 460.580 GWh until 2030 [21].

In 2011, with the release of the second phase of the program, it has been included the compliance of a water heating solar system, with the intention of insert energetic economy measures with the Energy National Plans 2030 and 2050. The in loco analysis of target group 1 residences in the city of Passo Fundo, a town with a harsh winter, it was evident that it is crucially important the system user attitude. The analysis result shows that the economy supplied by this system could be nominated as a “virtual economy”, because of the electric energy which is not used in the summer as a result of the solar warming having kept the reservoir full thus generating more energy to be used during the winter [22].

Regarding the delivered units’ performance, considering the natural ventilation to the city of Campinas, it has been identified that the best habitational typology to improve the natural ventilation in multi-family residences is the H format plan and orientated to 135º to the north. The worst plan is the linear one, in all sun orientations [23].

On interviews in the cities of São Paulo with 500 thousand habitants or more, 51 of the single-family residence owners, 62% of them with earnings between 0 and 3 minimum salaries, answered that the residences have defects: 8% of them regarding humidity; 6% lack of coating; 8% with noises; 17% considered the bathrooms too small; 4% with poor ventilation and lack of privacy; 6% few bedrooms and 9.8% observed the construction’s low quality (the appearance of pathologies and lack of flexibility and expansion of the property) [24].

In Viçosa, the thermic and acoustic evaluation, according to the Brazilian normative (15220; 15575; 10151 and 10152) had the following results: Thermic Performance: attended the minimum requested by the simplified method (project and calculus), by in loco verification, presented intermediary level (more than the minimum), but does not attend the minimum required for winter. The requirements and criteria of NBR 15 220, had not been observed in the project period. Acoustic Performance: the external isolation has been reached in 83% [25].

In the standard single-family habitational units, target group 1, the thermic performance by methods of NBR 15220, 15575, Selo Azul da Caixa and by prescriptive and simulation methods of RTQ – R were analyzed. The results observed that the ceramic construction systems with external light colors, as the aluminium blade under the tiles, presented better performance levels. The in loco concrete wall system failed in all Brazilian climatic zones. The efficiency level reached by the simulation were “E” maximum and maximum level obtained by the prescriptive method were in most cases “D” [26].

5. CONCLUSION

As a social housing program, the MCMV has not fulfilled its primary role of delivering homes in conditions to their users. It has served as a government tool to warm and improve the economy, without considering the consequences of a poorly built park, which increases the indebtedness of a low-income population and the social segregation of this community.

In environmental aspects, glimpsing at the climatic effects, it may affect the lives of all the owners involved, since it lacks the flexibility and modification of a building,
which is quite rigid and already delivered with constructive problems.

This paper aims to shed light on this scenario, which is certainly replicated in other Latin American countries, to show that there is a concern, regarding the improvement of these buildings, both for environmental and social issues. It also reveals that, with minor changes in design and construction, the MCMV Program would have a lower demand for energy and greenhouse gas emissions.

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PLEA 2020 A CORUÑA
Planning Post Carbon Cities

Getting off the Grid in Baja California
Passive Design for Mexico’s Hot and Dry Climate

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ABSTRACT: The energy viability of a Housing project in Baja California, was confirmed as off the grid, after optimizing the architectural design and implementing passive design strategies such as solar control, high thermal mass, night ventilation and evaporative cooling; it was possible to reduce the hours of internal overheating between 23% and 38%. The interior temperature peaks and hours of occupation were explored, finding that thermal comfort can be achieved without the need for HVAC mechanical systems, after enhancing air movement using ceiling fans; thus, achieving a reduction in energy consumption of up to 79% in comparison to the base case and 42% less than the Baja California State average. This percentage represents a saving in the acquisition of the solar system for the generation and electrical storage of up to 89%, from an initial investment of $3,063,232 to $647,548 USD.

KEYWORDS: Energy, Comfort, energy independence, passive design, desert.

1. INTRODUCTION

This paper reports on the environmental design analysis that was carried out during the early design stages of a holiday housing development, aiming to detect the energy viability of the project located in “La Ventana” Baja California Sur, Mexico, based on the premise that there are no services available on the site (electricity, potable water, or gas).

The success of the project relies on the possibility to produce and store its own energy without compromising the thermal comfort of the interior spaces.

Studying the hot and dry climate of the site, gave lead towards the different passive design strategies that were tested, aiming to optimize the architectural design by increasing the number of hours considered comfortable within each of the apartments, thus reducing the energy consumption destined for comfort which can represent up to 60% of the electricity consumption in the peninsula of Baja California given the use of mechanical air cooling systems. [2]

After optimizing the energy needs, solar panels with energy storage were suggested. Different scenarios were simulated to determine the economic feasibility and if the available space required for the panel installation was enough.

2. CASE OF STUDY

The development consists of a 7,400m2 site with six three-story buildings, each one with an apartment of 130 m2 plus terrace per level; a pool with a terrace and a palapa are considered as common areas. (fig.1)

3. Climate and Comfort

La Paz airport weather station was used to study the climate, being this one the closest to the evaluated site. The annual climate was divided into three main categories according to its dry bulb temperature, “mild” from December to March, “warm” for April and November as transitional months and finally the “hot season” from May to October. After doing so, the comfort range was determined [2]. (fig.2)
Taking into consideration the prevailing hot and dry climate, the strategies evaluated to improve the thermal performance of the tested building were optimal shading, natural ventilation, thermal mass + night cooling, thermal insulation and evaporative cooling. [1] [2]

4. ANALYTIC STUDIES

As previously described, the effectiveness of the passive design and material optimization strategies were tested on the chosen building for the base case. In general, the building is divided into three levels, ground floor, level one and level two (fig. 3), for the study each level represented a general unit composed by various thermal zones.

4.1 Base Case

Regarding the general construction parameters to establish the base case, the thermodynamic model included the typical materials used in the area. Hollow concrete blocks, single glazed windows, concrete slabs with clay tiles and plaster coatings on soffits and walls. Insulation was considered for the roof although that local regulations do not require insulation or windows with any special requirements, and it is not a common practice either.

The first analysis considered an enclosed scenario, with no natural ventilation to calculate the cooling loads (fig. 5). Afterwards daytime natural ventilation was implemented in order to establish a base line to improve the building performance with passive design; for the base case 56.4% hours above comfort for the master bedroom and 68.6% above comfort for the living room was established after the simulation.
4.1 Natural Ventilation

The natural ventilation strategy was the result of the initial climate analysis in which, after classifying the annual phases for the outdoor dbt, it was established that during the period classified as “mild” natural ventilation was enabled during the day (from 8am to 9pm) and during the “warm” and “hot” season, only night ventilation was implemented (7pm to 8am) to avoid the high dbt during daytime which could affect the interior thermal comfort limit.

After optimizing the natural ventilation schedule and implementing night flush the hours spent above comfort on the master bedroom dropped from 56.4% to 42.5% and for the living room from 68.6% to 39.8%.

4.2 Optimized shading

Shading on the proposal was addressed in two manners, the geometry of the building and additional elements of solar control.

1. Building geometry: as shown on figure 6, by generating a staggering of the building geometry, each level shades the one below. As for the openings on the facade, all windows were placed inwards between 50 and 75cm.

2. Solar control elements; louvers on the terrace were placed since the base case, but after the solar radiation analysis additional shading devices were included on the windows and on the terrace, to protect from the western solar exposure during the evening.

The effects of optimized solar control were barely notable on the comfort hours increasing by 1% comfort, but shading had an impact delaying and reducing the indoor operative temperature peak by 1 K and as seen on figure 7.

4.3 Construction Set

For the construction set optimization, insulation was applied on the exposed surfaces reducing the U-value, thermal mass was increased by thickening the concrete slabs from 10cm to 20cm and using terracotta bricks for the interior and exterior walls instead of “conventional” cavity concrete block. Windows remained 6 cm single glazing since there were no thermal improvement after simulating double glazing minding cost constraints as well. The general construction set can be visualized on figure 8.

The main purpose of increasing the thermal mass was to enhance the effect of night ventilation during the warm and hot period of the year, same criteria was applied for the insulation as the target to reduce overheating remained for the most critical months.

The result that these improvements had after the simulations were notable, reducing the discomfort...
percentage for the living room, from 26% to 18.5% (hrs. above the comfort) on the ground floor, from 39.4% to 30.2% in level 1 and from 40% to 31.8% in the second level. (fig. 2) (fig.9)

![Figure 9: The graphs show the reduction in the annual percentage of hours above comfort (over heating) on the living room, after having implemented the different passive design strategies, representatively at the different levels of the analysed building (GF left - L1 centre - L2 right).](image)

4.4 Active strategies

Despite the discomfort percentage still accounts for around a third of the time on level 1 and 2 and almost a fifth on the ground floor(fig. 9); after implementing the previous passive strategies and enhancements into the design, the maximum interior operative temperature rarely exceeded 34°C limit, making it possible to move forward into the final stage of the design enhancement, implementing active strategies such as air movement using low energy consumption ceiling fans and evaporative cooling on the outdoor terrace using water nebulizers.

According to Szokolay [3] physiological cooling can be achieved after air movement several degrees depending on the air velocity; as stated before, the highest OPT reached on any of the spaces was 34°C so after enabling air movement on the tested spaces by ceiling fans and increasing air velocity between 0.5 up to 2m/s for the hottest hour, thermal comfort was achieved for most of the time as comfort limit was increased 4K. (fig. 9)

After testing the previous strategy on the annual comfort hours, the results showed that hours above comfort dropped dramatically for all the tested spaces, on the ground floor overheating was completely avoided as for the level one on the master bedroom it was reduced form 34.6% to 4% and on the living room from 30.2% to 6.9% finally for the third floor the percentage decreased from 31.1% to 8.7% in the bedroom and from 36.4% to 4.9% for the living room. (fig. 10)

![Figure 10: The charts show how on a typical hot day, after implementing air movement thermal comfort upper limit can be extended, the living room and the main bedroom are expected to be in comfort.](image)

As it can be seen in figure 9, overheating occurs during the afternoon after 3pm, reaching its peak between 6 and 7pm, taking this into account it could be assumed that overheating will not be a problem for the bedrooms rooms since they are rarely occupied during this period of time. Anyway, roof fans provide the additional air movement needed to achieve comfort for most of the time.

Finally, it is expected that if evaporative cooling is implemented successfully taking advantage of the low humidity percentage during daytime, dbt can be reduced for the surrounding environment, on the commune areas, and terraces which are adjacent to the living room and main bedroom.

If air humidity can be increased on a typical hot day by 20%, taking it from 18% to 38% it could be expected that dbt could drop from 35°C to 28°C. This final strategy was not simulated, but water nebulizers were proposed to be placed on the terrace in addition to porous clay pottery to enhance evaporative cooling after air movement. (fig. 11)
5. OUTDOOR COMFORT

For the outdoor, comfort was assessed referencing climate control of open spaces Expo Sevilla 92, as most of the strategies that were used there, prove to be effective in a hot and dry climate.[4]

The main strategies followed on the design were, shade, evaporative cooling, wind barriers, reduction of the surrounding materials temperature and thermal inertia.

Outdoor spaces were divided into three zones: the adjacent, the transitional and the resting areas; each one was classified after different factors were taken under consideration such as, the activity and expected occupational time. For each zone different strategies were proposed and implemented with particularized design elements.

Adjacent zones were classified as contemplative areas in the project, therefore the main strategy consisted on reducing the direct solar radiation after integrating shading elements such as desert vegetation and palm trees; water elements and local grass for evaporative cooling.[1]

Transitional zones are those used to go from one area to another; to avoid heat stroke, apart from shade, paths were lowered by 1 meter and in some areas wet walls were proposed, prompting evaporative cooling and thermal inertia of the materials.

Resting zones integrate areas for sitting, sunbathing and recreation. Occupants are expected to remain in those spaces for at least 30 minutes making them the main outdoor areas. Shading elements were integrated with pergolas and the palapa, evaporative cooling was enhanced with water nebulizers, and some areas were caved for as much as 1.5m underground to take advantage of thermal inertia and in the case of the palapa to help the containment of the cooled air after the evaporative cooling effect.

An evaporative cooling tower was proposed for the palapa using as reference the bioclimatic roundabout in Seville [4]. (Fig.12)

5. ENERGY INDEPENDENCE

After the strategies tested before provided enough evidence to suggest that the viability of the project does not depend on the installation of HVAC. The energy consumption calculation per unit was created from the two final scenarios “with” and “without” HVAC managing to reduce by 79% the electric energy consumption. (fig.13)

For the scenario that considers the HVAC, the solar system is unfeasible given the cost of batteries for storage and the need for a larger space than is available for energy production. After comparing both scenarios, the cost of the initial investment to acquire the solar generation system was reduced between 89% and 79% between the “with HVAC” and “without HVAC” scenario (fig. 14).
Figure 14: The chart shows the comparison on the initial investment regarding the acquisition of the solar panels and batteries for storage between both scenarios.

6. CONCLUSION

The analysis yields enough evidence to suggest that if the strategies were implemented as described in the content, an energy saving of up to 79% could be achieved in respect to the base case. The thermal simulations gives enough evidence to suggest that the use of air conditioning equipment (HVAC) could be dispensed and still achieve comfortable spaces, that would represent a significant saving of up to 89% in terms of the initial investment of the energy generation system, supporting the energy viability of the project by acquiring solar panels and energy storage batteries.

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Modelling the impact of vegetation on building space cooling: a coupled simulation approach in a Dutch case study

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ABSTRACT: Among different measures to mitigate Urban Heat Island magnitudes, the increase of vegetative cover has shown to contribute significantly to lower urban temperatures in various climate regions. However, very few studies have investigated the thermal impact of vegetation in a climatic context characterised by frequent high wind velocities, like is the case in the Netherlands. Addressing this knowledge gap, this paper presents a combined analysis of the effects of urban roughness elements, including trees, on the urban microclimate and related building energy performance. A simulation method that couples ENVI-met and City Energy Analyst is employed in order to use local climate data to estimate space cooling loads for a district in Almere. The results underline a significant correlation between decreased wind speeds and increased air temperatures in the district. Moreover, for the hot summer day under study, energy demand assessments highlight that overall space cooling loads rise about 9% when microclimate boundary conditions are used as simulation input as an alternative to general rural weather data.

KEYWORDS: Microclimate, Urban Heat Island, Cooling demand, Vegetation, Wind speed

1. INTRODUCTION
Global warming influences the energy balance and consequently the thermal behaviour of urban environments. The increase of ambient temperatures, also due to the phenomenon of Urban Heat Islands, affects the energy performance of buildings and intensifies the consumption of electricity for space cooling between 0,5 and 8,5 % per degree of temperature rise [1]. In European cities, an intensification of extreme heat events is expected to affect continental latitudes [2]. Already in the last decade, northern cities have been experiencing a higher frequency of heat waves [3] and scenario projections show that a rise in temperature will likely occur in central-northern Europe, while an increase in heat wave days will mainly strike Mediterranean regions [4, 5]. In addition to the growing exposure to severe heat events and the recognised high level of vulnerability [6], cities in temperate and cold climates are also called to address the future potential impacts on energy consumption patterns. While traditional strategies have mainly focused on reducing building heating loads, more recently, the urge of mitigating the impacts of heat stress has asked for new research studies on cooling need of buildings, and assessment methods able to estimate the influence of urban form, materials and landscaping.
A large body of literature has investigated heat mitigation measures and their efficacy to reduce UHI magnitudes in arid, Mediterranean and tropical climatic contexts. These studies highlight the importance of vegetative surfaces, which have a cooling effect in urban environments through shading and evapotranspiration [7,8]. However, in climatic regions characterised by strong winds, the impact of vegetation on microclimate and energy performance of buildings is largely understudied.
Therefore, in this paper a coupling method that integrates urban microclimate simulations and building energy simulations is applied to evaluate the influence of vegetative cover on the thermal performance of an urban area characterised by high wind velocities. The masterplan for the development of the Floriade district in Almere (NL) is selected as a case study due to the city’s goal to make this district a green and energy neutral neighbourhood that includes efficient measures for reducing heating and cooling loads.
2. METHODOLOGY

2.1 The Floriade case study

The Floriade district is being developed with the purpose of hosting the International Horticultural Expo in 2022. After the Expo, the district will be transformed into a residential area. The new city neighbourhood (Figure 1) has been designed to accommodate 660 new residential units and to become an example of sustainable and liveable urban areas. Surrounded by a lake and conceptually structured on an orthogonal grid, the design is shaped by the ‘arboretum’, a green structure composed of 3000 plant species. The position on a large water body and the consequent low roughness of the surrounding are uncommon urban conditions. However, these characteristics can enhance the observation of high wind velocities on the district. Thermal and evaporative process are expected to be influenced by the proximity of deep water.

Figure 1: Planimetry of the Floriade Masterplan

In order to understand the impact of vegetation on the thermal environment in this case study, two scenarios have been simulated. In the first scenario (FABRIC), the vegetation as planned in the current masterplan was excluded - only the new street network and buildings are modelled, while all vegetation is included in the second scenario (GREEN). Spatial data for the two scenarios has been retrieved from the internal documents of the Municipality Design Department.

2.2 Coupling method

In order to estimate both local climate conditions and energy performance of the new district, two software tools are used in a coupled process:

- ENVI-met [9], an urban microclimate model for outdoor environmental prediction;
- City Energy Analyst [10] (CEA), an urban simulation engine for the assessment of district energy demand.

The coupling method has previously been tested in other studies [11] and consists of four phases. In a first phase, geometrical data, surface materials and vegetation attributes are collected and a shared data-set is created to allow coherent input for the two tools. Secondly, the scenarios’ spatial information is used to create two 3d models and simulate the microclimate performance in ENVI-met. For this purpose, weather data from the closest (rural) weather station is employed as boundary condition. A hot day with relatively high wind speed is chosen for this case study.

In a third phase, the ENVI-met output values of air temperature, wind speed, and relative humidity in the entire simulation domain are exported and an aggregation process is performed with a GIS tool, selecting only the tangent grid values around buildings. Finally, in the fourth phase, the obtained microclimate results can be used as input for the energy simulations in CEA.

The modelling results for both microclimate and space cooling demand are then compared against ‘BASECASES’. The Climate BASECASE consists of the original data retrieved at the closest weather station in Lelystad. As weather stations are usually installed in rural environments, the comparison will allow for an analysis of the UHI pattern and magnitude. Similarly, a CEA simulation using the Lelystad weather data constitutes the Energy BASECASE. Comparing this BASECASE with the GREEN and FABRIC scenarios – both using ENVI-met microclimate data as input for energy assessment - will help to observe the effect of microclimate patterns on variation in energy loads of the 260 buildings in the district.

Figure 2: Scheme of the methodological framework
2.2.1 Microclimate simulation and data aggregation

Urban microclimate simulations were carried out using ENVI-met with the goal to analyse the impact of the district design on the future local climate. This software has been used in a growing number of studies to estimate outdoor comfort [12,13], assess mitigation measures [14,15], and to model interactions between vegetation, built environment, and atmosphere [16,17]. The input data required by the tool can be divided in three main categories: spatial data to create an ‘Area Input File’, material characteristics stored into the database, and simulation settings.

To define the size of the simulation domain, an area of influence of 100 meters from the borders of the district was included, bringing the scope of the case study to one square kilometre. For the ‘Area input File’, a 3d grid with a cell resolution of 4x4x6m was used to build the spatial models including geometric and topographic characteristics. For both scenarios, materials from the ENVI-met database were applied to reflect the masterplan as closely as possible: light coloured concrete as paving material and sandy loam for soil. Due to the conceptual design state of the Floriade masterplan at the time of the study, information regarding building materials is not available. Therefore, a new ‘dark’ building material was created by the authors and homogeneously applied to all buildings within the district. This assumption was made with the goal of investigating ‘worst-case scenarios’ in which highly absorptive envelops are employed. The characteristics of the new material were stored in the ENVI-met user database and used also for the CEA simulations.

The spatial inputs described above are common for the two scenarios. Additionally, in the GREEN scenario, ‘simple’ plants were included; the high complexity of the arboretum was simplified by classifying the vegetative species in six categories according to the height of the roughness elements: grass, hedge (2m and 4m), and trees (10, 15 and 20m). For both spatial models – FABRIC and GREEN -, two simulations were run with ENVI-met for an extremely hot day with clear skies (the 19th of July 2006). For this day, data from the Royal Netherlands Meteorological Institute weather station of Lelystad were used in ENVI-met’s full-forcing method.

After the computation, results are reported with reference to the x, y coordinates in binary format for the full domain height. Therefore, in order to select values tangent to the buildings’ envelope, data were exported from LEONARDO interface to a GIS platform. Wind speed, air temperature and relative humidity data were selected within a buffer of 10m from the buildings’ facades and aggregated in 3D buffers using each building’s code for use in CEA as weather input data.

2.2.2 Energy demand simulation

Space cooling demand for the selected scenarios was estimated by using the City Energy Analyst (CEA). CEA is a computational framework for the analysis and optimization of energy systems city districts [18]. It is based on comprehensive mathematical models using the latest ISO and SIA standards. The tool allows users to analyse the energy use, carbon emissions and financial benefits of district-scale design scenarios.

Two groups of input are necessary to run a CEA simulation. The first are primary inputs to the modelling framework, consisting of topographical information, weather data and characteristics of the buildings such as geometry, construction year and functional program. The second group of input define supplementary building properties, including specifications of the building envelope(s) (materials, window ratio, occupancy), energy systems for supply and distribution, and set point temperatures and ventilation rate.

For the Floriade district, an input model was created in CEA based on information that includes building location, construction year, and energy supply systems from local data. The occupancy types for each building were obtained from a combination of GIS data and owner information. The “dark” (highly absorptive) material was defined for the building’s envelopes and space conditioning is defined as provided by radiant heating and cooling. Occupancy schedules and room temperature set points were extracted from literature on Dutch residential buildings [19,20].

Microclimate effects on energy consumption were assessed in CEA by substituting the original (rural) weather file with the results extracted from ENVI-met for the day being assessed. Thus, space cooling consumption patterns in the two scenarios can be compared against the Energy BASECASE simulation that uses the original weather data from the Lelystad station.

Figure 3: Comparison of simulated and weather air temperatures
3. RESULTS

This section analyses the results of the modelled FABRIC and GREEN scenarios against a Climate and an Energy BASECASE. While a microclimate analysis highlights the magnitude of the UHI and its daily pattern, the energy analysis pinpoints the impact on cooling loads.

The microclimate analysis focuses on the comparison between the local climate parameters of air temperature and wind speed for the two scenarios and the original measured data from the weather station (BASECASE). For the extremely hot day modelled, a significant variation in average air temperature is observed (Figure 3). While the meteorological station reaches a maximum temperature of 34°C, local temperatures at the Floriade rise to 35°C in FABRIC and to 37°C in the GREEN scenario. Local air temperatures during the day are significantly higher than rural ones with a maximum difference of 3.4°C and 1.6°C for the GREEN and FABRIC scenarios, respectively. A second comparison shows a significant decrease in wind speed, which drops from a maximum of 4 m/s in the rural measurement to 1.7 m/s in the FABRIC scenario and further decreases to 1.2 m/s when vegetation is taken into consideration (Figure 4). The simulation results suggest that in the Floriade district roughness elements (i.e. buildings and trees) significantly lower the wind velocity, contributing to a temperature increase during the central part of the day. This is particularly the case in the GREEN scenario where a Spearman’s correlation shows a significant relationship ($p<0.05$) between low wind speeds and higher air temperature values.

For the energy analysis, cooling loads calculated with the employed coupling method were compared against a CEA BASECASE simulation using original weather data. Over the entire day, the inclusion of microclimate boundary conditions in the CEA simulations causes an increase in the district’s cooling demand of 9.3% in the FABRIC scenario and 9.8% in the GREEN scenario, mostly due to the higher temperatures between 12:00 and 18:00. Figure 5 reporting hourly data shows that during night-time hours there is no need for space cooling while peak demand varies in intensity during the warmer hours of the day-time hours.

Figure 6: Variation of cooling demand (%) of the FABRIC Scenario compared against the BASECASE

Figure 7: Variation of cooling demand (%) of the GREEN Scenario compared against the BASECASE
The demand variation between BASECASE and scenarios presented has also been observed at the detailed building level. The variations for the 260 buildings range between 0 and 35%. As Figure 6 and 7 suggest, the variability of microclimate impact on energy can depend upon extrinsic and intrinsic factors. Extrinsic factors are the characteristics of context and position in the masterplan that might explain minor variation in the south-west compared to the north-east area. Intrinsic characteristics of the buildings depends upon geometrical characteristics such as compactness and height. Within the GREEN scenario, exemplary is the cooling demand increasing by 18% for a specific typology characterised by high surface to volume ratio.

4. CONCLUSIONS

The Urban Heat Island phenomenon that emerges in the study of the Floriade district is characterized by higher temperatures in the urban district compared to the rural area during the day time. This pattern has been observed for both FABRIC and GREEN scenario. Average temperatures are highest when the green structure is modelled. This finding appears to be in contrast with previous studies that support vegetation as an important strategy to mitigate the UHI effect [8, 21]. However, in the existing literature, the cooling effect of green areas and trees is observed mainly in tropical and arid urban environments [22, 23, 24] with relatively low wind speeds or when methods that do not consider wind velocity in the modelling are employed [25]. For this particular case, the effect of the vegetation on wind speed -leading to a decreased supply of cool air from the lake- seems to overrule the cooling effect from shading and evapotranspiration. This is reflected in the results of the overall energy demand. When considering the effects of microclimate, the space cooling need increases by roughly 9.8% as a result of higher air temperatures and lower wind velocity in the presence of vegetation. However, a detailed analysis at the building level shows that variation can reach 35% depending on building typology and position. The results suggest that further studies are necessary to assess the role of vegetation in temperate windy climates. Due to the increase of heat wave events and increase in UHI magnitude, continental areas in the north and central part of Europe need to adjust mitigation measures according to their environmental characteristics. Future studies should focus on the challenge of understanding possible impacts on thermal and energy performance at various scales.

5. ACKNOWLEDGMENT

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Open-joint ventilated façades performance with changing climatic conditions

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ABSTRACT: Ventilated façades are constructive systems used to reduce mainly the cooling requirements of the buildings. They are characterized by the existence of a ventilated cavity between an outer layer and the inner wall. In open-joint types, the ventilation is attained through the small gap between the outer layer tiles. This paper evaluates numerically the thermal and fluid dynamic behaviour of these ventilated façades depending on the climatic conditions. Furthermore, the direct impact of climate on the ventilation airflow and the heat transferred to the building are assessed. In order to evaluate the benefit of implementing these systems in areas with different climates, three specific climatic zones have been considered: Csa, Cfb, and BWk climates in the Köppen-Geiger climate classification.

KEYWORDS: Building envelope, Ventilated Façades, Natural Convection, CFD simulation.

1. INTRODUCTION
The new policies promoted for the reduction of energy consumption in the building sector are mainly focused on different actions to promote innovative and sustainable solutions that meet the energy requirements to thermal conditioning of new and existing buildings [1,2]. Façades mainly play a substantial role in the energy saving of energy efficient buildings [3], and require envelopes designed to fit the local and the climate zone. A detailed review of the techniques of current approaches and the design patterns has been recently done by Li et al. [4].

The use of Opaque Ventilated Façades (OVF) has significantly increased in recent years as an envelope solution in a variety of building types, climates and design configurations [5,6].

There are two kinds of external cladding on ventilated façades: continuous (closed joint) or discontinuous (open joint). As a result of the incident solar radiation on the slabs and the convection within the cavity, the upward air flow creates a ventilation effect that helps removing the heat from the façade. While in the case of continuous ventilated façades (closed joints) the upward flow is continuous, homogeneous and symmetrical along the wall, open joint ventilated façades (OJVF) are marked by localized discontinuities at the joints, which turn the flow much more complex, inhomogeneous and asymmetrical.

In this work, a specific opaque ventilated façade called “Open Joint Ventilated Façades” (OJVF) is evaluated as a constructive strategy to enhance the energy efficiency in buildings. This building element creates a ventilated air chamber between the exterior cladding and the isolation layer fixed to the external wall of the building. Its external coat is composed of multiple panels separated by open joints and anchored to the building by means of a metallic structure.

In the specific case of the OJVF, the description of the heat and mass transfer phenomena confirms the complexity of the fluid flow in the regions near the joints and along the ventilated cavity. This justify the use of advanced fluid dynamic simulation techniques given their high capacity to achieve a close description of the details of the internal air flows and heat transfer phenomena [7]. Previous numerical model of OJVF experimentally validated have been developed in real conditions [8] measuring thermal parameters, such as air temperature or heat fluxes, but without measuring airflow motion inside the air cavity. Regarding the experimental techniques, Giancola et al. [9] summarize the existing methods (real scale, test cell and/or laboratory application).

This paper evaluates numerically (using a CFD code) the thermal and fluid dynamic behaviour of these ventilated façades depending on real climatic conditions. Furthermore, the direct impact of different climates on the ventilation airflow and the heat transferred to the building are assessed.

2. OJVF HEAT TRANSFER PHENOMENA
The heat transfer through an OJVF exposed to solar radiation is represented in Figure 1. There is heat exchange by conduction, convection and
radiation (conduction through the solid walls has not been pictured to simplify the figure).

Figure 1. Heat transfer processes in an OJVF.

The heat fluxes and the temperatures along the whole cavity vary with height, gaining heat by convection from the exterior cladding as well as from the interior wall. In the OJVF the air enters in the cavity at the exterior temperature and heats while ascending, by chimney's effect. At a certain height, the air starts to exit the cavity through the joints, extracting thermal energy from the air inside the cavity. The structure of the convective heat transfer at both sides of the slabs is entangled with the inlet and outlet flow through the joints, as can be observed in the fluid pathlines showed in Figure 7. The thermal energy extracted by ventilation depends on the mass flow rate of air that circulates inside the cavity. The effectiveness of the ventilated façade relays on the amount of energy absorbed by the air as it rises in the cavity. This extracted energy does not enter the building and therefore, the cooling thermal load is reduced.

2. SIMULATION MODEL

2.1 Analyzed climate conditions

Three specific climatic zones have been considered to better analyse the OJVF performance in different areas of the world: the Csa, Cfb, and BWk climates in the Köppen-Geiger climate classification. The details of the coding system for the climatic areas can be found in Peel et al. [10] and the ones relevant to this article are included in Table 1.

Table 1: Details of the coding system for the Köppen-Geiger Climate Classification climatic areas

<table>
<thead>
<tr>
<th>Köppen-Geiger classification</th>
<th>Climate characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Csa</td>
<td>temperate, dry summer, hot summer</td>
</tr>
<tr>
<td>Cfb</td>
<td>temperate, without dry season, warm summer</td>
</tr>
<tr>
<td>BWk</td>
<td>arid, desert, cold</td>
</tr>
</tbody>
</table>

This classification divides the main climate in A: equatorial, B: arid, C: warm temperate, D: snow and E: polar. Moreover, it defines the level of precipitation in W: desert, S: steppe, f: fully humid, s: summer dry, w: winter dry, m: monsoonal. Finally, it provides details about temperature as h: hot arid, k: cold arid, a: hot summer, b: warm summer, c: cool summer, d: extremely continental, F: polar frost, T: polar tundra. The combination of the previous definitions gives an overall information about the weather conditions at each location. In this study, all the possible climates were analyzed except those that do not need any cooling supply during the whole year (E: polar and mostly all D: snow main climates). The weather conditions were extracted from long-term meteorological monitoring campaigns performed by Ciemat, after evaluating the availability of representative climate databases of the studied areas [11]. A summer day of each location was considered in order to evaluate the potential of the OJVF.

2.2 Model description

The numerical modelling of the ventilated façade has been performed using advanced Computational Fluid Dynamics (CFD) simulation tools, taking into account previous studies [12].

The CFD-model is based on real façades (layer structure and dimensions). The dimensions of the panels are 0.4 x 0.8 m (panel dimension frequently used by manufacturers). These panels are arranged creating 5 mm horizontal and vertical open joints. In addition, the 2.4 m total height corresponds to the representative distance between two consecutive floors (Figure 2).

In order to optimize and reduce computing time, only half of the volume has been simulated applying vertical symmetry in the model. The computational domain has been meshed with a structured grid, refining the zones close to the 5 mm open joints. The optimized mesh has 2.8 million cells approximately.

The boundary conditions (air temperature, direct and diffuse radiation) vary according to the simulated climatic location. Based on the experimental validation, DO radiation and k-ε RNG turbulence models have been applied. Buoyancy effects have also been considered. The incident solar radiation on the vertical surface has been entered in the calculation at the external boundary condition of the domain and the outdoor temperature as shown Table
2. The indoor air temperature for all cases has been fixed in 26°C as a typical value of the building normative.

Table 2: Boundary conditions for summer period in the three climate areas studied

<table>
<thead>
<tr>
<th>Climate</th>
<th>Outdoor Temperature (°C)</th>
<th>Direct Radiation (W/m²)</th>
<th>Diffuse Radiation (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Csa</td>
<td>29.48</td>
<td>344.97</td>
<td>213.84</td>
</tr>
<tr>
<td>Cfb</td>
<td>22.58</td>
<td>240.43</td>
<td>245.08</td>
</tr>
<tr>
<td>BWk</td>
<td>30.09</td>
<td>304.42</td>
<td>214.83</td>
</tr>
</tbody>
</table>

Finally, Table 3 shows the thickness and thermal characteristics of the materials.

Table 3: Constructive layer structure and material properties.

<table>
<thead>
<tr>
<th>Wall Type</th>
<th>Material</th>
<th>Thk (cm)</th>
<th>k  (W/mK)</th>
<th>P  (Kg/m³)</th>
<th>C  (J/KgK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Skin</td>
<td>Ceramic panels</td>
<td>2</td>
<td>3.5</td>
<td>2800</td>
<td>1000</td>
</tr>
<tr>
<td>Ventilated Cavity</td>
<td>Air</td>
<td>5</td>
<td>0.0242</td>
<td>1225</td>
<td>1006</td>
</tr>
<tr>
<td>Insulated Inner Wall</td>
<td>Rockwool + Brick + Gypsum plasterboard</td>
<td>29</td>
<td>0.0965</td>
<td>729.7</td>
<td>1000</td>
</tr>
</tbody>
</table>

2.3 Experimental validation

Experimental tests were carried out in a laboratory prototype of an open-joint ventilated façade in order to validate the numerical modelling. The design of the prototype is based on real façades, but with limited dimensions. The measurements include thermal monitoring with temperature probes and transversal velocity determination using PIV techniques [13-15]. Experimental heating conditions used to validate the CFD-model correspond to 460 W/m² absorbed solar radiation [16]. These experimental conditions were reproduced using electric heating mats adhered to the façade slabs.

The numerical simulations were performed for steady state conditions, and buoyancy as well as viscosity effects were considered in the model. Different radiation and turbulence models were tested. The opacity of the façade layers made the thermal radiation phenomena relevant in the global heat transfer. Rosseland, P-1, Discrete Transfer Radiation (DTRM) and Discrete Ordinates (DO) were the evaluated radiation models. Regarding the turbulence, the Sparlat-Allmaras, the k-ε Standard, the k-ε RNG, the k-ε REA, the k-ω Standard and the k-ω SST were the 3D RANS tested models.

The experimental and numerical data were compared in three vertical planes of the cavity perpendicular to the panels. Figure 3 shows the y-component velocity profiles measured (Exp) and simulated (CFD) in these three planes.

The results showed the numerical data in good agreement with the experimental ones, using the discrete ordinates (DO) radiation model and the k-ε RNG turbulence model.

To represent the prototype, a 3D ventilated façade model was developed considering the same geometry, materials and boundary conditions.

3. RESULTS

In order to analyse in detail the performance of the OJVF, the variation of the air velocity inside the cavity, the surface temperature of the panels and heat flux transferred into the building have been studied, particularly their variation with the height. These magnitudes have been evaluated in three different summer climatic conditions: Csa, Cfb and BWk. Figure 4, Figure 5 and Figure 6 show the respective results.

The slabs of the exterior coating absorb the solar radiation and increase their temperature. Part of this heat is transferred to the air inside the cavity, which rises due to the buoyancy effect, creating an effective ventilation. Consequently, this implies a reduction of the building heat transferred into the room.

In terms of energy performance, the effectiveness of a ventilated façade relays on the amount of energy absorbed by the air as it rises in the cavity. The thermal energy extracted by ventilation depends on the temperature and on the mass flow rate of air circulating inside the cavity.
**Csa: Hot-summer Mediterranean climate**

Figure 4: Velocity magnitude in the air cavity, exterior slabs temperature and heat transfer to the room in summer conditions in Csa climate.

**Cfb: Temperate Oceanic climate**

Figure 5: Velocity magnitude in the air cavity, exterior slabs temperature and heat transfer to the room in summer conditions in Cfb climate.
Figure 6: Velocity magnitude in the air cavity, exterior slabs temperature and heat transfer to the room in summer conditions in BWk climate.

Figure 7 shows the preferred path of the airflow along the ventilated façade. The visualization of the pathlines helps to better understand the complex three-dimensional fluid motion inside the ventilated cavity related to the discontinuities at the joints. It is apparent that some of the pathlines are entering through the horizontal open joint into the ventilated cavity in a vertical upward movement. However the pathlines next to the vertical joints ascend while deviating towards the vertical joints generating a spiral upward movement.

The induced natural convection generates an ascending airflow entering the cavity through the lower joints, with relatively high velocity jets and local recirculation vortexes. The air flow rate increases up to the central height of the cavity. From this height on, the air starts to leave the cavity through the upper joints. The heat transfer distribution in the inner layer (increasing with height) is also basically the same for all climatic zones although the values change substantially. The higher the incident solar radiation and air temperature, the higher the ventilation rate and heat flux transference. Main results are summarized in Table 4.

Table 4: Relevant performance results of the façades located in different climate areas (average values for one slab width)

<table>
<thead>
<tr>
<th>Climate</th>
<th>Heat Flux (W/m²)</th>
<th>Ventilation Rate (m³/s)</th>
<th>Air cavity temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Csa</td>
<td>7.33</td>
<td>4.64E-03</td>
<td>47.04</td>
</tr>
<tr>
<td>Cfb</td>
<td>4.41</td>
<td>4.31E-03</td>
<td>38.30</td>
</tr>
<tr>
<td>BWk</td>
<td>7.15</td>
<td>4.41E-03</td>
<td>46.77</td>
</tr>
</tbody>
</table>

4. CONCLUSIONS

Open-joint ventilated façades have been studied with a numerical model validated with experimental results. The open joints allow an effective ventilation flow in the cavity, reducing the heat transfer. The results show that both the thermal and the fluid-dynamic behaviour of the ventilated façades are very similar in all climatic areas analysed, but with different magnitudes. Although the most influential...
weather variable is the solar radiation, a low ambient temperature can also facilitate more intense ventilation, leading to important energy saving values. It was found that the most convenient locations for installing an OVF were those with severe climates.

And finally, although the thermal and fluid-dynamic behaviour of these façades is complex and does not adapt to the traditional calculation methods, with the model developed it is possible to evaluate their efficiency in function of the climatic data.

Further study should be done to evaluate the impact of using an OJVF in the winter period during 24h.

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ABSTRACT: The extensive use of air conditioning (AC) in buildings is directly related to Global Warming and Climate Change (CC). The application of passive cooling is a promising approach to mitigate this situation. This research presents the results of the performance of indirect evaporative cooling systems (IECS) applied in experimental modules conducted in a hot-humid location. The results showed that the IECS investigated presented lower temperatures than the external conditions and the control module. The alternative that combined indirect evaporative cooling with thermal mass, solar protection, and night radiative cooling was the most promising, with a temperature reduction of 4.2 K, relative to the mean exterior temperature, and a decrease of 8.3 K of its maximum temperature relative to the maximum exterior temperature. An additional strategy was implemented in this alternative using a Phase Change Material (PCM), Cocos Nucifera (Coconut Oil), that further reduced its temperature, with a reduction of 6.3 K, relative to the mean exterior temperature and a reduction of 11.5 K of its maximum temperature relative to the maximum exterior temperature. It is expected that these findings are applicable in actual buildings in hot-humid regions to reduce energy consumption for AC, whilst improving comfort to the building’s occupants.

KEYWORDS: Cooling, Comfort, Indirect Evaporative, Hot-Humid Regions

1. INTRODUCTION

Energy consumption in buildings has augmented worldwide by the escalation in Global Warming (GW) and the consequences of Climate Change (CC). Certainly, with the rapid rise in temperatures globally, it is getting hotter, which implies a greater use of air conditioning (HVAC) equipment in buildings to provide hygrothermal comfort to occupants, which at the same time provokes the unceasing emission of Greenhouse Gasses (GHG), and numerous climate alterations [1]. In particular, this situation is more severe in hot humid climates and, even in prevailing temperate climates under overheating conditions. A promising approach to alleviate this situation is the implementation of passive cooling systems in buildings, where the application of indirect evaporative cooling systems (IECS) is a viable and sustainable alternative. This paper presents the results of a work to evaluate the performance of IECS implemented in scaled experimental modules compared to a control experimental module (CM) and relative to the external ambient conditions of the site selected for this research, the City of Mérida, Yucatán, Mexico, a location with a typical hot humid climate. This work the experimental arrangement concept and the methodology was based on previous research by Gonzalez et al. [4, 5, 6, 7, 8].

2. ENVIRONMENTAL SITUATION RELATIVE TO ENERGY CONSUMPTION

Primary energy consumption worldwide in 2018 increased 2.9% compared to 2017, from 13,474.6 Million Tons of Equivalent Oil (MTOE) to 13,864.9 MTOE (Figure 1) [2].

These data reveal an increase in energy consumption that is directly related to a higher Greenhouse Gasses emission (GHG), mainly carbon to the atmosphere and consequently by the severe environmental deterioration. Certainly, carbon dioxide emissions are the main cause of the global average temperature rise, which countries seek to reduce to avoid the most devastating effects of CC. Global energy-related carbon emissions grew to an all-time high in 2018, as energy demand and coal use increased significantly, mainly in Asia [1]. Energy-related CO₂ emissions increased 2.7 percent, to reach 37.1 Gt CO₂, compared to the previous year, the highest growth rate since 2013, and the electricity sector accounted for almost two-thirds of this growth, according to the estimates of the Global Carbon Project [3]. It is clear that the current pace of progress is well below the accelerated transition with a sustainable approach, foreseen by the climate objectives of the Paris Agreement 2015 during the COP 21 Climate Conference, in which a global action plan to avoid further environmental damage on the planet, established a limit to the increase of
temperatures well below 2°C and making efforts to limit it to 1.5 °C.

Figure 1. Increase in primary energy consumption globally, from 1993 to 2018. Source: BP, 2019

2. SITUATION OF ENERGY CONSUMPTION FOR HVAC IN BUILDINGS

At present, the growth of GW and the intensification of CC at global level has a direct relationship to the exponential increase in the use of HVAC systems in buildings and shows a fast increase, particularly in urban locations. Currently, the use of HVAC represents almost 20% of the total electricity used in buildings worldwide and 10% of all world electricity consumption [2, 9]. This trend will increase due to factors such as economic and population growth and be evident with greater signals in hot regions as well as in prevailing mild climates during overheating periods. Within the utilization of HVAC systems, the fastest-growing use of energy in buildings is for space cooling, mainly in both hot humid and hot dry regions, where incomes are escalating, as well as in the advanced industrialised economies, where there are high consumer expectations of thermal comfort. Total energy use for space cooling in residential and commercial buildings worldwide more than tripled between 1990 and 2016 to reach 2,020 TeraWatt hours (TWh) [2] (Figures 2 and 3). In addition, due to the increase in world population, together with growths in urbanization and the expansion of industrialization, heat waves, such as those that have occurred in Europe and other regions of the planet, more recently in the summer of 2019, more cooling of the buildings will be required in the coming decades. In summary, the increase in the requirements of HVAC in buildings will generate a massive demand for electrical energy, which mostly comes from fossil fuels, which in turn will cause more pollution and CO₂ emissions, and the consequent deterioration of the environment, aggravating the situation and creating a noxious vicious circle, affecting the ecosystems of the planet, the economy of the building’s occupants, their quality of living, and, more importantly, people’s health [10].

A key first step to come up with is to improve HVAC system energy efficiencies, to reducing the need to build new power plants as well as to reduce GHG emissions, and mitigate the effects of Climate Change globally. This approach may contribute in a sustainable way to achieve economic benefits and indoor comfort conditions for building’s occupants.

Figure 2. Increase in energy use for building cooling systems in different regions of the world. Period from 2010 to 2018. Source: IEA https://www.iea.org/tcep/buildings/cooling/


3. CASE STUDY: INDIRECT EVAPORATIVE COOLING SYSTEMS. EXPERIMENTAL WORK

The main objective of this research was to evaluate and characterize various Indirect Evaporative Cooling Systems (IECS) in five experimental modules (EM) in their upper cover, aimed at achieving both thermal comfort conditions in buildings in hot-humid climates of Mexico and energy savings. The Case Study was located in the City of Merida, Yucatan, Mexico, which has a typical hot-humid climate (Figure 4). The experimental arrangement and methodology, based on previous studies [4, 5, 6, 7, 8], consisted of the development of experimental assessments during the overheating period. The initial process included the calibration of data loggers used in the experiments, and the results obtained indicated a consistency in the recorded values, which validated their use with reliability.
The EM were designed and built with five different IECS system configurations (M1, M2, M3, M4 and M5); integrating in their upper cover different IECS relative to a control or reference module (CM) (Figure 5).

Figure 4. Geographical location of the Case Study
Source: Google Earth, 2019

This climate has an average annual temperature of 26.7 °C, registering an average minimum of 21°C, and an average maximum of 33.5 °C. The hottest period is from March to August and the average annual rainfall is 1,036.9 mm, where the rainy season takes place from June to October with an average annual relative humidity of 71.48%, therefore its climate conditions corresponds to the classification of warm-humid.

4. METHODOLOGY OF THE EXPERIMENTAL WORK

The methodology consisted of the characterization of IEPCS through the monitoring of the hygrothermal conditions inside five experimental modules compared with a control module (CM) (Figure 5). These modules integrated different systems on its rooftop cover: Indirect evaporative cooling and solar protection (IEC + SP); thermal mass and thermal insulation (TM + TI); night radiative cooling and thermal mass (NRC + TM); indirect evaporative cooling, thermal mass and solar protection (IEC + TM + SP), and indirect evaporative cooling, thermal mass, solar protection and night radiative cooling (IEC + TM + SP + NRC). The monitoring of dry bulb temperatures (DBT) and relative humidity (RH) values was carried out concurrently for 30 consecutive days during the prevailing overheating period.

The modules geometry, based on previous research [4, 5, 6, 7, 8], consisted of an hexahedral geometry of 0.8 meters long x 0.8 meters wide and 0.47 meters high, with 0.015 cm thick plywood structure, covered inside by a foamular® panel of 0.045 meters as thermal insulation, to allow adiabatic conditions. This material is a thermal insulation made of rigid polystyrene foam with a thermal conductivity value (K); and for an average external temperature of 24 °C, is: 0.0288 W/mK; for an average outdoor temperature of 4.4 °C, its value is: 0.0259 W/mK. The configuration of the EM and the methodology were based on previous studies [4, 5, 6, 7, 8]. The thermal insulation was selected for its high resistance to humidity and steam; it is hydrophobic, that is, water repellent and due to its exclusive structure of closed cells, it does not allow spaces through which water leaks, therefore, it does not produce condensation.

The exterior was provided with a layer of wood sealer, to prevent weathering of the material exposed to the sun and rain; and lastly, coated with white epoxy paint. The base of the modules consists of two wooden bars of dimensions 3 " X 1.5" X 8.¼ ', to separate the six modules from the floor and to prevent heat gains (Figures 6 and 7).

In the process of the experimental work and in the modules where the NRC system was implemented (M3 and M5), a variant was included, with respect to the other modules, which consisted of removing the rooftop cover at 18:00 hrs and place it again at 6:00 am period (Figure 5).

After the calibration process and the climate analysis of the location were conducted, a simultaneous monitoring of indoor dry bulb temperatures (DBT) and relative humidity values (RH) was carried out in the modules. Concurrently with the monitoring, the climatic values of the exterior conditions were taken via the nearest EMA (Automated Meteorological Station) in the site analysed.

Figure 5. Geometry and features of experimental modules.
CM: Control Module; M1: indirect evaporative cooling + solar control; M2: thermal mass + thermal insulation; M3: radiative night cooling + thermal mass; M4: indirect evaporative cooling + thermal mass + solar control; M5: indirect evaporative cooling + thermal mass + solar control + radiative night cooling. M3 and M5, Night mode; 18:00-06:00 hrs. Diurnal mode: 06:00-18:00 hrs.

After the calibration process and the climate analysis of the location were conducted, a simultaneous monitoring of indoor dry bulb temperatures (DBT) and relative humidity values (RH) was carried out in the modules. Concurrently with the monitoring, the climatic values of the exterior conditions were taken via the nearest EMA (Automated Meteorological Station) in the site analysed.

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5. ANALYSIS AND INTERPRETATION OF THE RESULTS

Throughout the monitoring period, values of DBT and relative humidity were recorded at ten minutes interval during a typical overheating period in May, when the average exterior temperatures fluctuated from 27 °C and 38 °C. The values obtained were ordered and averaged over a 24-hour cycle. Results indicated that the average temperatures inside the modules decreased with respect to the mean and maximum external temperatures of the Automated Meteorological Station on the location (EMA).

The experimental module M1 showed an average temperature of 29.3 °C, with a maximum of 32.2 °C and a minimum of 26.7 °C, relative to the CM, that showed 31.3 °C, 38.6 °C and 25.6 °C, respectively. These values represented a temperature reduction of 2K, 6.4K and -1.1 K, correspondingly.

The temperature reductions of M1 relative to the external temperatures were 2.5 K, 5.5K and 0.2K, respectively (Figure 9).

The experimental module M3 showed an average temperature of 30.7 °C, with a maximum of 33.4 °C and a minimum of 28.0 °C, relative to the CM, that showed 31.3 °C, 38.6 °C and 25.6 °C, respectively. These values represented a temperature reduction of 0.6K, 5.2K and -2.4 K, correspondingly.

The temperature reductions of M3 relative to the external temperatures were 1.1 K, 4.3 K and 1.1 K, respectively (Figure 10).
The results of the performance of all strategies investigated inferred that the most promising cooling system investigated was the one that integrated indirect evaporative cooling, thermal mass, solar protection and night radiative cooling techniques (M5), which showed a mean temperature reduction of 4.2 K relative to the mean exterior temperature and a reduction of 8.3 K of its maximum temperature inside the module relative to the maximum exterior temperature (Figure 11).

An additional passive cooling technique was implemented in the most promising IECS (Module 5), using a Phase Change Material (PCM) on the rooftop cover by substituting the thermal mass of the water with a polycarbonate shell that encapsulated an organic element called *cocus nucifera*, an organic PCM, embedded in the polycarbonate panel placed at the cover of this experimental module, aimed at minimizing the energy use for space cooling. This material utilizes the temperature difference between day and night for the storage and release of thermal energy.

The monitoring of this passive cooling technique was conducted during the most critical overheating period in the location (May 11 to May 26), with maximum average temperature of 38.0 °C and a minimum of 26.6 °C. The results were compared with the temperatures in the CM and in the exterior. The average temperature in the CM was 30.2 °C relative with the average temperature in M5 with 25.3 °C, that infers an absolute reduction of 4.9 K (Figure 12).

Thus, the average temperature in the M5 was 25.3 °C relative with the exterior average temperature with 31.6 °C (Figure 12).

Therefore, the absolute results within the M5 with this supplementary passive cooling strategy presented a temperature reduction of 6.3 K relative to the mean exterior temperature and a reduction of 11.5 K of its maximum temperature relative to the maximum exterior temperature (Figure 12).

6. CONCLUSIONS

The results obtained confirmed the benefits found in previous studies [4, 5, 6, 7, 8], and proved that the IECS have an important energy saving potential by decreasing the use of HVAC systems, particularly in buildings located in hot humid climates, and/or during overheating periods, whilst achieving thermal comfort conditions for the occupants.

In the hot, and particularly hot humid regions of the world, thermal comfort is being increasingly challenged by the continuous rising temperatures. The values obtained in this work showed that low energy cooling is possible in such regions using a combination of enhanced passive cooling systems. This research demonstrated that it is feasible to achieve temperature reductions with the cooling systems investigated and, consequently, resulting in higher levels of comfort without the use of HVAC mechanical, fossil fuels-driven systems. The results also revealed a good potential for energy savings in the systems investigated, from which lessons can be extrapolated that can then be applied to the integration of other stand alone or combined cooling systems.
systems in real buildings in hot humid climates, whilst improving occupants thermal comfort conditions.

Certainly, the envelope of the buildings plays a very important role in the thermal behaviour of such systems, and has a huge impact on the HVAC requirements of the contained spaces. The choice of building materials is of great importance. In particular, the thermal mass, as also found in previous studies [4, 5, 6, 7, 8], is essential for the reduction of thermal swings. Therefore, the use of thermal mass, with integrated water systems and PCM, as applied in this research, pointed towards an important approach for the cooling of spaces that needs to continue with further research work. In addition, the implementation of these passive cooling systems in buildings and homes, where people cannot afford the purchase of HVAC equipment and the payment of electricity, may well provide a viable and effective alternative route to providing low energy thermal comfort to many people in a heating world due to current GW and CC situation. The implementation of these bioclimatic strategies has also a significant social-economic value as is associated with a reduction of energy consumption, directly related to energy savings and the improvement of the economy, the environment, and people’s health, providing multiple benefits to populations through a more climate-appropriate architecture for the present and future generations.

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