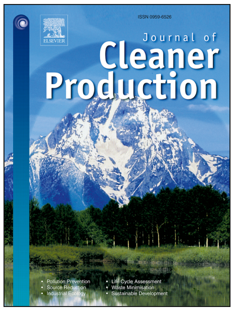

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MULTI-CRITERIA RISK ASSESSMENT: CASE STUDY FOR A LARGE HYDROELECTRIC PROJECT

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MULTI-CRITERIA RISK ASSESSMENT: CASE STUDY OF A LARGE HYDROELECTRIC PROJECT

Abstract. *Run-of-river hydroelectric plants along Amazon River tributaries have been shown to be an ecologically viable alternative to meet Brazilian energy demand. These plants are a solution to add capacity. However, due to geographic and socioeconomic characteristics of this region, there are risks that cannot be disregarded. This study reports the application of multi-criteria analysis to identify risk events for the Santo Antonio Hydroelectric Plant under construction, related to service packs relevant to the project. The choice of the appropriate technique took into consideration the imprecision of subjective judgment. The fuzzy analytic hierarchy process (FAHP) enabled inserting a measure of inaccuracy, represented by the degree of fuzziness, assigned to each pairwise comparison. Fuzziness was incorporated into the process by means of a triangular membership function. The convergence of opinion was assessed by comparing the hierarchical order of the perceived risks identified by two distinct groups, the owner consortium, and the builder consortium. These groups have similar risk perceptions, despite having different roles and asymmetric risk sharing caused mainly by the characteristics and provisions contained in the engineering, procurement and construction (EPC) contract. The model was efficient in ranking the risk events from the perspective of the two groups, therefore constituting a rational and transparent approach for risk management in large projects.*

Keywords: Risk Events, Service Packs, Santo Antonio Hydroelectric Plant, Fuzzy AHP

1. INTRODUCTION

The coexistence between a project and its environment is fertile ground for exposure to different types of risks. An infrastructure project is a unique undertaking. It consists of multiple interdependent tasks arranged to produce stages of the transformation of a product, which when concluded should be in conformity with expectations. The environment is multifaceted and almost all facets are beyond control, so it brings uncertainty to the project. On the other hand, the size and the participation of many different tasks that vary in intensity and time contribute to increase the project's complexity. The combination of uncertainty (Kalinina et al., 2016) and complexity (Baccarini, 1996) is an ideal setting for not achieving a project's targets. This is the main reason infrastructure projects pose many risks arising from a wide variety of causes, with a broad range of possible consequences. Such diversity requires greater commitment to the identification and control of risks.

Risk refers to uncertainty about an activity and the severity of its consequences (or outcomes) with respect to something that humans value (Aven and Renn, 2009). In the project context, it is an uncertain and possible event that, if occurring, will interfere in a project's objective (PMI, 2013). It includes the possibility of gains and losses or the variation between actual and planned project objectives, because of the uncertainty associated with a specific course of action. An action is risky when it demands deciding among different alternatives whose consequences are uncertain (Schubert, 2006). The risk can be measured in terms of impact and belief, i.e., it results from choices made or not (Emblemsvåg and Khalistan, 2006).

Successfully managing risk is an important component of successful project management because accurate risk management can support efforts to mitigate unexpected events of all types. The misunderstanding of effective risk management can cause projects to incur cost overruns, time overruns and failure to achieve relevant project requirements, besides causing harm to third parties. As projects grow in complexity and size, the involvement of engineers and experts in different fields of knowledge is needed to help identify the main sources of uncertainty and prioritize them.

In terms of categories, risks can be subdivided into: (i) technical, quality or performance – such as unverified or complex technology and unfeasible performance goals; (ii) project management – such as lack of technical and managerial skills; (iii) organizational – such as resource conflict with other projects, lack of funds; and (iv) external – such as regulation and interference from trade unions and social movements (PMI, 2013). The last category includes some classes of risks which are common to infrastructure projects, and they can cause delay in receiving and nonconformity of raw materials, parts, and components. Particularly in emerging economies, changes in laws and regulations, unclear ownership rights and actions by lobbying groups can negatively affect projects (Miller and Lessard, 2001).

In the case of a large construction project, the key elements can be classified as: (i) technical – design, process, instrumentation; (ii) estimation – capex, scheduling; (iii) delivery – engineering, procurement, management, construction, interfaces, commissioning, resources; (iv) operation and maintenance (Cooper at al., 2005). These elements are organized on a timely basis and are related to the project step sequence. Therefore, depending on the phase, increased emphasis will be placed on the risk events inherent to a few relevant and specific elements of that phase. In relation to the subject matter of this study, we are concerned with construction and interfaces of an ongoing facility, which means the attempt to mitigate possible negative consequences if such events occur, such as nonconformity, time and cost overruns.

The construction of large hydroelectric plants involves a wide spectrum of processes, some of them subject to unpredictable events caused by nature or man. Hydrological instability arising from seasonal rainfall and flow patterns (Braga and Molion, 1999) and conflicts with social movements like the anti-dam movements (Sobreiro Filho et al., 2016, Mccormick, 2007) are examples of events that threaten the project objectives and cause delays and cost overruns (Fidan, et al., 2011). The most common targets for control for these projects are costs, scheduling, and conformity. Moreover, the project manager seeks to mitigate risks related to health, safety, and environment during construction, by means of knowledge, resources, and engineering skills (PMI, 2013; Rasoola, 2012; Rafaele, et al., 2005; Hillson, et al., 2006). Project risk assessment involves identification and quantification of impacts and estimation of their likelihood. Assessments are conducted individually, giving support to priorities, resource allocation and definition of the best action plan to deal with each risk (Cooper, et al., 2005; Chapman and Ward, 2003).

In this context, multi-criteria decision analysis has been widely used in risk assessment, such as the Fuzzy Analytic Hierarchy Process (FAHP) (Zou, et al., 2013; Chan and Wang, 2013; Arikana, et al., 2013; Li, 2013; Avdi, et al., 2013; Zeng and Smith, 2007; Arce, et al., 2015; Govindan, et al., 2015). In the case of construction projects, Rahmana (2013) proposed a simple hierarchy tree with five risk categories and corresponding risk factors, which were assessed by four experts through pairwise comparison and FAHP, with the weights broken down in terms of time, cost and quality. Kim and Yarlagadda (2013) presented a procedure based on AHP and fuzzy comprehensive appraisal to select indicators and model a risk early-warning system of electric power engineering projects in western China. Zhang, et al. (2013) proposed an evaluation model based on the interval analytic hierarchy process (IAHP) and extension of the technique for order performance by similarity to ideal solution (TOPSIS), with interval data to improve the reliability of risk identification in hydroelectric generation projects. Wang and Zhou (2013) evaluated the differences in the allocation of existing contractual risks between builders and owners. With respect to risk sharing, projects with government funding have been characterized by transferring the responsibility for the design, procurement, contracting third-party services and construction to private companies or consortiums, requiring only that they deliver the plant with certain predetermined functional characteristics (Kang, et al., 2013). The FAHP technique has been used in these projects in the same way. Zhang, et al. (2013) proposed risk assessment of a hypothetical hydropower project divided into four steps: gathering potential risk data; structuring the decision hierarchy and assigning weights via IAHP; making decisions by extension of TOPSIS; and ranking potential risk factors. Teeng et al. (2016) performed risk assessment of an inter-plant chilled and cooling water network combining a multi-objective linear programming model with FAHP. Ren and Dong (2018) adopted FAHP and Grey Rational Analysis to evaluate the electricity supply sustainability and security of the five major emerging national economies (Brazil, Russia, India, China and South Africa) in terms of availability and security of supply, affordability and reliability, energy and economic efficiency, and environmental stewardship. Dong et al. (2015) adopted the environmental scanning method and FAHP to perform risk assessment for the planning and construction of charging facilities for electric vehicles. Wang and Li (2013) performed FAHP and TOPSIS assessment of six types of risk factors in energy performance contracts of energy saving projects.

One shortcoming identified in most of the cited references was the adoption of a risk factors list stipulated in advance, which is likely to create specification bias. Our method instead performs an exploratory assessment of service packs and risk events relevant to a certain stage of the project, which are identified by experts belonging to the top management of the builder consortium and owner consortium, through in-depth interviews and content analysis. The model hierarchy was specified with one level of service packs under a Work Breakdown Structure (WBS) and one level of risk events under a Risk Breakdown Structure (RBS). A second shortcoming observed in some of the cited references was the lack of a single straightforward procedure connecting the relative importance of service packs at a certain stage of the project with their corresponding risk events. We adopted the FAHP technique and pairwise comparison to calculate the weights for the service packs and risk events, estimated by the two groups of experts in two rounds of interviews held in a single meeting. Finally, this paper assesses the existence of convergence of perception of risks between the two groups of players. That is, a new evaluation model intended to improve the reliability of risk identification in hydropower projects was developed. A case study was performed of the Santo Antonio hydroelectric plant, a facility located in the Brazilian Amazon rainforest which in currently in operation. At the time of the present research was carried out the project was in the construction phase. The paper is structured as follows: First, the literature on risk assessment is briefly reviewed, and the FAHP is introduced in detail. Then, the method for risk identification of hydroelectric projects is explained in detail. Next, risk identification and sensitivity analysis of the case study in Brazil is conducted and discussed to show the application of our proposed model. The last section presents our conclusions.

2. WORK BREAKDOWN STRUCTURE

A useful framework for risk assessment is the combination of the Work Breakdown Structure (WBS) and the Risk Breakdown Structure (RBS), as proposed by the Project Management Institute (PMI, 2013). WBS has three bases for disaggregation: scheduling, deliverables, and resources. At the end, these three bases will result in the service packs, the lowest level of disaggregation. The RBS is a structure of potential risk sources or events (Hillson, et al., 2006), acting as a framework to assist the risk management process.

Schedule-oriented WBS is broken down into tasks or activities, which involve actions that team members may perform to attain the project's objectives. These actions occur sequentially, dictated by constructive restrictions. The deliverable-oriented WBS is divided into product, functional and physical. The product basis fragments the final product into parts or components, which together comprise the complete project. The functional basis splits the project into its purposes, such as, for example, electrical and mechanical systems. The physical basis involves the geographical scope of the project. The resource-oriented WBS is separated into discipline, administrative and budget. The discipline category includes the job qualifications and academic background of employees. The administrative category involves consideration of administrative or organizational division lines. The budget aspect involves the financial structure, normally identified according to the source of funds (multilateral, private, public, etc.).

The method proposed here involves the use of the schedule-oriented WBS as a basis for risk assessment by adopting smaller and more manageable parts of the project, called service packs. Therefore, the project manager, team members and clients are compelled to detail the necessary steps to create and deliver the product. The WBS upper level formulation can be developed by the project manager, but the breakdown into service packs demands a certain level of knowledge that only teams working together can accomplish. Two important advantages of the schedule-oriented elements are that the resulting WBS can be used for many projects and is applicable when the project is not fully defined. Because projects are carried by doing things such as developing, drawing, printing, fixing, and/or fabricating, the elements at the lowest level always will be service packs (Rad and Anantatmula, 2006). With scheduled-oriented WBS, it is possible to segregate the project's components and obtain an accurate picture of the objectives. Effective project management depends on a well-defined and fully implemented WBS and the corresponding RBS. With such tools, the success of risk mitigation depends on accurate analysis.

3. FUZZY ANALYTIC HIERARCHY PROCESS

The analytic hierarchy process (AHP) is widely used in decision-making processes involving multiple criteria. One of the strengths of this method is its pairwise comparison, very useful in complex decisions, in which human perception is important and will have long-term repercussions.

However, since this method does not consider the inaccuracies and ambiguities that are characteristic of decisions made in complex contexts, the FAHP is better suited to dealing with the uncertainties inherent to the process.

The method allows including a measure of inaccuracy in every step of a decision. This measure is represented by the degree of fuzziness (δ), necessary to determine the α-cuts of the membership functions, which are assigned to each pairwise decision comparison. Thus, inaccuracy is incorporated into the decision-making process and allows a more coherent approach to the real world, thus influencing the final choice.

Chang (1996) proposed a method for synthesizing the model solution, whose algorithm was tested to solve hierarchy problems associated with fuzzy logic (Zhua, et al., 1999), considering some modifications to optimize the method proposed by Leunga and Caob (2000), suggested the inclusion of a degree of tolerance in the weights according to their order of importance. Gu and Zhu (2006) used the fuzzy vector of a symmetric matrix containing the covariance of random variables in a decision table.

For the problem analyzed here, both service packs and risk events should be sufficiently detailed to assist the elicitation process when using the FAHP method. The pairwise comparison of service packs allows the assignment of weights to them. Then, the paired comparison of risk events for each service pack results in the risk performance metrics.

The FAHP method as proposed by Chang (1996) has proven to be practical and transparent (Kahraman et al., 2003), but it suffers from problems of *zero is used as divisor* or *data is out of range* (Zhu, et al., 1999), which are solved by adjusting the fuzzified value to 1, 9 or 1/9, depending on the case. In addition, the extent analysis method may assign a zero weight to some dominated decision criterion or alternative, leading that criterion or alternative not to be considered in the decision analysis (Wang et al., 2008), which is solved by avoiding the assignment of low values to δ. Finally, it is difficult to meet the consistency requirement in pairwise comparison, which is aggravated when the number of elements is large. Li, et al. (2013) proposed the adoption of IAHP to improve the comparison matrix consistency and convenience. However, the method proved to be ineffective when specified with a certain number of elements. Ribas and da Silva (2015) proposed the adoption of the Simos method (Figueira and Roy, 2002; Pictet and Bollinger, 2005), which overcomes the problem of inconsistency among pairwise comparison and reduces the effort of subjectively assigning the weights, which can be exhausting (Li, et al.; 2013).

4. METHODOLOGY

The proposal consists of four phases and the outcome is a hierarchical list of risk events classified by their weights (Lin and Hsieh, 2004), which can help project managers to set priorities, allocate resources and implement actions that increase the project's chances of success. The flowchart of Figure 1 shows the progress of the four phases of the proposed methodology.

1. Elicitation phase: 1.1. An interview roadmap is drawn up to ensure the assessment of the service packs and related risk events that can unfavorably change the project targets necessary to specify the model; 1.2. The experts are divided into two groups of stakeholders - the owner consortium and the builder consortium. The experts in the owner consortium are the technical manager (P.1), proprietary engineering manager (P.2) and health and safety engineer (P.3). The representatives of the builder consortium are the project manager (C.1), contracts and civil works manager (C.2), electromechanical equipment manager (C.3), electromechanical assembly manager (C.4), contract administration manager (C.5) and environmental manager (C.6); 1.3. Matters covered in the road map interview are posed to the experts, such as: “From this point onwards, what are the most critical issues requiring your special attention?”, and “Why are such issues critical? Can you identify the potential threats are?” 1.4. The experts are invited to read their statements and make the necessary adjustments; 1.5. Through content analysis (Hsieh and Shannon, 2005), a direct approach may be used in

which a list of service packs and a list of related risk events previously coded is constructed.

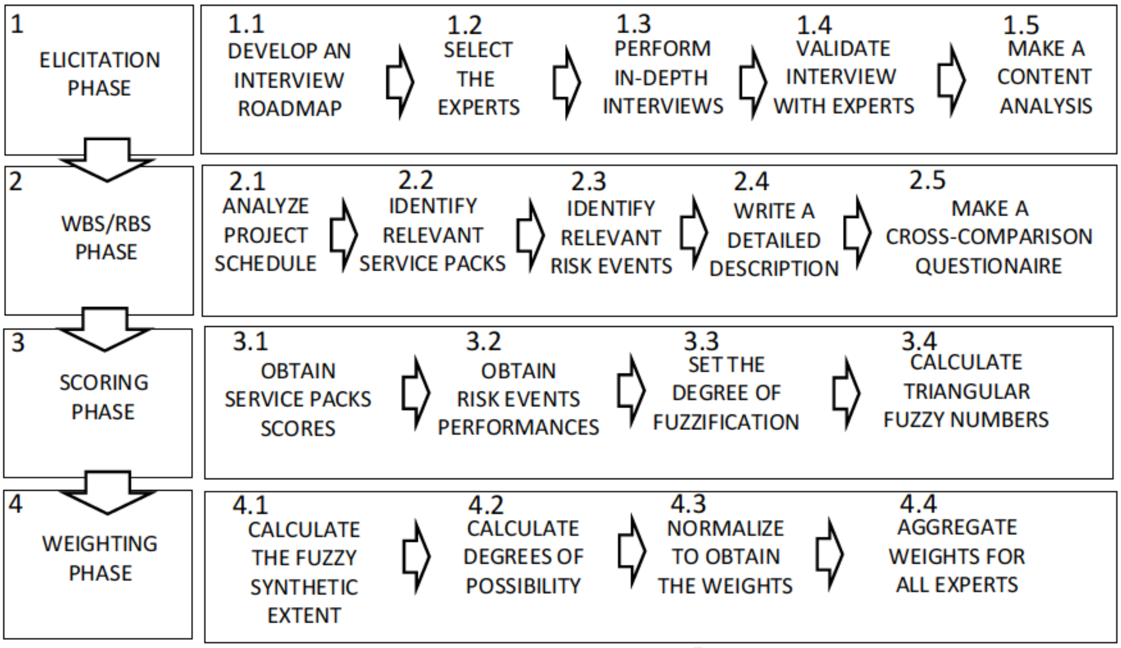

Figure 1: Flowchart showing the proposed method

2. <u>WBS/RBS phase</u>: 2.1. The further steps of the project timeline still pending to conclude the project are identified; 2.2. The service packs mentioned by the experts in the previous phase are aligned with the project timeline; 2.3. Likewise, RBS contains the risk events to which the project is subject. Based on the construction characteristics of large dams, the related risk will be assessed accordingly; 2.4. The service packs and the risk events are defined and categorized; 2.5. Two types of questionnaires are constructed: one containing the paired comparisons of importance among the “k” service packs and; “k” other factors containing paired comparisons of importance among the “n” risk events relative to each of the service packs.

3. <u>Scoring phase</u>: 3.1. To obtain the weights, the experts who participated in the interviews are invited to take part in this phase, when they are asked to fill out a paired comparison form divided into two parts: paired comparison between service packs and between risk events from the point of view of each service pack. In this way, for each combination of two service packs, the expert indicates which has the highest impact, and then assigns a score, according to the nominal scale proposed by Saaty (1970), whose odd scores range from 1 to 9, to estimate the level of importance. This is repeated until the exhaustion of the number pairs. Second, each service pack is compared to the pairwise risks. Likewise, the procedure is repeated for each service pack until the last pairwise comparison of risk events.; 3.3. The degree of fuzziness (δ) is set subjectively for each respondent based on his/her background knowledge related to the subject under consideration (Espino et al., 2014; Keprate and Ratnayake, 2016). This aims at reflecting the inaccuracy involved in the scoring phase. The δ value is 1.0 when the respondent: (i) has relevant background knowledge of similar projects and; (ii) has demonstrated during the elicitation phase being highly involved with the engineering, procurement and construction issues. The value of δ is 2.0 when either one of these two criteria is satisfied, and is equal to 3.0 otherwise. A fuzzy number characterized by a triangular membership function (TMF) assumes values in the interval [1/9.9]. TMFs are widely used since they are computationally simple, which facilitates the processing of

data (Tang and Beynon, 2005). For instance, if $M = \{M_{ij}\}_{n \times n}$ are pairwise comparisons between members of a set, then $M_{ij} = \{l_{ij};\ m_{ij};\ u_{ij}\}$ is a TMF with a fuzzification degree δ, which is represented by the minimum, modal, and maximum values where:

$$M_{ij} = \{l_{ij} = m_{ij} - \delta;\ m_{ij};\ u_{ij} = m_{ij} + \delta\} \tag{1}$$

4. Weighting phase: 4.1. The fuzzy synthetic extent (S_i) for each M_{ij} is determined by equation (2), noting that each M_{ij} is a TMF according to equation (1), so S_i is a triplet containing minimum, modal and maximum values:

$$S_i = \sum_{j=1}^{n} M_{ij} \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{n} M_{ij}\right]^{-1} \tag{2}$$

4.2. Comparing two convex fuzzy numbers S_1 and S_2, the degree of possibility must be one of the following values as shown in equations (3), (4) and (5), where *hgt* is the ordinate of the highest intersection point between S_1 and S_2, here represented by d in Figure 2.

$$V(S_1 \geq S_2) = 1\ iff\ m_1 \geq m_2 \tag{3}$$

$$V(S_2 \geq S_1) = hgt(S_1 \cap S_2) = d = \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}\ iff\ d \geq 0 \tag{4}$$

$$\text{if } d < 0 \rightarrow V(S_2 \geq S_1) = 0 \tag{5}$$

4.3. For a specific convex fuzzy number S_j to be greater than the remaining S_i, then in equation (6), using the *min* operator:

$$V(S_j \geq S_i) = d_j' = \min(S_j \geq S_i)\text{ , i=1...n} \wedge \text{i}\neq\text{j} \tag{6}$$

The weight vector (7) and the normalized weight vector (8) are:

$$\text{W}=\{d_1', d_2', \ldots, d_n'\} \tag{7}$$

$$W' = {}^{W}\!/_{\sum_i d_i'}\text{ , i=1…n} \tag{8}$$

4.4. The independent results of each interviewee are obtained by FAHP. For each interviewee, there are two vectors of normalized weights, one for the service packs and another one for risk events. Finally, these results are joined for each stakeholder and the means of each group for the service packs and risk events are computed.

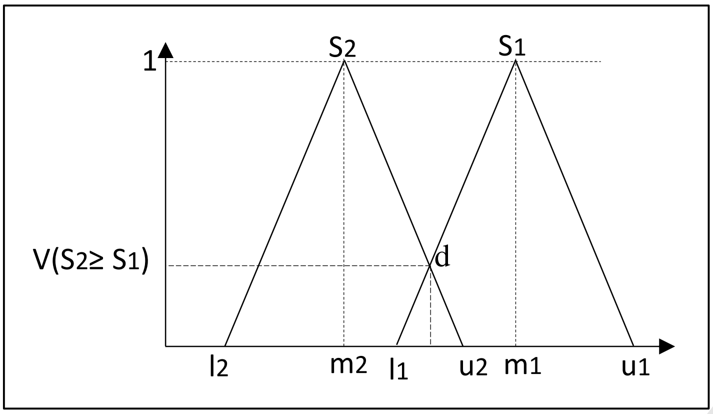

Figure 2: Comparison between two fuzzy numbers S_1 and S_2

5. CASE STUDY

The Santo Antonio hydroelectric plant is in operation on the Madeira river in the Brazilian Amazon rainforest, as seen in figure 3. The Madeira river is one of the biggest tributaries of the Amazon, accounting for about 15% of the water in the basin. The project, completed in 2017, has 50 Kaplan bulb turbines to generate 71.37 megawatts (MW) of power each, totaling 3,568.3 MW. The construction plan started from the banks to the center of the river and allowed for work to be carried out simultaneously on both sides of the Madeira River. The 50 turbines are distributed among four power houses. Two of these (Powerhouse 2 and 3, with 12 turbines each) are located on the left bank of the Madeira River. Powerhouse 1 (the first to start operating) has 8 units and was constructed on the right bank. Powerhouse 4 has 18 turbines installed in the center of the river bed. The dam has two spillways and a total of 18 floodgates, allowing up to 84,000 m^3 of water to pass per second (Santo Antonio Energia, 2019).

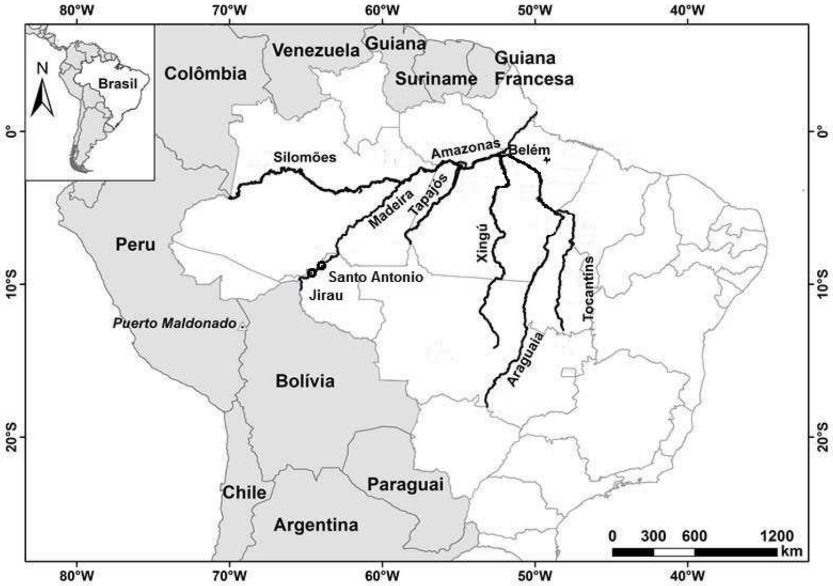

Figure 3: Santo Antonio plant location

The organization of the on-site construction was under the responsibility of the owner consortium, with an electric power public service concessionaire acting as the owner's engineer, including certifying the project designs and supervising on-site construction. The on-site construction was being carried out by an engineering, procurement, and construction (EPC) builder consortium, under a lump-sum turnkey contract to the owner consortium (IHA, 2014).

The economic feasibility study showed an energy cost of US$ 23.02/MWh (ANEEL, 2005) for a concession of 50 years. The energy sale price offered by the consortium in the auction for new energy was US$ 25.86/MWh (ANEEL, 2007).

The work on the Santo Antonio Hydroelectric Plant was a challenge for Brazilian engineering. A project of this size is dynamic and complex and demands the ability to manage its activities in accordance with the best engineering practices. In this sense, risk management emerges to help make decisions.

6. RESULTS AND DISCUSSION

6.1. Elicitation phase

The interviews were conducted during the construction of Powerhouse 4 in January-2013. In-depth interviews were conducted with members of the two groups in person to obtain a detailed account of the principal service packs and concerns about risk events relative to the stage Santo Antonio power plant construction. Through content analysis, a direct approach was used in which a list of likely service packs and a list of risk events identified from the in-depth interviews was previously coded.

6.2. WBS/RBS phase

The service packs and risk events were identified and extracted from records of interviews with both groups, carried out during the first round of data collection. Through content analysis, the information was extracted from the text of the interviews. The service packs correspond to a list of activities that are essential for meeting all legal and contractual requirements. The risk events are single specific occurrences that affect the service packs in a negative manner.

The identified service packs were:

- Contractual modality (CM) - The type of contract used was lump-sum, namely, delivery of the work with the default specifications at a fixed price.
- River management (RM) - In the context of hydroelectric generation, the river management achieved by the combination of ecological and sustainability principles with the construction engineering techniques and procedures, aiming to mitigate the impacts on the local ecosystem and make possible the construction and operation of the project.
- Electromechanical assembly (EA) – This involves the installation and commissioning of the turbines, generators, transformers and buses, the electrical panels and automation hardware.
- Civil works (CW) –This includes the diversion of the riverbed by constructing a cofferdam, the construction of the dam itself and the porches, gate systems, spillway, water intake and penstock, works to enable the internal organization, stone crushers, sand production plants, concrete production plants, metal structures, overhead cranes, gantry cranes, among others.
- Workforce (WF) – All the human resources necessary for civil works, electromechanical assembly, support services, inspection, supervision, and management are included in this service pack, both own labor and outsourced services.

The identified risk events were:

- Hydrological cycle (HC) - The seasonality of climate, with reflexes in the Amazon region, are enhanced by the large existing flow in the Amazon river, its tributaries, and effluents, is essential elements in the planning and construction of engineering works in this region.

- Product specification (PS) - A project with the size of the Santo Antonio Hydroelectric Plant uses a huge amount of materials, parts, components, and equipment manufactured by different vendors. The technical and functional characteristics of these inputs are specified in technical designs and specification sheets, many of them with very small tolerances regarding dimensions and types of materials. When one of these does not satisfy the required compliance standards, it causes loss of time, materials, and services, among others, and can cause schedule delays, loss of quality and increase in costs.
- Quality of service (QS) - The ability, qualification and proper sizing of human resources, planning activities, coordination of services, control and organization, detail, and clarity in the work to be performed and safety, among other aspects, are essential to prevent problems of noncompliance of the result of the work.
- Interface (IN) - In a large project, different teams work on steps that complement each other, resulting in a complete product. This occurs with organization, civil works, assembly, testing and details of engineering procedures. Equipment and services are interdependent and therefore subject to coupling problems, synchronization, among others. General or isolated failures compromise the completed product.
- Stoppages (ST) - Unscheduled work stoppages can happen because of strikes, poor planning of labor allocation, and various problems faced by suppliers (like unscheduled production shutdowns, problems of transportation and customs clearance). Shutdowns primarily affect the component of time, but are not limited to this. The consequences can spread to structural uniformity problems (e.g., cracks in concrete), damaged parts and components subject to weather, among others.

6.3. Scoring phase

For each respondent, filling in the paired comparison form generated an array of importance of service packs and another for risk events applicable to a specific service pack. Table 1 reports the scores for service packs indicated by the respondent identified as C.2, the contracts and civil works manager of the builder consortium.

The measurement of preferences was performed through pairwise comparison following the guidelines proposed by Guitouni and Martel (1998). The interviewer posed the following questions to the respondent C.2: “Compare these cards containing the river management and the contractual modality. Please indicate which of them causes the greatest impact to the project if any unexpected problem occurs.”

After he chose the former, the interviewer showed a Saaty scale containing odd numbers ranging from 1 to 9 and followed: "In your opinion, what is the level of this importance, according to the scale here?". By assigning a score 7, C.2 believes that the river management is much more important than the contractual modality. The respondent was asked to make the paired comparisons corresponding to the cells located above the main diagonal, with the cells below reciprocals being his choices.

This procedure was repeated until all pairs of service packs were compared.

Table 1: Scores of service packs indicated by C.2

	CM	RM	EA	CW	WF

Contractual modality	CM	1	1/7	1/7	1/5	1/9
River management	RM	7	1	1	3	1/3
Electromechanical assembly	EA	7	1	1	3	1/3
Civil works	CW	5	1/3	1/3	1	1/5
Workforce	WF	9	3	3	5	1

Table 2 reports the risk event scores in relation to the contractual mobility indicated by the same respondent C.2. The paired comparison of the risk events related to each service pack followed a similar procedure. In this case, the interviewer asked him the question: "Between the risk events hydrological cycle and product specification, which one has wider adverse consequences to the contractual modality?"

Once the former was chosen, the interviewer continued: “And which, in your opinion, is the level of this importance, observing the scale? In other words, to what extent is the hydrological cycle relevant to the contractual modality, when compared with the product specification?” By assigning a score 5, C.2 believes that the hydrological cycle is more important than the product specification, when considering the influence on the contractual mobility.

Again, this procedure was repeated until all pairs of risk events corresponding to the cells above the main diagonal were compared for each service pack.

Table 2: Scores of risk events for by contractual modality indicated by C.2

		HC	PS	QS	IN	ST
Hydrological cycle	HC	1	5	3	7	1/5
Product specification	OS	1/5	1	1/5	1/7	1/5
Quality of service	QS	1/3	5	1	1/5	1/5
Interfaces	IN	1/7	7	5	1	1/5
Stoppages	ST	5	5	5	5	1

6.4. Weighting phase

Calculations by the FAHP method were performed individually for each respondent, according to the algorithm, assigning δ equal to one. By means of the results found in the matrix of paired comparisons and the FAHP technique, it is possible to determine the weights for each of the benefits and rank them. The set of weights W for service packs and risk events was calculated for each respondent, and the resulting vectors were aggregated for all respondents belonging to the owner consortium and the builder consortium, respectively, and subsequently normalized in both groups.

The results for the owner consortium group are shown in Table 3 for the service packs and Table 4 for risk events. The last column of each table shows the ranking of the average opinion of respondents from the corresponding group. The scores arising from subjective opinions are ordinal, so their average is a meaningless statistic. However, the weights are interval measurements, so their average is useful information. In the context of absolute values, there are zero weights happening for all respondents. This is due to a combination of low scores given in pairwise comparisons and the FAHP criterion for weight calculation. When an alternative is consistently dominated by others, the set of fuzzy numbers originated from such comparisons is affected by the minimum operator criterion, whose outcome is a weight of zero. The civil works with a zero weight is due to a consensus with respect of the dominated alternative, arising from the fact that all owner consortium respondents believe this service pack has lower impact than the others. The advanced construction stage of the dam, spillway, intake, penstock, and power house influenced the pairwise comparisons, turning the builder's concern toward the electromechanical assembly.

Table 3: Weights of service packs for the owner consortium

		P.1	P.2	P.3	Average	Order
Contractual modality	CM	0.7108	0.0000	0.0000	0.4349	1st
River management	RM	0.0000	0.0000	0.0000	0.1354	4th
Electromechanical assembly	EA	0.2892	0.2081	0.2081	0.1658	3rd
Civil works	CW	0.0000	0.0000	0.0000	0.0000	5th
Workforce	WF	0.0000	0.7919	0.7919	0.2640	2nd
Standard Deviation		0.2789	0.3067	0.3067	0.2792	

In the owner consortium's vision, the contractual modality, the workforce and the electromechanical assembly were the service packs causing the greatest negative impact on the project. In the opinion of P.1, "Because of the EPC contract, all the design and construction risk is borne by the contractor. However, a turnkey contract is not transparent with respect to unit prices, and when deadlines are short, conformity is relegated to the background avoid any penalty for time overrun." He went on to say that "the delivery of the electrical-mechanical equipment is delayed and many parts do not meet the design specifications."

Table 4: Weights of risk events of the owner consortium

		P.1	P.2	P.3	Average	Order
Hydrological cycle	HC	0.0010	0.0000	0.0000	0.0003	5th
Product specification	PS	0.0000	0.5223	0.0480	0.1901	3rd
Quality of service	QS	0.7108	0.4777	0.1688	0.4525	2nd
Interfaces	IN	0.0000	0.0000	0.0681	0.0227	4th
Stoppages	ST	0.6503	0.0000	0.7151	0.4551	1st
Standard Deviation		0.3338	0.2454	0.2634	0.1987	

Representatives of the owner consortium considered the downtime caused by employees of the builder consortium or situations involving suppliers is the risk event that ranks first, mainly affecting the project schedule. Quality of service was classified second, which refers to noncompliance with technical and functional criteria in civil and electromechanical works. One issue mentioned by P.2 was the bulb turbines' water filtration quality. The Madeira River carries a heavy sediment load. During the flood season, these sediments tend to block the filtration system of all turbines, demanding repetitive shutdown for cleaning. Other risk events dominated the hydrologic cycle mainly because the cofferdam and the dams were almost completed and the spillways were operational, making it possible to mitigate the flooding impact during the wet season. quality of service as the event capable of bringing the most serious consequences for the work. Results for the builder consortium are shown in Table 5 for service packs and Table 6 for risk events.

Table 5: Weights of service packs of the builder consortium

		C.1	C.2	C.3	C.4	C.5	C.6	Average	Order
Contractual modality	CM	0.7096	0.0000	0.6458	0.0000	0.3829	0.0000	0.2897	2nd
River management	RM	0	0.2049	0	0	0	0.4047	0.1016	4th
Electromechanical assembly	EA	0.2904	0.2049	0.3542	0.2881	0	0	0.1896	3rd
Civil works	CW	0	0	0	0	0.0408	0.0048	0.0076	5th
Workforce	WF	0	0.5903	0	0.7119	0.5762	0.5906	0.4115	1st
Standard Deviation		0.2785	0.2156	0.2617	0.2792	0.2368	0.2500	0.1411	

The workforce was the main reason for concern. Although the builder conducted a wide range of training programs involving residents of the Brazilian town of Porto Velho, located next to the project, there was a shortage of qualified manpower in the region, aggravated by a significant risk of strikes. The contractual modality was ranked second. As mentioned by C.2, the EPC turnkey lump-sum contract transfers all the engineering, cost, and time overrun risks to the builder, which is solely responsible for satisfying all the power plant requirements, with emphasis to the environmental and operational targets.

Electromechanical assembly is the last construction step before commissioning. From the point of view of C.2 and C.4, it depended on the successful completion of some relevant previous steps, such as civil works and parts delivery, both in terms of timeliness and conformity. The logistic of equipment transport to the Amazon region and the customs clearance of imported equipment are issues related to EA. The electromechanical parts suppliers were also committed to deliveries to Jirau Hydroelectric Plant, also under construction on the Madeira River, causing most of them to almost reach their installed capacity ceiling. Also, even if all imported goods are manufactured and delivered to the destination port on time, they could be held in customs for an indeterminate period when the Internal Revenue Service agents were on strike.

Table 6: Weights of risk events of the builder consortium

		C.1	C.2	C.3	C.4	C.5	C.6	Average	Order
Hydrological cycle	HC	0	0.1209	0	0	0.0076	0.2662	0.0658	5th
Product specification	PS	0.2946	0.1209	0.5748	0	0.2104	0.0007	0.2002	3rd
Quality of service	QS	0.1463	0.1209	0.4252	0.3296	0.1918	0.2449	0.2431	2nd
Interfaces	IN	0.2915	0	0	0.0392	0	0.1459	0.0794	4th
Stoppages	ST	0.2676	0.4501	0	0.6312	0.5902	0.3423	0.3802	1st
Standard Deviation		0.1138	0.1512	0.2495	0.2484	0.2142	0.1177	0.1155	

From the perspective of the builder consortium shown in Table 6, the risk event that raises most concern was the downtime resulting from the occurrence of strikes. The quality of service was the next issue, which shows the difficulty of meeting the service specifications, generating noncompliance that requires rework. Product specification was next in order, due to problems with size or composition of parts and elements that require the builder to ask the supplier for repair or perform the work itself.

If the fuzzification degree equals zero, the values are crisp, and according to the minimum criterion for weight calculation, the dominating element has weight of one and the remaining elements have zero weight. Therefore, in a case study having five elements, the number of both service packs and risk events, the standard deviation for a dominating element equals 0.4, defining the range for such statistics. Through observation of the highest standard deviation values, according to Table 3 of service packs for the owner consortium, respondent P.1 considers contractual modality as a dominating service pack, while respondent P.3 considers workforce instead. The same difference is found with the builder consortium, in Table 5, where the respondent C.1 gives importance to contractual modality, unlike his colleagues, who believe the workforce is the most impacting service pack. Such diversity is usual, and a reasonable way to propose a common weight for a group is in terms of its average.

We used Spearman's correlation coefficient to test the convergence of views between the two stakeholder groups, in which the statistics calculated for a one-tailed test at 5% significance level and sample size with five pairs of observations resulted in a number greater than 0.829. This means that if the calculated value lies below the threshold of accepting the H_0 hypothesis, that the weights between the two groups do not have the same distribution. If this condition is confirmed for both comparisons, the groups have no consensus about any of them.

For service packs, Spearman's statistic was equal to 0.782, a value calculated by comparing the "Average" columns of Tables 3 and 5. This result confirms the hypothesis H_0 and is below the value 0.829, which is the acceptance threshold. Thus, a situation of conflict was found between the owner and builder groups regarding the areas that represent the greatest impact on the project. This can be confirmed by analyzing the simple averages of responses for each group. On the one hand, the representatives of the owners attached great importance to contractual modality, electromechanical assembly, and workforce, in that order. On the other hand, the builder group listed the same elements, but in reverse order of importance.

For risk events, the correlation is 0.922, above the threshold, indicating no controversy. As indicated in Table 4, the owners expressed concern about the stoppages, quality of service, and product specification, in that order, while the builders (Table 6) indicated concern about the same problems and in the same order of importance.

The coincidence of the impact and importance of the risks identified by both groups is understandable when observing the responsibilities of each consortium. The design, works and supply are under the responsibility of the builder consortium. There is great effort by this group to deal with the difficulties inherent in these aspects. To solve the labor deficiency, the builder consortium established an educational program to train local workers. Regarding electromechanical assembly, there is a technical deficiency the labor responsible. The three major suppliers deliver the electromechanical equipment on time, but the builder consortium had to carry out a considerable amount of rework.

Regarding the contractual modality, because it is a lump-sum contract, all the risks are under responsibility of the contractors. However, from the viewpoint of the owners, the contract management is difficult because there is no way of knowing the unit price and quantity of services performed, ultimately making it hard to refuse possible claims of suppliers.

7. SENSITIVITY ANALYSIS

Uncertainty in problem-solving is a consequence of information deficiency. In this aspect, two types of uncertainties exist when dealing with information in human communication and cognition. The first is epistemic, arising from a lack or gaps in knowledge, which should be reduced through improvement or increase of expertise. The second is aleatory, intrinsic to the elements of the model, which should be reduced by gathering additional data or information (Melchers and Beck, 2018). The vagueness resulting in imprecise boundaries of a fuzzy set is epistemic, caused by incomplete or insufficient knowledge or unfamiliarity with the problem. In this study, the adoption of fuzzy numbers is an attempt to mitigate such inaccuracy, a common problem found when dealing with subjective estimates, such as opinions. However, inferring δ is not clear-cut; it is estimated instead. Thus, the matter is whether the value of δ is likely to alter the order of a specific set of alternatives. In order to address that concern, we performed sensitivity analysis by comparing the rank order of risk events under a range of δ values.

In the owner consortium we first set the δ values to range from 1.0 to 3.0, then we assigned δ values equal 1.0 to the technical manager (P.1) and proprietary engineering manager (P.2), and equal 3.0 to the health and safety engineer (P.3). Table 7 demonstrates that the rank order was almost stable with such δ values, with the lower limit being the value used in our baseline case. The changes are to positions 1 and 2, where stoppages (ST) and quality of service (QS) have swapped places, and to positions 4 and 5, where interfaces (IN) and hydrological cycle (HC) also have swapped places.

Table 7: Weights of risk events of the owner consortium for different values of the degree of fuzziness

		δ=1.0		δ=2.0		δ=3.0		δ=mix	
Hydrological cycle	HC	0.0003	5th	0.1121	4th	0.1510	4th	0.0317	5th
Product specification	PS	0.1901	3rd	0.2135	3rd	0.2110	3rd	0.2135	3rd
Quality of service	QS	0.4525	2nd	0.3566	1st	0.3000	1st	0.4698	1st
Interfaces	IN	0.0227	4th	0.1136	5th	0.1465	5th	0.0852	4th
Stoppages	ST	0.4551	1st	0.3134	2nd	0.2696	2nd	0.3205	2nd
Standard Deviation		0.1987		0.1004		0.0617		0.1588	

In the builder consortium, the operating method is the same as that of the owner consortium. We first ranged δ values from 1.0 to 3.0, then assigned δ values equal 1.0 to the project manager (C.1), contracts and civil works manager (C.2) and electromechanical assembly manager (C.4); of 2.0 to the electromechanical equipment manager (C.3) and the environmental manager (C.6), and of 3.0 to the contract administration manager (C.5). Table 8 demonstrates that the rank order was stable with such δ values.

Table 8: Weights of risk events of the builder consortium for different values of the degree of fuzziness

		δ=1.0		δ=2.0		δ=3.0		δ=mix	
Hydrological cycle	HC	0.0658	5th	0.0720	5th	0.0903	5th	0.0718	5th
Product specification	PS	0.2002	3rd	0.1857	3rd	0.1910	3rd	0.1996	3rd
Quality of service	QS	0.2431	2nd	0.2673	2nd	0.2563	2nd	0.2470	2nd
Interfaces	IN	0.0794	4th	0.1346	4th	0.1682	4th	0.1113	4th
Stoppages	ST	0.3802	1st	0.3016	1st	0.2728	1st	0.3391	1st
Standard Deviation		0.1155		0.0842		0.0656		0.0956	

When looking at Tables 7 and 8, one aspect that calls attention is the decreasing standard deviation among alternative weights with increasing δ values. This can be explained by fuzzy logic theory, since when vagueness increases, the possibility that a dominated alternative is outranked increases too, even though its crisp value is the smallest of the set.

8. CONSISTENCY OF RESPONSES

The inconsistency takes place when numerical values are assigned to subjective preferences of the experts. Thus, it is necessary to check what is acceptable. The consistency ratio (CR) is obtained by comparing the consistency index (CI) of the matrix of pairwise comparisons against the consistency index of a random-like matrix (RI). The consistency index for criterion weights higher than zero is calculated as follows:

$$C.I. = \frac{\lambda_{max}.(n-1)}{n} \tag{9}$$

Where λ_{max} is the eigenvector and *n* is the number of criteria. The Consistency Ratio equals:

$$C.R. = \frac{C.I.}{R.I.} \tag{10}$$

The denominator RI is the random index table value according to the number of criteria (Saaty and Vargas, 2012). The optimal value for the criteria to be evaluated as consistent would be CR ≤0.1 (Saaty, 1990). For n equal 5, the RI value is 1.12. We checked the consistency of the experts' pairwise comparisons for the service packs. Table 9 shows that all the participants of the owner consortium and the builder consortium had CR values equal to or lower than 0.1.

Table 9: Consistency ratios of the experts of the owner consortium and the builder consortium

	Owner Consortium			Builder Consortium					
	P.1	P.2	P.3	C.1	C.2	C.3	C.4	C.5	C.6
λ_{max}	5.24	5.33	5.24	5.18	5.13	5.31	5.43	5.47	5.28
C.I.	0.06	0.08	0.06	0.05	0.03	0.08	0.11	0.12	0.07
C.R.	0.05	0.07	0.05	0.04	0.03	0.07	0.10	0.10	0.06

9. CONCLUSIONS

Some limitations of the proposed methodology may be addressed. One of the steps of the elicitation phase is the holding of in-depth interviews, where the goal is to collect as much information about the critical points of design. One of the major pitfalls of this technique is called *prone to bias* (Boyce and Neale, 2006), which means that the builder consortium members want to prove that construction is running according to plan, making their interview responses biased. The data collection should be designed, instruments created and interviews conducted to minimize bias. Considering the high degree of education of the respondents, the elicited statements followed a straightforward line of reasoning. However, organizational culture can discourage experts from disclosing difficulties of the project, which hinders the identification and ranking of risk events. The content analysis, performed in the elicitation phase, aims to extract the relevant service packs and risk events from the interviews. The limitation at this point arises when one fails to develop a complete understanding of the context, thus failing to identify key elements. This can result in findings that do not accurately represent the data (Hsieh and Shannon, 2005). In this case, the development of a large hydroelectric plant, where the expectation of success also concerns numerous external stakeholder groups, creates a situation where there is no room for failure. Therefore, the interviewer must be sensitive enough during the content analysis to focus on the risk identification and capture the critical points.

The pairwise comparison, adopted in the scoring phase, requires the specification of a parsimonious model containing a small number of elements, hence reducing the effort of subjectively assigning the weights, which can be exhausting. This is because their determination by pairwise comparison has the disadvantage of requiring the interviewee to comprehensively judge, evaluate and estimate the criteria in pairs, making the elicitation process unnecessarily long. In the case study described in this paper, we selected few key elements, restricted to five service packs and five risk events, aiming at reducing the time spent in the dialogue.

To summarize, the FAHP technique and pairwise comparison were used in the proposed method to assign weights to the criteria and decision makers, while WBS and RBS were employed to specify the model hierarchy: one level of service packs and one level of risk events, respectively. The method applied provided a fair indicator to rank risk events and reveal the relative strengths and weaknesses when they were evaluated under a set of relevant service packs. The proposed method exploits the knowledge and perception of the experts, because they are required to focus on the problem, explain and justify their opinions, and at a later moment, weight the degree of importance of the relevant risk events. Because they helped to identify the risk elements during the modeling process, they were more likely to accept and adopt risk management of these elements. Based on the stage structure, the proposed model differs from other risk identification procedures. That is, this model contains the elicitation, specification and scoring phases executed within the same stream of interviews, providing fast and low-cost assessment. The accuracy and feasibility of the model were proved in the application. Based on the above, it can be concluded that the proposed model is more effective than conventional methods to evaluate these types of issues. Although the method was tested for risk identification of a hydroelectric project, it can also be applied to other projects.

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HIGHLIGHTS

- In-depth interviews and Fuzzy Analytic Hierarchy Process FAHP were used to specify and rank the risk events.

- The method uses the schedule-oriented Work Breakdown Structure (WBS) as a basis for risk assessment.

- The builder consortium was mainly concerned with the downtime due to strikes.

- The owner consortium was mainly concerned with the quality of service.