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WASTE MANAGEMENT IN CIVIL ENGINEERING: A DYNAMIC FRAMEWORK

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Abstract

The recycling and later use of construction and demolition waste (C&D waste) as construction materials present a strategic inconvenience for many stakeholders involved in the sustainable construction. In some countries, the recycling percentage of C&D waste is around 80% of the C&D generated. However, in other countries this percentage is much lower. This complexity requires a better understanding of the recycling dynamic. In the specific case of Spain, the National Integrated Waste Management Plan (PNIR 2008-2015) suggests a number of goals for recycling and recovery of building materials that are difficult to meet without laying down policies intended to stimulate the companies´ behaviour of consumption of recycled C&D waste. This paper presents a conceptual framework within which the issue of recycling can be raised from a multidisciplinary approach, taking into account the technical conditioning factors as well as the socioeconomic aspects that might influence the behaviour of companies and the government. On the basis of a systemic problem approach, a dynamic simulation model was designed to evaluate the consequences of incentives policies by promoting the use of recycled aggregates. Actions aimed at increasing the use of C&D waste materials in construction, by providing economic incentives to the industry, are proposed as a short-term policy to balance the achievement of goals for sustainable construction in the future. This conceptual framework possesses a transferable potential that might be applied to other countries involved in the same dynamic.

Key words: demolition waste, strategic management, sustainable construction, system dynamics

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1. Introduction

At the present time the concept of sustainability has attained great importance in all fields, and even more so, in the construction field. According to the *International Council for Research and Innovation in Building and Construction* (CIB), the main goal of the sustainable construction is the development of a healthy building environment based on the efficiency of the resources and an environmentally friendly design. For the promotion and legal regulation of the use of construction and demolition (C&D) waste in the economic activity, the European Public Institutions have recently designed a legal framework by which the management and recycling of C&D waste can be regulated. Thus, On 17 June 2008, the European Parliament approved a proposal for the modification of the Waste Framework Directive, which includes an agreement with the Council of the European Union, setting out a number of objectives related to specific waste flows that includes C&D waste. In this new directive, the EU Member States are required to adopt the necessary measures to guarantee that, prior to the year 2020, the 70% of the weight of non-hazardous waste originating from construction and demolition (with the exception of natural materials as defined in code 17 05 04 of the EWL) will be earmarked for reuse, recycling and other operations related to the

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recovery of materials, including landfill operations that use waste to replace other materials (EC Directive, 2008).

The National Integrated Waste Management Plan 2008-2015 (PNIR) (MERMA, 2009) is the legal framework that regulates the management of C&D waste in Spain. This regulation came about in response to the social and economic problems created by the accumulation of waste in this country over the last few years. According to this Plan, the average production of C&D waste per inhabitant and year is estimated to be around 790 kg/inhab./year (MERMA, 2008, annex 6, p. 408). Approximately 10 million tonnes of C&D waste (roughly 29%) are disposed of at inert waste disposal facilities accomodated to the regulation on waste disposal sites currently in force. However, at the present time, in Spain over 21 million tonnes of the C&D waste generated, i.e., more than 60%, undergo uncontrolled disposal in dumps, holes or abutments or simply scattered on the outskirts with the consequent environmental and social impact (MERMA, 2009).

For this reason, the PNIR lists the following specific quantitative goals (MPW, 2001):

- environmentally friendly separation and management of 100% of C&D waste starting in 2010;
- recycling of C&D waste (tonnes of C&D waste subjected to recycling processes divided by the tonnes of C&D waste generated) of 15% by 2010, 25% in 2012 and 35% in 2015;
- % of C&D waste subjected to other recovery processes (tonnes of C&D waste subjected to C&D waste recovery operations other than recycling, including landfill operations, divided by the tonnes of C&D waste generated) including landfill operations, of 10% by 2010, 15% in 2012 and 20% in 2015;
- % of C&D waste disposal in controlled waste disposal sites 100 – (% of recycled C&D waste) – (% of C&D waste subjected to other recovery processes, including landfill operations) of 75% in 2010, 60% in 2012 and 45% in 2015.

These are very ambitious goals that are extremely difficult to meet. Therefore, it is necessary to develop the basic actions initially proposed to promote sustainable construction (i.e., designing administrative incentives, the technical selection of materials using different percentages of C&D waste, the development of recycling technologies).

However, even though the PNIR presents a global recycling objective of 55%, the program has not yet been translated into a legal framework that oblige construction companies to use aggregates made with C&D waste in works of civil engineering. Moreover, among all the criteria used to assess construction bids, the most important aspect remains the costs reduction.

On the basis of the analysis presented above, the goals set out in the PNIR cannot be achieved, considering the current behaviour of the construction industry companies. This plan does not envisage specific actions to facilitate effective decision-making that will ensure the compliance of the specified goals. Data available indicate that the rate of C&D waste recycling in Spain is nearly 15% of the total C&D waste produced, while the average percentage of recycling in the European Union is around 45%, and it is even higher in countries like Netherlands or Germany, where the percentage is close to 80% (GERD, 2010). The lack of a common definition of the term C&D waste at European level, the different construction practices among European countries and the shortage of natural aggregates in some countries are factors that contribute to explain this variability (Gómez-Limón et al., 2009).

The complexity of this issue and the difficulties to achieve the expected goals make necessary to understand and streamline the dynamic of the C&D waste recycling process in Spain. This paper proposes the design of a conceptual framework, which by considering a number of different factors (technical, economic, social and environmental) and agents involved will make possible to obtain a global diagnosis of the C&D waste recycling difficulties, and in particular, the use of these materials as aggregates in civil engineering works. The final objective of this analysis is to establish a frame of reference in order to harmonize the goals of recycling and waste disposal set out in the PNIR with the economic interests of the companies involved.

After determining the need for doing this analysis, an initial diagnosis was performed in regards with the factors conditioning the decision-making process when assessing the possibility of using C&D waste as aggregates in civil engineering works. On the basis of this preliminary diagnosis and following a systemic approach to the analysis, it was possible to establish a series of key elements to bear in mind when making decisions in relation with which aspects to emphasize in order to condition the companies´ behaviour of consumption regarding the recycled C&D waste.

A simulation model was designed as a result of the previous analysis, to reflect the implications of institutional policies geared towards boosting the recycling and use of recycled C&D waste in construction. The final goal of this paper is improving the understanding of the effects of these policies in the companies´ behaviour of consumption concerning recycled C&D waste. The analysis was carried out with a simulation methodology based on System Dynamics (Forrester, 1961; Saleh et al., 2010; Stearman, 2000; Wolstenholme, 1992), able to represent complex problems entailing myriad interrelations between variables, as well as certain anti-intuitive effects caused by temporary delays resulting from changes in the decisions and goals.

In this case, this technique adds value by directing experts and indicating which pieces of information would be required in order to make conclusions possible, even when many uncertainties about data occurred (Homer and Oliva, 2001). This methodology was previously used, by several authors, in the field of waste management (Hao et al., 2007; Mashayekhi, 1993; Sudhir et al., 1997), and it is now an active line of research.

2. Case study

2.1. Characteristics of the problem

Construction deals with a physical manifestation, so construction "rework" is normally accompanied by the demolition of what has already been built, and also it implies the alliance among multiple organizations in order to contribute to the dynamic of sustainable construction (Park and Peña-Mora, 2003; Slaughter, 1998). To implement the main objective of sustainable construction, a number of different actions must be taken at the same time, i.e.: a) to incorporate administrative incentives that stimulate the rational use of building resources, b) to assess the selection of construction materials manufactured with varying percentages of waste, making it possible to maintain the quality criteria and durability of the works and c) to promote the development of new technologies to improve efficiency in the procurement and use of recycled materials.

The use of waste in the composition of construction materials is a basic principle of the concept of sustainable construction, since it helps to mitigate the problem of waste management and treatment. Moreover, recycling in construction reaps a number of different benefits such as, for example, reducing the need for energy, natural resources and optimizing the use of disposal sites. Following this approach, a kind of waste material that can be used in civil works is the C&D waste. These wastes come mainly from the demolition of buildings or from construction material debris from new buildings and small renovation works on homes and developments. This type of waste is known as "rubble".

In fact, over three-quarters of the C&D waste stream is building rubble (concrete, brick, rubble and soil) (PCAG, 2006). C&D waste is usually taken to a dump, given the favorable price conditions, with disposal costs that no other more environmentally friendly operation can compete with. Most C&D materials are considered to be inert or equated to inert; therefore their pollution potential is relatively low (Simion et al., 2013).

Otherwise, their visual impact is often high owing to the large volume of space they occupy and the lack of enforcement of environmental control on the lands chosen for their disposal (Dosal et al., 2012). According to the data contained in the II National Construction and Demolition Waste Management Plan for 2001-2006 (PNRCD), another negative environmental impact is due to the squandering of the raw materials involved in this type of management, for which recycling is not considered (MPW, 2001).

According to the data contained in the PNRCD and included in the PNIR, the estimated amounts of C&D waste generated in Spain from 2001 to 2005 are listed in Table 1. During the period 2001-2005 the generation of C&D waste in Spain increased by 8.7% annually, owing mostly to building demolition. This trend was interrupted in 2007 resulting in negative rates starting in 2008, due to the drop in construction activity which still remains in decline at the present time, a decrease that is more pronounced in building construction (INE, 2013). In addition to this intense production of C&D waste, a large percentage of the C&D waste generated up to date (estimated to be over 60% (GERD, 2007)) has been associated with uncontrolled disposal and no treatment whatsoever.

Based on the information provided by waste treatment plants, in 2009 the Spanish Ministry of the Environment published a list of the volume of waste materials that were recycled and accumulated at disposal sites (Table 2). These data sharply contrast with those from other countries, with Spain lagging far behind countries that have advanced in the development of C&D waste recycling plans.

With a total average recycling level of 17% in 2005, Spain is one of the countries with the fewest number of recycling plants, which would account for the accumulation of waste and its failure to be used as building material (Table 3). The following preliminary conclusions may be drawn from the above analysis:

I. The failure to meet the objectives for the disposal of C&D waste in controlled facilities as they are set out in the PNIR;

II. The fulfillment of the recycling goals of C&D waste established in PNIR 2008-2015 (15% in 2010, 25% in 2012 and 35% in 2015) appears to be associated more with the decline in activities resulting in waste generation (building demolition and public works) due to the economic difficulties in the sector than to the functioning of model for the generation, recycling and later use of C&D waste proposed by the institutions. So this raises the question of the future problem consolidation when construction activity grows again. Therefore, from a systemic perspective, it is necessary to determine which variables may actually condition the companies´ consumption of recycled C&D waste, in terms of explaining the achievement of recycling and reusing goals in the construction industry.

2.2. Systemic approach

Previous research on the use of C&D waste have focused on assessing the effects of strategies to tackle waste generation (Vandecastelo et al., 2011; Yuan et al., 2012), although there is a lack of studies concerning the proper management of the use of these recycled materials. The volume of civil works awarded over a specified period of time, determined by the budget surplus available to the Government for these purposes, conditions the demand for construction materials. This increasing demand on construction materials will impact on the also incremented use of natural aggregates, according to the general operation of the construction sector (MPW, 2001), creating a greater environmental cost generated by the exploitation of quarries. In this sense, measures to reduce this environmental cost will adversely impact the government's budget for new civil works (CIB, 2010; GERD, 2010).

Table 1. Generation of construction and demolition waste by type of work

Type of work	*2001*	*2002*	*2003*	*2004*	*2005*
Building :	17,667,189	17,495,175	20,298,601	23,054,631	25,427,665
Civil works	6,543,403	6,479,649	7,518,000	8,538,752	9,417,654
Total C&D waste generated	24,210,592	23,974,824	27,816,601	31,593,383	34,845,319

Source: MPW, 2001

Table 2. Construction and demolition waste management (2002-2005) (MERMA, 2009)

	2002		*2003*		*2004*		*2005*	
	Recycled	*Disposal site*	*Recycled*	*Disposal site*	*Recycled*	*Disposal site*	*Recycled*	*Disposal site*
TOTAL	375,106	6,502,428	333,640	7,519,755	519,370	4,978,410	1,769,836	8,544,578

Table 3. Construction and demolition waste management in Europe (MERMA, 2009)

Country	*Production of C&D waste (mil. Tonnes)*	*Mean (kg/inhab)*	*No. of recycling plants*	*Destination in percentage*		
				Disposal site	*Recycled*	*Other*
Netherlands (1999)	11.7	718	120	9	90	1
Belgium (1999)	6.7	666	92	17	81	2
Denmark (1999)	2.6	509	30	16	75	9
United Kingdom (1999)	30.0	509	50-100	55	45	0
Austria (1999)	4.7	580	150	59	41	0
Germany (1999)	59.0	720	1.000	82	18	0
France (1999)	23.6	404	50	85	15	0
Spain (2005)	**10.3**	**229**	**58**	**83**	**17**	**-**

This dynamic is reinforced when we consider that new orders for civil works often involve the demolition of previous work, and this increases the stock of C&D waste, generating higher costs coming from their management (transfer to landfills, pollution associated usable space for waste accumulation etc.).

The costs of waste disposal on landfill include the owner's costs of operating the landfill (a private financial cost). But in many cases, they also include environmental costs (such as possible impacts on the community from any contamination of groundwater), and social costs (such as loss of amenity for people living nearby during the operational phase of the landfill) (PCAG, 2006).

Lastly, it is important to note that the accumulation of C&D waste largely depends on the demolition of previous constructions. Thus, the current standstill in the construction industry may actually mitigate the problem of waste accumulation, distorting the internal dynamics related to the need to provide incentives for recycling.

Nowadays, some regions in Spain are raising the issue of an existing excess on waste treatment capacity in relation to the amount of C&D waste being introduced into the recycling plants, reversing the trend of previous years. Therefore, these organizations also have problems marketing their products for treatment (recycled aggregates and other materials) (MPW, 2001).

This situation helps to explain the current lack of effective measures to promote the preferential use of aggregates made from recycled C&D waste by construction companies. However, the demand in the building sector is expected to increase in the future, which could perpetuate the problem in the long term (CIB, 2010; GERD, 2010). Given the undesirability of the previous approach, the use of recycled aggregates from C&D waste could reduce the consumption of quarried aggregates, thereby reducing the environmental cost generated by the exploitation of quarries, and reversing the undesirable dynamic, as it shown in the Fig. 1.

This approach reinforces the importance for Public Institutions to establish mechanisms that encourage the use of recycled aggregate instead of natural aggregates as construction materials. In this sense, if there is an increase of the use of recycled aggregates in construction works, this will cause a decrease in the use (consumption) of quarried aggregates.

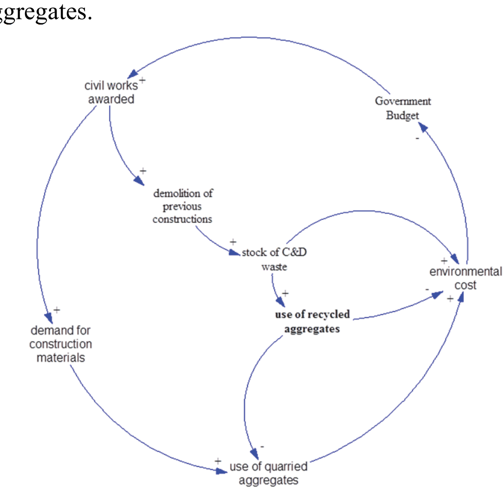

Fig. 1. Causal loop diagram of the dynamic of C&D waste

However, from the construction companies' point of view, the choice between aggregates from quarries or from recycled C&D waste relies mainly on the cost and accessibility of the materials. Hence, it is necessary to take into consideration that the companies´ behaviour is an economic behaviour. Market-based instruments usually work better than legal framework in environmental innovation (Kemp and Pontoglio, 2011), unless there are incentives that condition the companies´ behaviour.

According to these previous assumptions, a model has been designed to analyse the potential applicability of the external incentives for using recycled C&D waste. As it is shown in Fig. 2, in the short term, external incentives aimed to reduce the cost of recycled C&D waste, compared to quarried aggregates, are necessary to increase the consumption of recycled aggregates, reducing the consumption of quarried aggregates. However, in the long term, the internal incentives for using recycled C&D waste, based in firm´s investments aimed to reduce the cost of their production, will affect to the market-base functioning, reducing the consumption of quarried aggregates and avoiding the maintenance of the dynamic of external incentives. Prior research has focused on studying factors involved in the C&D management, grouped in three vectors: legal framework, low-waste construction technologies or education and awareness (Del Río et al., 2010; Lu and Yuan, 2010).

However, it is necessary to analyze systems of incentives vs. penalties to allow variations in the current behaviour of construction companies, in order to meet the goal of recycling C&D waste marked by the legal framework of developed countries.

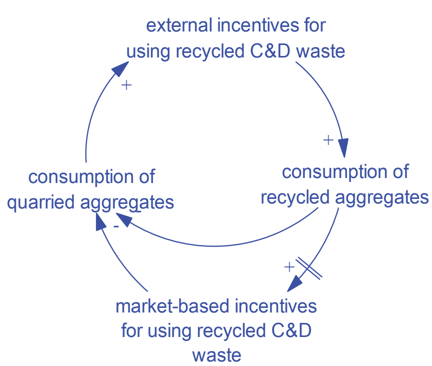

Fig. 2. Causal loop diagram of the dynamic of incentives (*The two lines intersecting the arrow indicate time delay)

This case study responds to the need of research of the effects of different policies in the companies´ behaviour concerning the use of recycled C&D waste, taking into account the economic behaviour of the companies along the time. As a novelty, compared to previous studies (Del Río et al., 2010; Kartam et al., 2004; Lu and Yuan, 2010; Ortiz et al., 2010; Rodríguez et al., 2007; Solís-Guzmán et al., 2009; Vandecasteelo et al., 2011; Yuan et al., 2012), in this study we have chosen the Systems Dynamics methodology as an useful tool for describing the problem situation and its possible causes, potential risks and uncertainties (Wolstenholme, 1999). Some previous studies have already advanced in this recent line of research (Hao et al., 2007; Yuan et al., 2012).

3. Methods: modeling the problem

3.1. The problem

The previous systemic approach indicated the existence of a dynamic flow between the generation of C&D waste and the use of these materials as recycled aggregates in works of new civil projects. However, the fulfillment of the recycling goal, as pursued in the PNIR, requires a technical and economic analysis. The demand for recycled C&D waste as aggregates depends on the companies´ assessment as to the relative impact derived from the use of these aggregates as construction materials on the final cost of the construction work, compared to the use of quarried aggregates.

Considering that the main criteria used by the Administration to award a contract are the cost and the technical specifications of the project for civil works, the stimulus to boost the use of aggregates from C&D waste will depend on two issues: the analysis of their technical properties versus those of natural aggregates, and the relative cost of the recycled C&D waste aggregates, compared to quarried aggregates, for the companies.

Following the Systems Dynamics methodology, and using Vensim DSS 6.1 software (Ventana Systems UK Ltd.), the model aimed to reproduce the current behaviour of the recycling behaviour of the companies, from a systemic approach (Forrester, 1961; Stearman, 2000), and thereby to establish a useful support tool for decisions related to the management of incentives (Senge, 1990), allowing the government to influence the future recycling behaviour of companies. The System Dynamics methodology allows the simulation of systems and policies over time to such an extent that the behaviour of the model unfolds continuously (Pruyt, 2013). In this sense, the proper use of models of social systems, characterized by a complex behaviour, can lead to far better systems, and help to promote more effective laws and programs than those created in the past (Forrester, 1971).

Following the System Dynamics terminology (Yuang et al., 2012), the variables used in the model are quantitative variables, constant parameters and dependent variables (stock and flow variables) (Table 4). The flow diagrams proposed below (Fig. 3) reflect the existing flow between the generation of C&D waste from building and civil works and the use of these debriefs –previously recycled- as an alternative material to natural quarried aggregates in new constructions.

The final goal of this model is to provide the institutions and companies with a better understanding of the dynamic implications of the use of recycled C&D waste in civil works, by analyzing how their decisions regarding the promotion or use of specific incentives in the selection of recycled C&D waste as building materials may affect the behaviour of the construction companies, as a result, also affecting the fulfillment of the recycling goal set out in the PNIR. The definition of most relevant variables is provided in Table 5.

Table 4. Types of variables

Variable	*Unit*	*Type of variable*
% of mix	%	Constant parameter
% of recycled material	%	Constant parameter
consumption of aggregates	Tons	Dependent variable (flow)
cost ratio quarried aggregates/aggregate demand	€	Quantitative variable
demand of aggregates	Tons	Quantitative variable
difference between the goal of utilization/reuse of treated C&D waste	%	Quantitative variable
difference between the recycling goal/actual recycling	%	Quantitative variable
difference in cost between C&D waste and quarried aggregates	%	Quantitative variable
Disposal of untreated C&D waste	Tons	Dependent variable (stock)
external incentives offered for using treated C&D waste	€	Quantitative variable
generation of natural quarried aggregates	Tons	Dependent variable (flow)
generation of untreated C&D waste used in building	Tons	Dependent variable (flow)
generation of untreated C&D waste from civil engineering	Tons	Dependent variable (flow)
goal of utilisation	%	Constant parameter
growth	Tons	Quantitative variable
medium cost of C&D waste	€	Quantitative variable
output of natural quarried aggregates	Tons	Dependent variable (flow)
output of natural quarried aggregates previous year	Tons	Dependent variable (flow)
output of treated C&D waste	Tons	Dependent variable (flow)
recycled C&D waste	Tons	Dependent variable (flow)
recycling goal	%	Constant parameter
shipments to disposal sites	Tons	Dependent variable (flow)
Storage of aggregates	Tons	Dependent variable (stock)
Storage of natural quarried aggregates	Tons	Dependent variable (stock)
Storage of treated C&D waste	Tons	Dependent variable (stock)
Utilization of treated CD waste used previous year	Tons	Quantitative variable
ungrowth	Tons	Quantitative variable

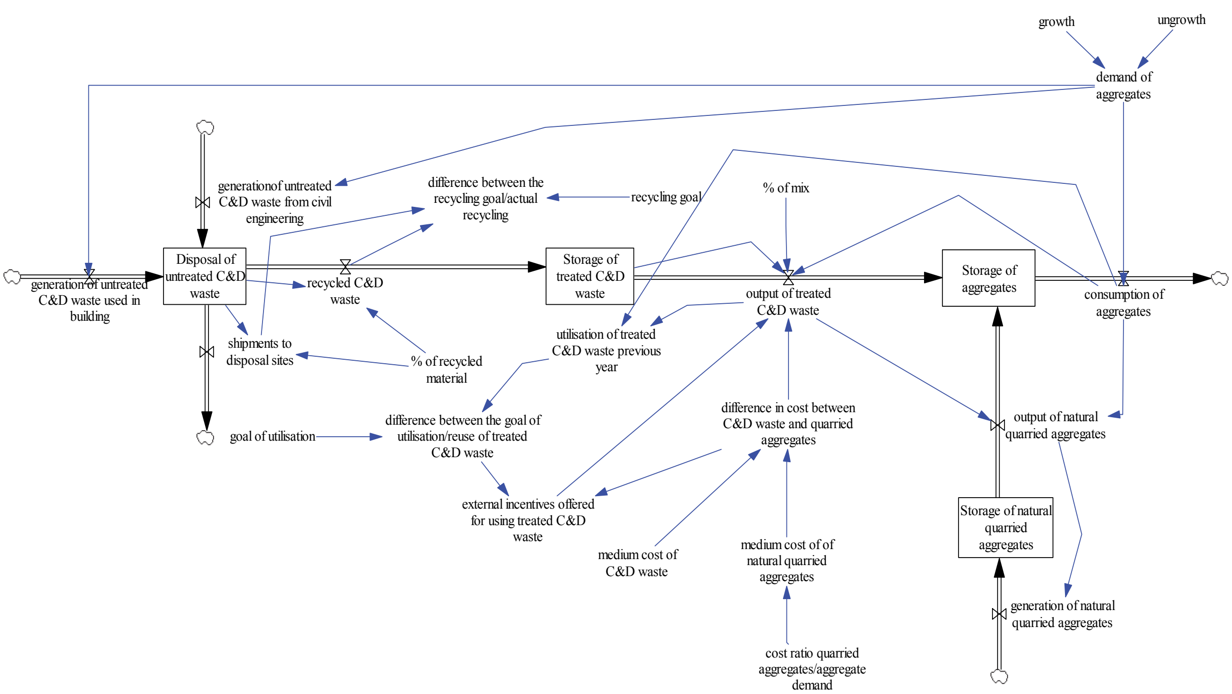

Fig. 3. Flow diagram of C&D waste management

The generation of C&D waste was triggered by the previous demand for construction materials. The flow of C&D waste begins with the accumulation of C&D waste generated from the works of demolition (*disposal of C&D waste*).

The accumulation of these materials will depend on the continuous inflow of waste from the demolition of buildings (*generation of C&D waste used in building*), on the demolition of civil engineering works (*generation of C&D waste from civil engineering works*), as well as on the outflow of materials treated in the recycling process. This process allows for the separation of materials unsuitable for future use, which will be sent to controlled disposal sites (*shipments to disposal sites*), and materials suitable for treatment and recovery as aggregates made from C&D waste (*recycled C&D waste (It is included in the concept of recycling the % of recycled C&D waste as well as the % of C&D waste from other recovery operations.))*. The difference between the waste generation and the recycling volume will allow assessing the fulfillment of the established recycling goal, in each period of time.

The stock of recycled C&D waste (*storage of recycled C&D waste*) will depend on the inflow of recycled materials (*recycled C&D waste*) and on the output of these materials *(output of recycled C&D waste)*, as aggregates, to become part of the materials used in civil engineering works. The amount of inflow of C&D waste will also depend on the percentage of materials potentially transformed into aggregates (*% of recycled material*) versus those unsuitable for this purpose and subsequently sent to the disposal facility. This distribution is contingent upon quality of the recycling process, whose percentage may change depending on the technology or infrastructure used. In the model, we have considered the 17% as recycling percentage, according to the data published by the Ministry of Environment and Rural and Marine Affairs (MERMA, 2009).

The improved quality of recycled materials is directly related to sustainable construction goal c) to promote the development of new technologies and improve efficiency in the procurement or use of recycled materials. According to the previous assumptions (economic behaviour of the companies), the outflow of C&D waste relies on the companies´ decision of substituting a specific proportion of quarried aggregates for recycled C&D aggregates at the moment of developing the concrete mix, and also dependent upon the relative cost incurred (*difference in cost between C&D waste and quarried aggregates*).

3.2. Technical specifications of the mix C&D waste aggregate/quarried aggregate:

As starting point, the model presents a maximum distribution percentage of 30% (*% of mix)* of the C&D waste in the mixes stated in (1), which has been analyzed in previous studies that examine the behaviour of hot mix asphalts in the construction of roads with low to medium traffic volume (Pasandín and Pérez, 2013, 2014; Pérez et al., 2007, 2011).

The increase in this percentage, which favors the use of recycled C&D waste, will be, in turn, directly linked to sustainable construction goal b) assess the selection of mixtures in construction materials to facilitate the preservation of the quality criteria and durability of the works. Level structure of equations is presented in Table 6. The sensitivity analysis of scenarios has let us changing our assumptions about the value of the demand of aggregates through the time and also examining the resulting output (Stearman, 2000). Because it impossible to compare simulation results with the historical data of the variables, sensitivity analysis is the procedure by which tests for understanding how the proposed model can behave if the variable values are varied over a reasonable range are carried out (Maani and Cavana, 2000).

The results of the multivariant analysis Monte Carlo, based on 200 simulations, show different values for the output of treated C&D waste of the scenario of balanced demand of aggregates, compared to a growth scenario of demand (Fig.4). However, the value of the storage of natural quarried aggregates does not change (Table 7), and it shows how the economic behaviour of companies can be modified using a system of incentives, in order to achieve a goal of utilization of C&D waste.

3.3. Economic behaviour of companies

According to the assumption of the companies´ economic behaviour, if the mix made with recycled C&D waste and quarried aggregates has similar technical properties to mix composed of 100% natural aggregates, the construction companies will choose the option offering the lowest cost (*difference in cost between C&D waste and quarried aggregates*).

In this sense, while the relative cost of recycled C&D aggregate remains lower than the quarried aggregates, the government will find a better match between the specified usage goal in relation with recycled C&D waste and the amount of recycled C&D waste really used (*Difference between the goal of utilization/later use of recycled C&D waste/Later use of recycled C&D waste*).Following this approach, companies should tend to use the maximum percentage of recycled C&D waste recommended by experts in the mix while obtaining economic incentives for it.

3.4. Incentives policy:

The model proposed in this study presents an external incentive policy offered by the Spanish Government which consists of compensating the companies for the cost difference that may arise between using material made with the mixture of C&D waste/natural aggregate and 100% natural aggregate (*external incentives offered for using recycled C&D waste*).

Table 5. Variables definition

Variable	*Definition*
% of recycled material (Dmnl [0,1]) = 0.17	% of recycled material.
consumption of aggregates(t/year)= IF THEN ELSE (demand of aggregates>0, demand of aggregates, 0)	aggregates consumption each year
cost ratio quarried aggregates/aggregate demand (Dmnl)= [(0,0)(7.05033e+008,10)],(0,1),(1,6),(3e+008,6),(4e+008,7),(8e+008,7.5),(1.6e+009,8),(2.5e+009,8.5),(5e+009,9)	relation between quarried aggregates and demand of aggregates
demand of aggregates (t/year) = 4.6e+008*(1+SWC*growth+SWD*ungrowth)	initial value of aggregates consumption for construction for 2005. Source: aggregates statistics
difference between the goal of utilization/reuse of treated C&D waste (Dmnl)= goal of utilisation-utilisation of treated C&D waste of previous year	difference between goal and reality
difference between the recycling goal/actual recycling (Dmnl [0,1])=recycling goal-(recycled C&D waste/(recycled C&D waste+shipments to disposal sites))	difference between goal and reality
difference in cost between C&D waste and quarried aggregates (Dmnl)= medium cost of C&D waste/medium cost of natural quarried aggregates	cost difference
Disposal of untreated C&D waste (t/year)=∫generation of untreated C&D waste used in building+generationof untreated C&D waste from civil engineering-shipments to disposal sites-recycled C&D waste *dt* + [3.15934e+007]	initial value: C&D waste generated in 2004
external incentives offered for using treated C&D waste (Dmnl)= IF THEN ELSE((DIFFERENCE BETWEEN THE GOAL OF UTLISATION/REUSE OF TREATED C&D WASTE>0 :AND: difference in cost between C&D waste and quarried aggregates>1),(difference in cost between C&D waste and quarried aggregates-1), 0)	external incentives for consumption
generation of natural quarried aggregates (t/year)=output of natural quarried aggregates	generation of natural aggregates
generation of untreated C&D waste used in building (t/year)=percentage of generation*(percentage of distribution*demand of aggregates)	First % is the relation cd according to aggregates consumption. The second % shows the distribution between generation of C&D waste of building and construction works
generation of untreated C&D waste from civil engineering (t/year)=percentage of generation*(1-percentage of distribution)*demand of aggregates	First % is the generation of C&D waste according to aggregates consumption. The second % shows the distribution between C&D waste from building and construction works
goal of utilisation (Dmnl [0,1]) = 0.35	legal goal
growth (t/year) = -RAMP(0.05, 0, 20)	growth scenario of demand of aggregates
medium cost of C&D waste (€)= 7*(1+SWcrec*growth scenario+SWdec*ungrowth scenario)	real cost of recycled aggregates of C&D waste (0-60 mm)
medium cost of natural quarried aggregates (€)=cost ratio quarried aggregates/aggregate demand (output of natural quarried aggregates previous year)	real medium cost
output of natural quarried aggregates (t/year)=consumption of aggregates-output of treated C&D waste	output of natural aggregates
output of natural quarried aggregates previous year (t/year) = DELAY FIXED(output of natural quarried aggregates, 1, 0)	output of previous year
output of treated C&D waste (t/year)= IF THEN ELSE(Storage of treated C&D waste>0, IF THEN ELSE((difference in cost between C&D waste and quarried aggregates<1 :OR: external incentives offered for using treated C&D waste>0),% of mix*consumption of aggregates, 0), 0)	output of treated C&D waste from recycled material
recycled C&D waste (t/year)=% of recycled material*Disposal of untreated C&D waste	% of recycled material"*"Disposal of untreated C&D waste
recycling goal (Dmnl [0,1])= 0.25	% of recycling for 2010
shipments to disposal sites (t/year)=(1-% of recycled material)*Disposal of untreated C&D waste	shipments managed to disposal sites
Storage of aggregates (t/year)=∫output of natural quarried aggregates+output of treated C&D waste-consumption of aggregates *dt* + [initial value aggregates]	stock of aggregates (natural and treated) considering initial data of real consumption of aggregates for 2005
Storage of natural quarried aggregates (t/year)=∫generation of natural	stock of natural aggregates considering initial

quarried aggregates-output of natural quarried aggregates *dt* + [initial value natural aggregates]	value of real consumption of natural aggregates for 2005
Storage of treated C&D waste (t/year)=recycled C&D waste-output of treated C&D waste *dt* + [initial value cd aggregates]	stock of treated aggregates. Because there is no initial data for this concept, the initial data considered is a value enough high to let the study of the behaviour of external incentives and no cost scenarios without considering the recycled C&D exhaustion
Utilization of treated CD waste used previous year (t/year)=DELAY FIXED ((output of treated C&D waste/consumption of aggregates), 1, 0.3)	initial value 0.3.We considered that, as starting point, the utilization of the maximum percentage of recycled C&D waste
ungrowth (t/year)= -RAMP(0.05, 0, 10)	ungrowth scenario

Table 6. Level structure

Disposal of untreated C&D waste= *∫(generation of untreated C&D waste used in building +generation of untreated C&D waste from civil engineering-shipments to disposal sites-recycled C&D waste) dt*
⇒ *generation of untreated C&D waste used in building* = percentage of generation*(percentage of distribution*demand of aggregates) ⇒ *generation of untreated C&D waste from civil engineering* =percentage of generation*(1-percentage of distribution)*demand of aggregates ⇒ *shipments to disposal sites* = (1-% of recycled material)*Disposal of untreated C&D waste ⇒ *recycled C&D waste* = % of recycled material*Disposal of untreated C&D waste
Storage of aggregates = *∫(output of natural quarried aggregates +output of treated C&D waste-consumption of aggregates) dt + [initial value aggregates]*
⇒ *output of natural quarried aggregates* = consumption of aggregates-output of treated C&D waste ⇒ *output of treated C&D waste* = IF THEN ELSE(Storage of treated C&D waste>0, IF THEN ELSE((difference in cost between C&D waste and quarried aggregates<1 :OR: external incentives offered for using treated C&D waste>0),% of mix*consumption of aggregates, 0), 0) ⇒ *consumption of aggregates* = IF THEN ELSE(demand of aggregates>0, demand of aggregates, 0)
Storage of natural quarried aggregates *=∫(generation of natural quarried aggregates-output of natural quarried aggregates) dt + [initial value natural aggregates]*
⇒ *generation of natural quarried aggregates* = output of natural quarried aggregate
Storage of treated C&D waste *=∫recycled C&D waste-output of treated C&D waste dt + [initial value cds aggregates]*

Table 7. Sensivity analysis. Statistics results

	Mean	***StDev***
Balance		
Storage of natural quarried aggregates	460 M	0
Growth scenario		
Storage of natural quarried aggregates	460 M	0
Balance		
Storage of treated C&D waste	3.282 B	797,82 M (0,2431 Norm)
Growth scenario		
Storage of treated C&D waste	2.862 B	1.184 B (0,4136 Norm)

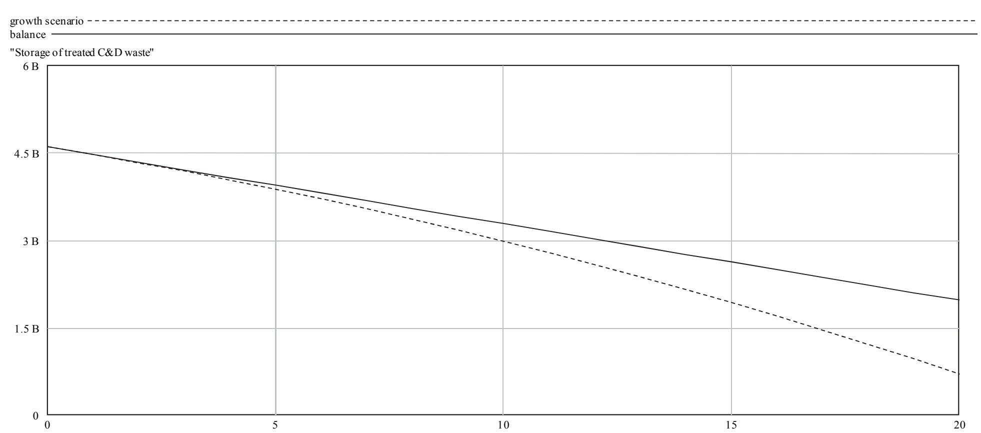

Fig. 4. Sensitivity Analysis of scenarios

A policy previously designed to incentive the energy generation through clean sources in the electric industry. *Endogenous behaviour of the demand of aggregates:* The cost of quarried aggregates is not considered to be constant; rather it depends on market demand for these materials. Increased demand will cause a rise in cost of this material in the following period (*cost ratio quarried aggregates/aggregate demand*). Therefore, the behaviour of the demand of aggregates is not exogenous, but it depends on the fulfillment of the objective of reusing treated C&D waste, as it was discussed in section 2.2. To such an extent, the model designed will allow for the assessment of both the fulfillment of the recycling goal (*Difference between the recycling goal/actual recycling*) and the objective of using C&D waste (*Difference between the goal of utilization/later use of recycled C&D waste*), pursued in the PNIR. Compliance with the objective of reusing of treated C&D waste will allow the construction companies to seek new roles as providers of civil works, and this will influence the growth of the demand of aggregates. In the event of being unsuccessful it will discourage their participation in new civil construction awards, ultimately reducing the demand of aggregates.

Thus, in the model designed, an institutional policy promotes external incentives that compensate economically for the increased cost assumed by the companies using recycled C&D waste. In the long term, this policy will let the autonomous functioning model for the generation, recycling and later use of C&D waste in the future. Once the volume of generation and management of C&D waste is high enough to make the investments in recycling and waste treatment plants viable, the relative cost of the waste material will be lower than the natural aggregate. Hence, to eliminate the external incentive offered by the Administration, thus consolidating the functioning of the model with no need for public intervention.

5. Results and discussion. Effects of the incentives to stimulate the use of recycled C&D waste

The System Dynamics methodology is especially interested in describing the general dynamic tendency of a system, in order to identify the policies that condition the stability of the system (Meadows and Robinson, 1985). Following this approach, the model designed includes the flow dynamics of C&D waste from the generation of these materials until they are used to satisfy the demand for aggregates to be used in construction.

Currently, the average cost of recycled C&D waste exceeds the cost of the natural quarried aggregates, due to their poor utilization, thus increasing the cost of treatment and transport to the construction site. Because of this situation, if the Public Institution changes its incentives policy, compensating the company with the cost difference between recycled aggregates and natural aggregates over time, the behaviour of the system will minimize the cost of this policy in the long term.

Because the increase in consumption of natural aggregates increases its cost, due to its scarcity and environmental impact, the differential cost between the two aggregates will decrease along the time, and this dynamic will reduce the economic impact of this policy for the institution in medium term (Fig. 5). Ultimately, this situation will result in a change in companies´ behaviour towards a greater use of recycled aggregates and thus meeting the recycling later use objective will influence future demand for aggregates (Fig. 6).

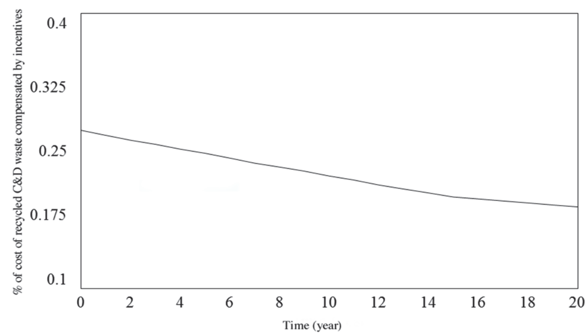

Fig. 5. Evolution of incentives to use recycled C&D waste

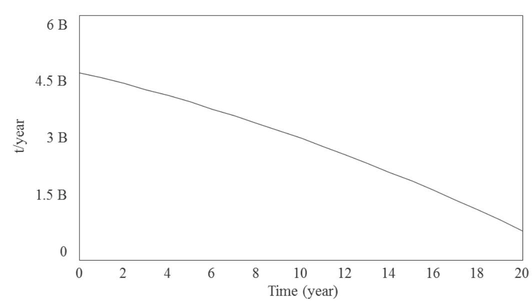

Fig. 6. Evolution of recycled C&D waste storage

Hence, the model enables to assess the dynamic completion of the recycling goal (*Difference disposal/recycling goal*) as well as the goal for the later use of C&D waste (*Difference between recycling/ C&D waste use goal*). In this model, the application of external incentives that will compensate for the difference in cost between the use of recycled C&D waste and quarried aggregates allows the proposed goals to be fit in the medium term.

In the presented model, the aspects receiving the greatest impact on the accumulation and later use of debris (leverage points) are: a) the % of recycled material (recycling quality), which affects the percentage of waste feasible to recycled in relation to the debris stored in controlled disposal sites; b) the external incentives encouraging the use of recycled C&D waste, that will ensure the economic opportunity for construction companies to use waste materials and c) the maximum % of C&D waste permitted to be used in aggregate mixtures, contingent upon technical viability, and which also affects the accumulation of waste in treatment plants.

5. Conclusions

Following the analysis of the difficulties related to C&D waste management from a technical and economic approach, we can conclude that the fulfillment of the established goals concerning the recycling and reusing of waste materials for construction, a key aspect in sustainable construction, demands for the active participation of the Public Institution in the short term. This might be granted through investment and economic incentive policies that allow the harmonization of the legal framework with the companies´ consumption of recycled C&D waste. According to these assumptions, the mentioned policies are expected to lead the future autonomous functioning of the model assisting in the generation, recycling and later use of C&D waste as a feasible model from an economic approach.

The dynamic approach has let to identify the aspects that may cause the greatest impact on the internal functioning of the waste management system. Two courses of action have been proposed through institutional intervention:

1. Actions provided in order to improve the recycling quality (such as better impurities removal in the recycling sites and the use of friendly environmental treatments that improve the quality of the recycled aggregates, particularly the strength and the water absorption of the attached mortar onto its surface), promoting investments in technologies and infrastructures to increase the percentage of recycled C&D waste materials suitable for collection from construction sites. These activities will prevent the accumulation of debris at controlled and uncontrolled disposal sites.

2. Proactive measures provided for the achievement of the established goals such as increasing the use of C&D waste materials in construction, on the one hand by providing economic incentives to construction companies using suitable aggregates as well as granting a compensation for the difference in cost whilst using C&D waste materials instead of quarried aggregates. Similarly, by encouraging the assessment and selection of mixes (C&D waste/quarried aggregates) directly influencing the percentage of C&D waste materials in these mixes (currently, recommended by experts is 30%).

Both courses of action are intended to reduce failure in meeting the objectives set by the PNIR, considering the gap between the goal of recycling rate and the current recycling rate (Difference between the recycling goal/actual recycling). Only through the proper combination of the economic incentives system and advancement in recycling technology, companies involved will perform differently.

The use of dynamic simulation methodologies as a tool to support the design of new policies of encouragement of the consumption of recycled materials is, from our point of view, a good starting point for encouraging a broad understanding of the technical and socioeconomic implications of sustainable construction, in addition to promoting the assessment of different policies to be applied.

Future research is intended to focus on developing the model described, delving deeper into the technical and economic elements conditioning the cost differences between the use of quarried aggregates and C&D waste, in conjunction with assessing the waste management model in different countries.

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