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Article

A Dynamic Model for Construction and Demolition (C&D) Waste Management in Spain: Driving Policies Based on Economic Incentives and Tax Penalties

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Abstract: According to the recent Spanish legislation, the amount of non-hazardous construction and demolition waste (C&D waste) by weight must be reduced by at least 70% by 2020. However, the current behavior of the stakeholders involved in the waste management process make this goal difficult to achieve. In order to boost changes in their strategies, we firstly describe an Environmental Management System (EMS) based on regulation measures and economic incentives which incorporate universities as a key new actor in order to create a 3Rs model (Reduce, Reuse and Recycle) in the C&D waste management with costs savings. The target areas are focused mainly on producer responsibility, promotion of low-waste building technologies and creation of green jobs to fulfill three main objectives: valorization of inert wastes, elimination of illegal landfills and stimulation of demand for recycled C&D wastes. To achieve this latter goal, we have also designed a simulation model—using the Systems Dynamic methodology—to assess the potential impact of two policies (incentives and tax penalties) in order to evaluate how the government can influence the behavior of the firms in the recycling system of C&D waste aggregates. This paper finds a broader understanding of the socioeconomic implications of waste management over time and the positive effects of these policies in the recycled aggregates market in order to achieve the goal of 30% C&D waste aggregates in 12 years or less.

Keywords: construction and demolition waste; sustainable construction; policy instruments; strategic management; systems dynamic; economic development

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1. Introduction

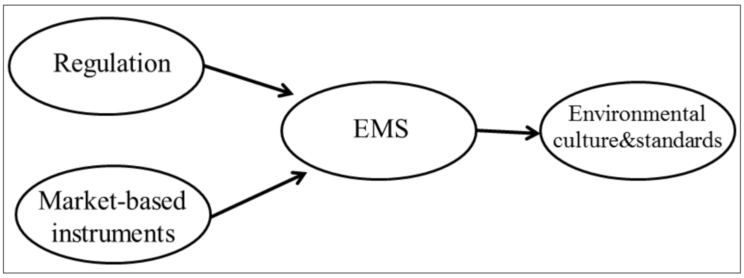
In Spain, the construction sector had a key role in the economic and social development of the country until the arrival of the crisis [1]. The interest in the management of construction and demolition wastes (hereafter, C&D wastes) arises as a result of increased waste generation behind the housing boom of the past decades. Since then, C&D management has become an environmental problem, not because of its hazardous nature (since it is mostly inert) but for the lack of treatment of these wastes, which are taken to landfill in an uncontrolled way [2]. This situation ties down the landfill space, increases the number of illegal dumping and generates social opposition to the environmental degradation caused by the demolition process [3]. For this reason, in recent years, models for managing C&D waste have been developed trying to reconcile economic progress with sustainable construction and demolition projects [4–9].

In the EU, a regulatory framework has been set up with the Directive 99/31/EC on landfill to comply with the 3R regulations (Reduce, Reuse and Recycle) aiming towards sustainable construction. Some of the goals of the framework include reducing waste that ends up in final disposals for incineration or landfill sites, saving natural resources, gaining better control of C&D waste and unauthorized landfills, developing new recycling infrastructure and, in general, avoiding negative environment impacts. Despite this homogenization process, pronounced disparities have been observed in relation to the recycling rates of C&D wastes. In the case of Spain, the high volume of C&D waste generated is accompanied by a low rate of recycling. The processing of building waste has become more and more common in most industrialized countries since the early 1980s. However, the concern for waste management in Spain did not arise until 2001 with the first national plan on C&D waste [10]. Royal Decree (Spanish Government-Ministry of the Presidency, 2008) implement the principle of producer responsibility (Extended Producer Responsibility, EPR), waste prevention and responsibility among the actors involved in the production and management of C&D waste. It also incorporates the obligation to introduce waste management plans and previous study to obtain a construction permit and aspects of control such as waste quantities and treatment cost. Recently, it has entered into force Law 22/2011 of waste and contaminated soil, introducing new quantitative targets that were not included in the aforementioned previous laws. Specifically, the amount of non-hazardous C&D waste accumulated from reuse, recycling and other recovery of materials should constitute at least 70% of waste production by 2020.Thus, it sets specific measures in terms of 3R regulation for achieving three main objectives: inert waste recovery, eradication of illegal landfills and promoting demand for the recycling of C&D wastes, especially of recycled aggregate. However, there are still outstanding issues of particular relevance such as the prevention of pollution caused by landfills and the creation of 'green jobs' in this sector [8].

On the other hand, the lack of effective regulation is not the root cause of these disparities in Europe. The relationship between environmental innovation and policy is also important. Market-based instruments (taxes, subsidies and other incentives) are better than laws promoting environmental innovation [11]. Otherwise, there are still few studies focused on the production methods of construction materials using waste materials for different applications or products instead of regular ones [12]; the main reason being the lack of incentives for consumers to purchase recycled materials [13]. However, not only are economic aspects important for adequate construction waste management but environmental, legal and social aspects can also have an enormous influence in this field. In fact, health and safety was found to have the most significant and dominant impact on the achievement of sustainable construction waste management [9]. Indeed, it would be necessary to point out the environmental impacts caused by construction activities. Thus, in recent years, the concept known as Extended Producer Responsibility has been developed in an attempt to generate widespread awareness of sustainable construction and improve the effectiveness of waste management [14].

Therefore, the availability of effective regulation and economic incentives determines the amount of waste reutilized and reduces the level of C&D waste [15]. Specifically, recent studies have identified the main success factors for managing C&D waste: waste management regulations, waste management systems, awareness of C&D waste management, low-waste building technologies, fewer design charges, R&D in waste management, and vocational training in waste management [3,16]. Indeed, the existence of strong market demand for recycled C&D materials is essential. The highest recovery rates are found in those regions with a strong demand and high use of recycled products [17]. All these factors can be implemented in an Environmental Management System (EMS). An EMS is a system and database which integrates procedures and processes for training of personnel, monitoring, summarizing, and reporting of specialized environmental performance information to internal and external stakeholders of a firm [4]. The development of this system in an efficient way can make companies change their strategies in new directions, especially in countries with low recycling rates in C&D wastes, such as Spain. If all participants involved in the 3R process integrate a successful EMS in their activities, a global environmental culture in the treatment of C&D waste is achieved (Figure 1).

Figure 1. Environmental Management System (EMS): an economic and social objective.



The aim of this paper is to investigate the unexplored effects on recycled C&D waste by launching scenarios encompassing policies where dominant feedback loops of the system can be identified and the effects of recycled C&D waste can be maximized [8]. First, we advance the study of different guidelines for the adoption of an effective EMS in Spain with patterns that can be expected in other European countries, especially those with low recycling and reuse levels of C&D waste. We introduce the universities as a novelty in the system to become a key role in achieving the three main objectives in the 3R regulation with low costs: valorization of inert wastes, elimination of illegal landfills and stimulation of demand for recycled C&D waste. Next, we develop a dynamic model in the case study of recycled aggregates that could be applied in Spain according to current legislation and policy instruments (incentives and tax penalties) available in this area. The findings reveal that a complete integration of recycled C&D wastes (30% as a percentage of total aggregates) can be achieved in the construction process in just 12 years through economic incentives and in only 10 years using tax penalties.

The structure of the paper is as follows. In the second section, we describe the current situation in Spain compared to the EU and identify drivers and barriers in terms of policy implications. In the third section, a whole analysis of the 3R process is developed for the Spanish case in an EMS, to assess the impact of a market-based incentives policy and effective regulation to achieve the 70% target set out in the Spanish legislation. In the fourth section, a dynamic model is put forward to evaluate the consequences of two different policies (incentives and tax penalties) on the recycled C&D waste management process for the case of aggregates. Finally, the main conclusions of the paper are provided as well as future lines of research in the field of C&D waste management.

2. Generation and Recycling of C&D Waste in the EU

The current studies of C&D waste management present very high uncertainty regarding quality of available data [18,19]. Despite this lack of information regarding generation and recycling of C&D waste, we analyze the current situation in the EU comparing Spain with the other member states. Our aim is to identify the stage of development of the treatment of C&D waste in Spain to be able to deduct the drivers and barriers towards the 70% target.

C&D waste is a residual material generated by the construction, renovation and demolition of buildings, public works and urban developments, and is the major part of industrial waste [20]. In the EU, the construction industry generates about 531 million tons of C&D waste and represents about one fourth of all the waste generated in the world (Table 1). For this reason, it is identified as a priority waste stream by the European Union because it makes up one of the largest waste streams within the EU (Directive 2008/98/EC). The bulk of production comes from, in this order, United Kingdom, France, Germany and Italy.

Table 1. Average rate of recycling of construction and demolition (C&D) waste.

Country	RCD *	% Recycled	Country	RCD *	% Recycled
Denmark	5,27	94%	Malta	0,8	0%
Estonia	1,51	92%	Netherlands	23,9	98%
Finland	5,21	26%	Poland	38,19	28%
France	85,65	45%	Portugal	11,42	5%
Germany	72,40	86%	Romania	21,71	0%
Greece	11,04	5%	Slovakia	5,38	0%
Hungry	10,12	16%	Slovenia	2,00	53%
Ireland	2,54	80%	Spain	31,34	14%
Italy	46,31	0%	Sweden	10,23	0%
Letonia	2,32	46%	UK	99,10	75%
Lithuania	3,45	60%	EU-27	531,38	46%
Luxembourg	0,67	46%			

* million tones.

Source: European Commission (DG ENV), 2011.

On this scale, Spain ranks sixth. During the period 2000–2006, the generation of C&D waste in Spain rose 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 remains in decline at the present time. In particular, the decrease is more pronounced in housing construction [10]. Although the economic crisis has reduced the consumption of aggregates, once the construction activity recovers, environmental costs and economic waste generation will persist. In addition to this, intense production of C&D waste, a large percentage of the C&D waste generated (estimated to be over 50%) has, up to now, been associated with uncontrolled disposal and no treatment whatsoever.

On average, in EU-27 the 46% of the produced C&D waste is reused or recycled. In contrast, Spain has a level of recovery of materials quite low (14%). Only Italy, Portugal, Greece, Sweden, Malta, Romania and Slovakia have lower recycling rates than Spain. This data for Spain finds its justification in the limited availability of infrastructure involved in recycling of these wastes and the lack of demand for recycled products [21], the main uses of the recycled material being quarry restoration, rural tracks and land refills [22]. The current Spanish plan [1] proposes recycling 25% of C&D waste by 2012. However, nowadays, most stakeholders involved think that this goal is an impossible one. In Section 4, we propose a conceptual model based on the establishment of rules and economic instruments to achieve successful management of C&D waste in Spain.

3. Policy Implications in the 3R Regulations: A Conceptual Model of Sustainable Construction for Spain

In recent years, the management of C&D waste has become a complex task [2]. There are several barriers to achieving a successful framework in the application of waste management for construction companies in Spain. In addition to the deficiencies common to other countries, we must specify the barriers faced by countries with a weaker policy of recycling. In the Spanish case, there is a significant lack of planning and implementation measures that minimize the generation of waste and encourage recycling. The principle of reducing waste is neither applied in practice, considered as an activity in the C&D plans [23], nor are there incentives to recycle [5]. Indeed, there is a significant deviation between the theoretical models applied and what actually happens in practice [7]. In our opinion, this greatly prevents implementing appropriate policy measures for proper waste management.

According to [18], the main barriers to developing a regulatory framework to support the treatment of C&D waste and achieve the 70% target are described in Table 2.

Taking into account the barriers mentioned above, in this section we determine an Environmental Management System (EMS) applied with special conditions in Spain (low recycling rate, noncompliance of legislation, decentralization) aimed to create a general interaction 3Rs (Reduce, Reuse, Recycle) adjusted to current legislation and directed to fulfill the three main objectives of the [1]: valorization of inert wastes, elimination of illegal dumping, and stimulation of demand for recycled C&D wastes. These results can be applied to other countries, especially those with low rates of recycled C&D waste.

Hao *et al.* define an Environmental Management System (EMS) as a vehicle for organizations to develop environmentally friendly practices [2]. A standard framework should include five stages: (1) environmental policies, (2) planning, (3) implementation and operations, (4) checking, and (5) corrective action and review and improvement measurement. The implementation of an EMS requires the interaction of various actors involved in the activity of C&D waste management. Following this approach, we have compiled the main economic policy instruments for the Spanish case in order to build an efficient and adequate system. These measures are based on the deficiencies in the interaction among the actors involved in the waste management process shown below, and try to separate materials for reuse or recycle so as to improve the recycling rate in Spain. As a novelty, the model looks for the most efficient measures from an economic perspective.

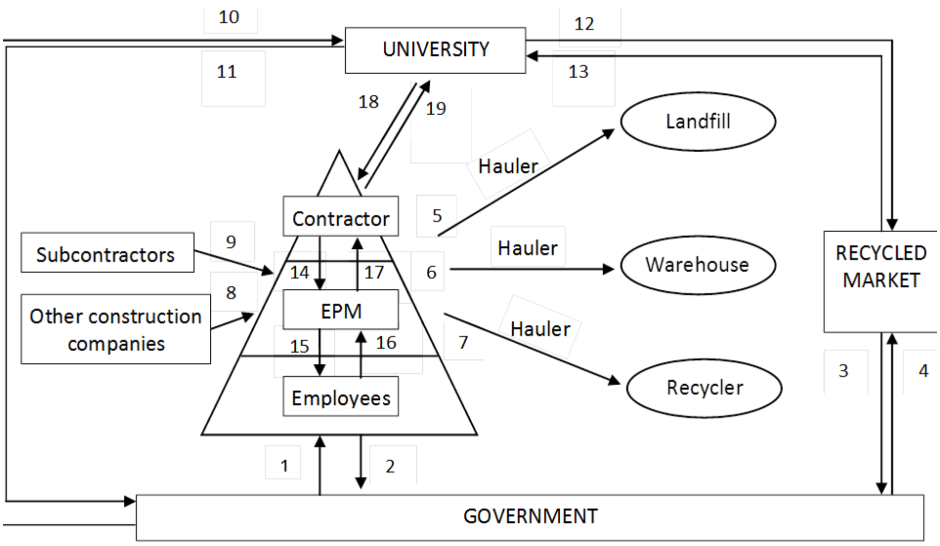
Table 2. Main barriers for C&D waste management in Spain.

Political Barriers	Non reliability data on recovery and recycling rates of C&D waste in the EU and its manner of collection Lack of control over C&D waste management plans approved by national and regional governments Legislation independent and highly dispersed at regional level
Social Barriers	Lack of coordination between the agents involved in C&D waste management No initiatives to launch information and awareness programs for agents involved in the sector Lack of enforcement and unclear responsibility of the 3Rs regulations
Economic Barriers	Constructors usually do not include specific allocations for C&D management Constructors do not facilitate waste management plans by including them in the technical specifications Constructors do not currently fulfill their obligations as producers of hazardous waste due to the high costs of managing C&D waste and the imprecision of current legislation
Technical Barriers	Constructors do not make provision for the use of recycled material Technical standards do not make provision for the use of recycled material No EU legislation to regulate installations for the treatment of C&D waste

Source: Own elaboration adapted from [18].

Figure 2 shows a closed loop system from a business management point of view. For the analysis, we have used the work of [3,8]. Our model is based on the relationship between all agents involved in the management of C&D wastes by introducing important views to explore the options for sustainable construction goals. If any of the participants fail in their action, they break the chain leading to successful waste management. Once the cycle is completed, a global environmental culture in the treatment of C&D waste is achieved (Figure 1). The links between agents is represented by means of lines in the system from line 1 to line 19.

Figure 2. Conceptual model of C&D waste management for Spain: an EMS based on regulation measures and market-based instruments.



EMP: Environmental Manager Project

Source: on the premises.

3.1. The Role of Government in the 3R Regulations

The diagram shows the central role of government which affects all agents involved in the process. The government has two key roles: regulator and supervisor. The government as regulator is essential to implement the objectives of sustainable construction through the 3Rs' measures. The government as supervisor is also important to control the obligations and responsibilities of the construction contractors and to inspect the management of waste from the recyclers. According to [24], several instruments to support the role of government as regulator should be defined (Line 1). This author proposes three measures to avoid market frictions in the construction sector: market creation, information programs and liability rules. The first measure is related to the implementation of a comprehensive recycled market, as we will analyze later (Line 4). On the one hand, public information programs funded by the state should be implemented for the treatment of these wastes to standardize techniques and methods. The Ministry of Environment, Rural and Marine should be responsible for using the media as a platform to raise awareness of the need to reduce the problems associated with the treatment of C&D waste in the general public. On the other hand, there are no penalties for those who break the rules, even though there is already a regulation for waste. Insufficient monitoring of compliance with legislation can be avoided with liability rules, including fines for noncompliance. This measure is strongly related to the government's role as a supervisor and requires a very specific and concrete normative. Construction companies usually are self-regulating and do not follow effective 3R regulations. Therefore, it is also necessary to launch a mandatory auditing system carried out by supervisors of local authorities. With this information, the government will be able to reduce the existing gap between the current situation and the objective established by developing a continuous feedback process (Line 2). These links will be a vital task in achieving the waste management plans, complying with legislation and controlling disposal [22].

3.2. The Role of Universities in the 3R Regulations

Studies on C&D waste often forget to include a key player in waste management, considered the starting point of any effective EMS. In this sense, the role of universities can be crucial. Universities can advance the possibilities of solving technical problems and applying new methods of recycling and new market-oriented applications according to the current legislation. The use of data provided for the government allows the creation of indicators for preventing waste collection [6] and helps universities improve C&D management plans (jointly with the constructors) according to the 70% target set in Spain for 2015 (Line 10). In the same way, universities are able to demonstrate recycling achievements to be applied in the recycled market (Line 12). The research institutions have the advantage of the availability of infrastructure and qualified staff to successfully develop R&D in this field so that the cost of concentrating research efforts can be reduced. In this sense, the research interest for C&D management has increased in the last years but there is not yet systematic research development [25]. Therefore, there should be programs to support scientific R&D in this discipline (Line 11). On the other hand, this activity of growing importance in Spain can contribute to increasing the qualified employment in this area (vocational training) [8]. For this reason, it would be relevant to include subjects and activities related to C&D management in postgraduate courses for construction. This would provide adequate training towards a future specialized workforce in the sector (Line 18). Also, these training programs or even seminars and conferences at university centers could be taught by professionals from companies of the construction sector—related to the reduction of waste at the source (line 19) or at recycled market agents—involved in the recycling process (Line 13).

3.3. The Role of Construction Companies in the 3R Regulations

In relation to construction companies, it would be necessary to distinguish the measures for each phase comprising C&D waste: reduce, reuse and recycle.

(a) Generation reduction: In the generation phase, it is essential to monitor the collection and selection of different materials at the beginning of the cycle to eliminate the costs and storage space. Since the reduction of waste by construction companies (generators) has become a very complex task, the importance of specialized staff for directing the waste management tasks has emerged as an important new topic [25]. Reinforcing the external control of public supervisors, an effective in-house measure would be the creation of the so-called Environmental Project Manager (EPM). Its main function would be to enforce mandatory source separation with the advantages of time and cost savings in the subsequent recycling process and preventing the severe barrier to recycling through the pretreatment of waste prior to being taken to landfill [23,26]. This information would be forwarded to the managing directors and will serve to review and improve waste management plans in the future (Lines 14 and 17). The channels of information flow from top to bottom and from bottom to top (lines 15 and 16). On the other hand, despite the lack of European legislation to regulate installations for the treatment of C&D wastes, it would be highly recommended the creation of a net of public facilities [3]. Technology difficulties can be avoided by means of grants to purchase equipment that minimize waste generation and reduce adverse effects on human health [26]. The development of green technologies (low waste building technology) will help increase employees' work safety and raise awareness of C&D waste environmental problems. As large capital investments are not normally required, the cost to the construction companies is reduced. Otherwise, there could be tax benefits (for example, accelerated depreciation) for purchases over a certain amount of money. Indeed, funded firms are significantly more R&D-active than non-funded firms [27]. In any case, this expenditure could be considered as an investment because it leads to a reduction in costs (reducing the amount of waste generated) and, therefore, the negative externalities caused by C&D waste. These grants can also be applied in the recycled plants (Line 4).

(b) Disposal recovery: The main political measures for reducing the quantities of waste disposed in landfills are an effective charge system [24]. Waste management aimed at recycling is expensive because it is necessary to transport waste to recycling plants after the previous process of separation. Without the existence of adequate controls, construction companies have a high incentive to send the waste directly to landfill without treatment. Therefore, under the principle "the polluter must pay" [14], an effective measure may be increasing the cost of landfill disposal by means of effluent charges. The greater the amount of waste deposited, the greater the charge to pay and, therefore, greater incentives to recycle. The Spanish legislation (PNIR) recommends implementing a deposit-refund system whose rates vary with the volume of waste. This system guarantees that contractors manage their own C&D waste in an adequate way before any building or demolition permit is provided by the local authorities. C&D waste, once separated, would be brought to a warehouse for recycling (Line 6). The rest of it would be taken to landfills (Line 5). Landfill taxes or even landfill bans for specific materials might be applied to reinforce this measure.

In this competition between recycling and disposal, the main measure for reducing the percentage fraction going to disposal will be tax differentiation. On one side, levies on virgin construction material increase its price and discourage its use for recovery materials (tax differentiation). This will be especially effective in places where raw materials and adequate disposal sites are scarce [18]. On the other side, the introduction of tax benefits to the use of recycled waste, as discussed next, further strengthens incentives for recycling.

(c) Reuse-recycle: Firstly, the location of recycled plants is a crucial aspect for reducing transport costs and providing incentives for construction companies to recover materials from waste (Line 7). Second, a growing demand is also necessary and it depends on external factors. The recycled market would be reduced because consumers perceive less value in recycled materials [13]. To avoid this, the government needs to provide a regulatory environment to develop the recycling market, requiring certain quality standards for these products. In this case, the role of universities on developing products is crucial (Lines 4 and 12). As a complementary measure, the recycled market can also grow by promoting the use of recycled materials through the implementation of reduced sales taxes on new construction using quality recycled material (Line 3).

With regard to the external relations of construction companies, two kinds of relationships can be considered: contractors–subcontractors and contractors–contractors. In the first case, business opportunities and competitiveness between companies can lead them to compare their own techniques with those of its competitors, establishing a benchmark to compare the performance of different options in the management of waste [28], including the use of recycled products. In this case, the goal of implementing economic policy instruments will be to create incentives and comparative advantage over other companies through costs (e.g., subsidies for the purchase of machinery or incorporation of new techniques for recycling) or via income (e.g. incorporate recycled materials as a condition in the award of public projects). Another option is the creation of eco-industrial parks, a community of businesses located together on a common property using each other's wastes as materials for production (Line 8). In the second case, responsibility is dissipated among various agents. The contractor will have the final responsibility (EPR) in order to avoid the enormous costs of assigning responsibilities to each agent. The government should establish a list of authorized subcontractors with a fair price. The implementation of administrative charges for non-compliance [24] forces construction companies to keep track of the generation of waste across the project, including subcontractors' activities (Line 9).

3.4. The Role of the Recycled Market in the 3R Regulations

The links between this agent and the rest of the actors in the EMS proposed has been analyzed in the previous sections. The impact of using recycled materials in the system will be analyzed as a case study in the next section.

4. A Model Based on Final Destination Wastes: An Application for Reusing Recycled Aggregates in Spain

Investigations often focus their efforts on evaluating effects of strategies for reducing C&D waste but not the final destination of resources, *i.e.*, in the management of the use of these recycled materials [12]. Thus, to complete a comprehensive model of management of C&D wastes, this section proposes a simulation model which focuses on the last stage of the process: the final destination of waste. Our work has focused on the recycled aggregates quarry as a case study. We look for economic policy instruments that stimulate the incorporation of these materials in the recycled market [22]. In Spain, as in other countries with low percentages of recycled C&D wastes, it will be especially necessary to provide incentives for the use of these materials, where raw materials are abundant and very cheap.

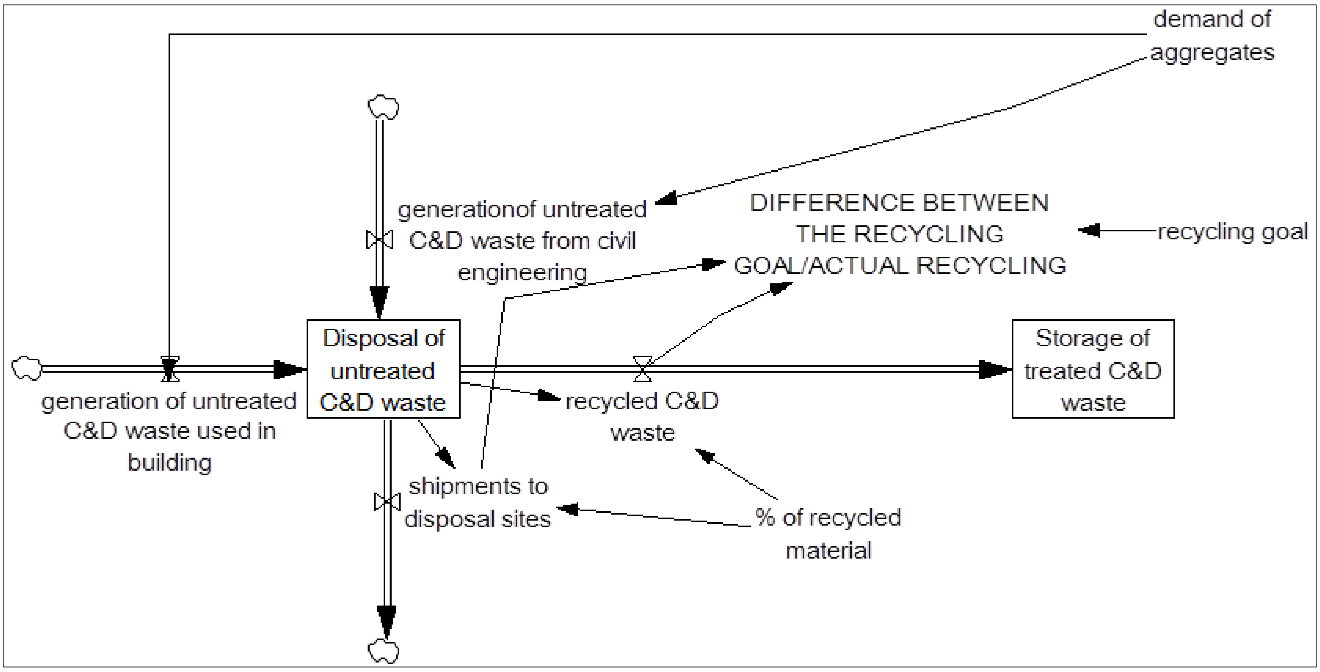
4.1. Dynamic Modeling of the Problem

Having analyzed the situation to be modelled through a conceptual understanding, we developed a dynamic simulation model capable of showing the effects of different policies of incentives to the use of C&D waste on the flow of generation, recycling and reuse of C&D waste. Following the Systems Dynamics methodology and using Vensim DSS 6.1. (Ventana Systems UK Ltd.: Wiltshire, UK) software, the purpose of the model was to reproduce the current behaviour of the system [29,30] and, thereby, establish a useful support tool for executive decision-making processes [31] in order to influence the recycling behaviour of the firms.

The causal analysis developed by [8] pointed to the existence of dynamic relationships between the activity of the generation of waste from C&D and the use of such debris—previously recycled—in works of new construction. The demand for recycled materials depends on the assessment made by the companies as to the relative impact of the use of aggregates made from C&D waste as construction materials on the final cost of the construction work *versus* the use of quarried aggregates. Following the strategy considered by the Spanish Government in the PNIR 2008–2015, we have designed a model which reflects the flow between the generation of waste from the C&D of civil works and the use of these waste materials as an alternative to natural quarried aggregates in new constructions, in terms of economic parameters and using system dynamics' methodology [29,30]. The final objective of this model is to provide to the institutions involved in this area a better understanding of the problem of recycling in works of civil engineering. To do this, we analyzed how their decisions regarding the promotion of economic incentives or penalties in the use of C&D waste as building materials may affect the behavior of the construction companies, and, as a result, these decisions also affect the fulfilment of the recycling goal set out in the National Integrated Waste Management Plan (PNIR 2008–2015).

The generation of waste has been triggered by the demand for building materials. Pressure in civil engineering works and new building has led to the demolition of current works. Following this approach, the process of analyzing C&D waste management begins with the accumulation of untreated waste (disposal of untreated C&D waste) (Figure 3). The accumulation of this waste will depend on the continuous inflow of waste from the demolition of buildings (generation of untreated C&D waste used in building), on the demolition of civil engineering works (generation of untreated 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) (included in the concept of recycling is the percentage of recycled C&D waste as well as the percentage of C&D waste from other recovery operations). The difference between the generation of waste and the recycled volume makes it possible to assess progress towards the established recycling goal in each time period.

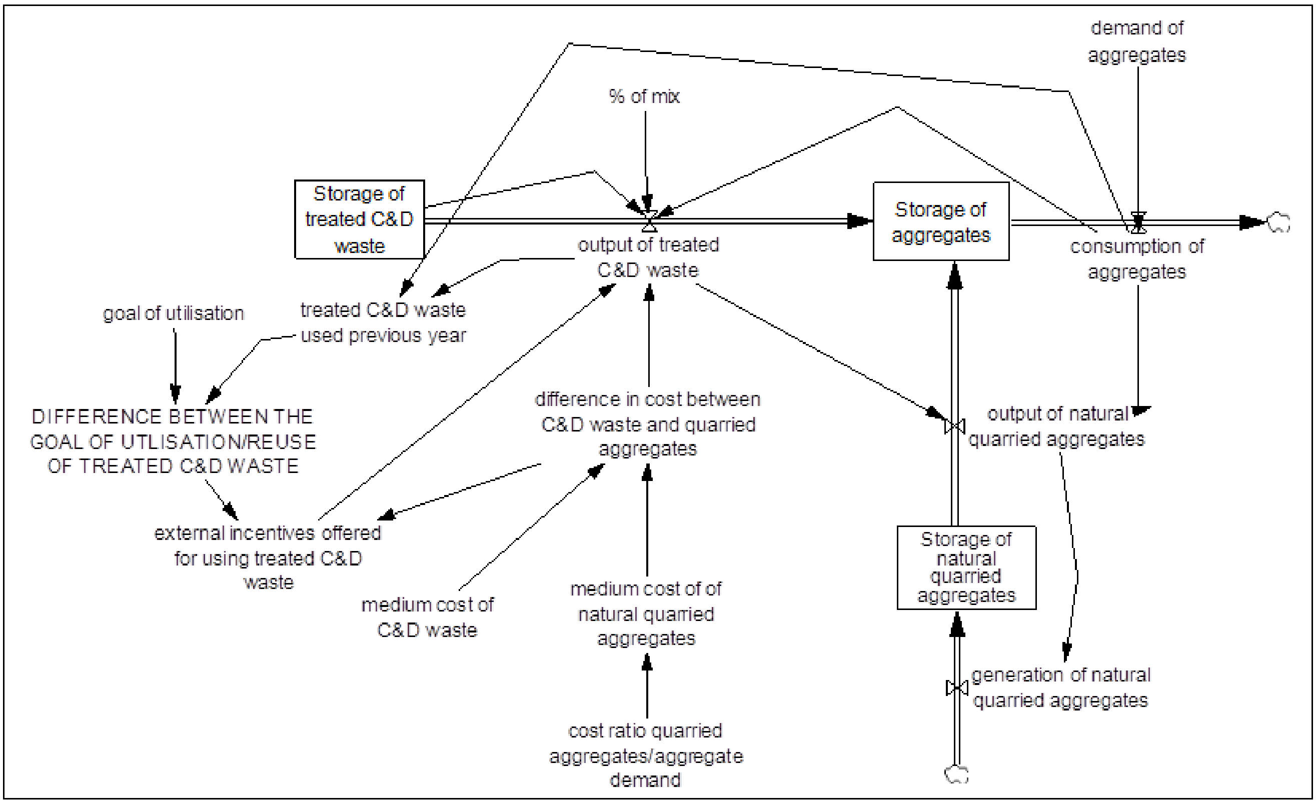
Figure 3. Disposal of untreated C&D waste.



The accumulation of recycled C&D waste (storage of treated C&D waste) will depend on the inflow of recycled materials and on the outflow of these materials as aggregates, to become a 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 that can be transformed into aggregates *versus* those that are unsuitable for this purpose and are sent to the disposal facility. This distribution is contingent upon the quality of the recycling process (percentage of recycled material), whose percentage can be changed depending on the technology or infrastructure used. The improved quality of recycled materials is directly related to the sustainable construction goal and promotes the development of new technologies to improve efficiency in the procurement and use of recycled materials.

The storage of aggregates will be the result of the sum of the output of treated C&D waste and the output of natural quarried aggregates in each period of time (Figure 4). The institutional policies should aim to balance the total aggregates in favor of the C&D waste instead of natural quarried aggregates. However, it requires a better understanding of the system behavior. Because the final behavior of the firms is an economic behavior, the outflow of C&D waste will depend on the internal and external economic incentives available during construction activity. The decision to substitute a specific proportion of natural quarried aggregates for aggregates made from C&D waste will depend on the relative cost incurred.

Figure 4. Storage of aggregates.



The model proposed here presents the analysis of a potential incentive *versus* a penalties policy offered by the government. This policy consists of, on the one hand, 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 treated C&D waste) or, as an alternative, punishing the absence of use of C&D waste by increasing the initial cost of quarried aggregates with a specific tax (non-recycling tax) [32]. The novelty of this approach is that it shows the effects of these policies in the EMS system and how this stakeholder's behavior is influenced over time.

As the technical specifications of the mix C&D waste aggregate/quarried aggregate, the model presents a maximum distribution percentage of 30% (Weight C&D waste aggregate/Weight quarried aggregate + Weight C&D waste aggregate) × 100, which has been analyzed in previous studies examining the behavior of hot mix asphalts in the construction of roads with low to medium traffic volume [33,34]. The increase in this percentage which favours the use of C&D waste will be, in turn, directly linked to the sustainable construction goal of the government.

In order to understand the economic behavior of the firms in the model, if the material made with C&D waste and natural quarried aggregates has technical properties that are similar to the use 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). Thus, meeting the goal of reusing C&D waste will be directly related to the differential cost between the two types of aggregates (Table 3).

The cost of quarried aggregates is not considered to be constant; rather it depends on market demand. Increased demand will cause a rise in cost of this material in the following period (cost ratio quarried aggregates/aggregate demand). Given the lack of statistical data to provide information on the breakdown of the cost components of C&D waste, this aspect was examined using a scenario of T growth in the use of these materials.

Table 3. Equation description of variables.

Variable	Equation Description
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)
Storage of treated C&D waste	∫ (recycled C&D waste-output of treated C&D waste)
Storage of natural quarried aggregates	∫ (generation of natural quarried aggregates-output of natural quarried aggregates)
Storage of aggregates	∫ (output of natural quarried aggregates + output of treated C&D waste-consumption of aggregates)
Generation of untreated C&D waste used in building	(Total C&D waste consumption/ Total C&D waste generation)* (C&D waste consumption building/ Total C&D waste consumption) * demand of aggregates)
Recycled C&D waste	% of recycled material* Disposal of untreated C&D waste
Generation of untreated C&D waste from civil engineering	(Total C&D waste consumption/ Total C&D waste generation)* (C&D waste consumption civil engineering/ Total C&D waste consumption) *demand of aggregates)
Shipments to disposal sites	(1% of recycled material)* Disposal of untreated C&D waste
Difference between the recycling goal/Actual recycling	recycling goal-(recycled C&D waste/(recycled C&D waste + shipments to disposal sites))
Output of natural quarried aggregates	consumption of aggregates-output of treated C&D waste
Difference in cost between C&D waste and quarried aggregates	medium cost of C&D waste/medium cost of natural quarried aggregates
Difference between the goal of utilization /Reuse of treated C&D waste	goal of utilization-treated C&D waste used previous year
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)
generation of natural quarried aggregates	output of natural quarried aggregates

In this way, the model designed will allow for the assessment of both the fulfilment 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/reuse of treated C&D waste), set out in the National Integrated Waste Management Plan (2008–2015), according to institutional policies (for a detailed overview of the evolution of the C&D waste generated in Spain, see Section 2).

In the model designed, we tested two policies: an institutional policy based on external incentives and the use of a fixed non-recycling tax as negative incentive for the use of quarried aggregates.

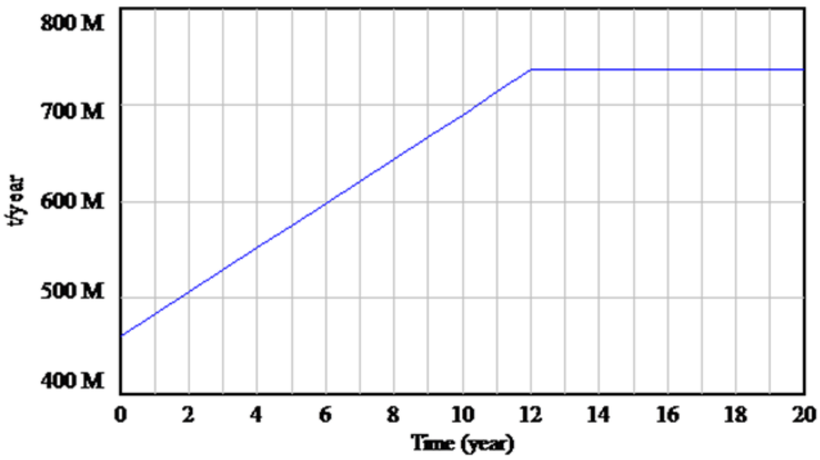
First, the policy based on external incentives relies on economically compensating the firms for the increased cost of using C&D waste. The final goal of this policy will be to change the recycling behavior of the firms until it is economically justifiable. Once the generation and management of C&D waste 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 cost of natural aggregates. In the future, it will be possible to do away with the external incentive offered by the administration, thus consolidating the autonomous functioning of the model with no need for public intervention.

The second policy consists of requiring the firms to pay a fixed non-recycling tax if they use a 100% quarried aggregate mixture. In this sense, this policy would provide direct incomes to the administration, and also would discourage the use of quarried aggregates in economic terms, because it increases the medium cost of the materials.

4.2. Modeling Results

We considered a scenario of demand for aggregates to be used in construction with an initial growth combined with the subsequent period of stagnation (Figure 5). This scenario reflects the historical behavior of these materials over the decade from 2001–2010.

Figure 5. Demand of aggregates.

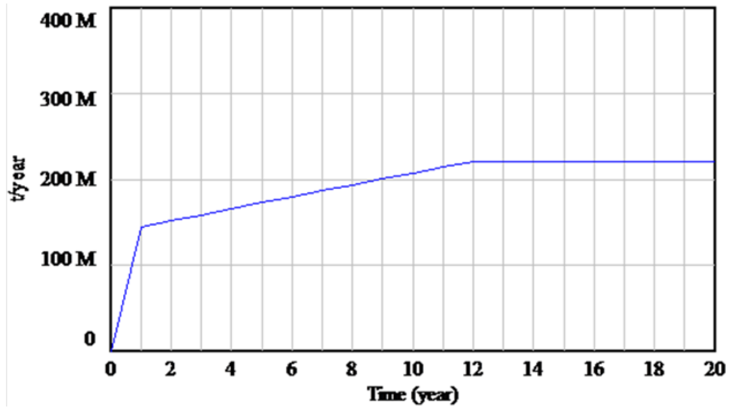


Source: Own elaboration.

4.2.1. First Measure: Policy Based on External Incentives

The scenario of demand of aggregates affects the flow of waste from the time these materials are generated until they are reused through recycling. Considering a C&D waste cost as a constant, the administration will be obliged to apply external incentives while the cost of C&D waste is higher than the cost of natural aggregates, until the increased cost of the latter materials allows the cancellation of this policy due to lack of demand. In this case, the flow diagram will help firms and institutions understand the dynamic behavior of the recycling system. In this model, the application of economic incentives that compensate for the difference in cost between the use of C&D waste and quarried aggregates allows to achieve the proposed goals (Figure 6). Eventually, firms change their behavior and increase the use of the treated C&D waste in the aggregate mixtures until reaching the rate technically permitted (30% of the total mix of aggregates).

Figure 6. Output of treated C&D waste.



Source: Own elaboration.

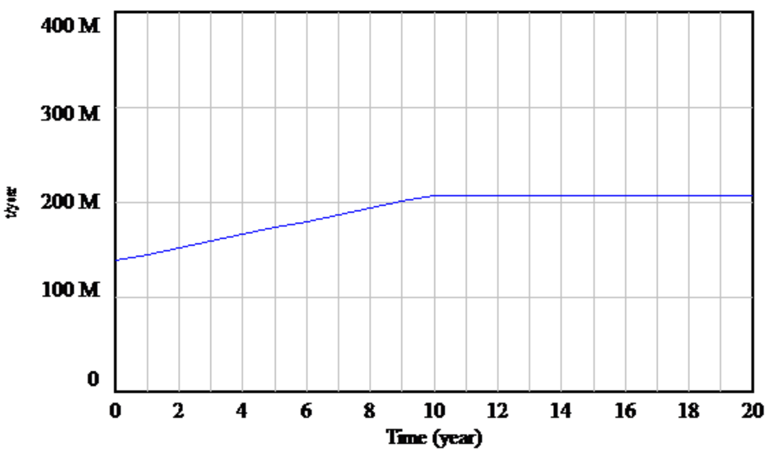
This policy would be aligned with the economic behavior of the firms, and it would allow exponential growth in consumption of C&D treated waste during the first year. Between year 2 and 12, the growth of the consumption will dampen. Finally, the use of C&D treated waste will remain at the percentage technically allowed (30% of the total mix of aggregates).

4.2.2. Second Measure: Use of a Fixed Non-Recycling Tax

In the absence of any economic incentive for recycling, the administration could try implementing a policy of economic penalties to help to achieve the goal of recycling C&D waste. We consider the same scenario of growing demand for aggregates for 12 years followed by a stagnation of demand, according to historical data (2001–2010).

In this case, instead of proposing economic incentives to reduce the cost differences between C&D waste and quarried aggregates, in what means an added cost for public institutions, the government may impose a fixed non-recycling tax to the use of quarried aggregates used in civil construction. According to the model proposed, this measure will affect companies' recycling behavior only if the non-recycling tax increases the cost of natural aggregate over 10% (Figure 7). We also have to take into account that often fiscal measures only have consequences one year later, so there will be a delay in the desired influence on companies.

Figure 7. Output of treated C&D waste.



In this case, the policy of penalties (non-recycling tax) will cause a continuous and slight increase in consumption of C&D treated waste from year 1–10. From year 10 onwards, the consumption will stabilize at the maximum percentage technically allowed (30%). Based on this measure, the results are shown with a one year delay since companies are not subjected to this penalty policy until the next period when they are affected by the measure and, therefore, change their behavior. This is the reason why in the graph the levels of tons of waste start from positive values instead of from zero, compared to the scenario of incentives shown in the previous subheading.

The scenarios of simulation we have proposed will serve as a supporting tool for a better understanding of the consequences of different policies that stimulate the use of recycled materials in civil construction. The final goal of this methodology is not to answer the question of which policy should be implemented by the administration, because there is no optimum in this complex reality. In this case, providing economic incentives to construction companies through economic compensation for the difference in cost will increase the percentage of C&D waste materials used by the companies in 12 years. Nevertheless, in the short term, the administration will repay the cost of this policy. On the contrary, the use of economic penalties (non-recycling tax) to help achieve the goal of recycling C&D waste might be considered a most profitable policy for the administration in the short term since the goal is achieved in less time—only 10 years. However, increasing the global cost of quarried aggregates will also boost the total cost of materials of the companies, reducing their competitive advantages in the global market. To sum up, the simulation tool will help us understand the consequences of potential decisions from a dynamic approach, but, ultimately, the public administration will be responsible for selecting the policy most suitable to the complexity of the situation.

5. Conclusions

In recent decades, the increasing activity of the construction sector has led to an excessive accumulation of C&D wastes. The landfill space is reduced and can cause environmental damage. The treatment of this waste has become a complex task because their management results in a 3R process involving new techniques and huge costs. Since construction companies have no incentives to waste management, the only solution is to resort to administrative measures or policy instruments. Past research on C&D waste management was mainly focused on the separate aspects such as reduction, reuse, recycle and response. A new approach is presented in this paper to improve the whole C&D waste management (using an EMS model), focusing on the often forgotten last stage of the process: the final destination of waste through the case study of recycled aggregates (using a simulation model).

Therefore, it is necessary to implement measures that prevent the high amounts of waste disposal. Effective regulation and economic incentives determine the amount of C&D waste and reduces the levels reutilized. In Spain, the lack of effective regulation has led to low levels of recycled material from these wastes compared to other European countries. However, the essential tools for the creation of an EMS are market-based instruments. Therefore, the aim of our study was to develop a theoretical model establishing the main guidelines for a successful waste management process through regulation and, most importantly, the use of market-based policy instruments. The EMS proposed has the potential to assist stakeholders to better understand the complexity of information and relations involved in managing C&D waste to establish a successful 3R process. Our model requires the inclusion of universities with a key role for efficient C&D waste management, especially in the R&D aspects, since these institutions provide cost savings and highly qualified staff. When a specific regulatory framework is implemented and all agents obey the 3R regulations, recycling of C&D materials is promoted. Increasing the benefits of recycling waste can provide an incentive for the building and civil construction industry to make better use of C&D waste. This also affects business competition and the implementation of waste diversion. In our opinion, in the future, this will lead to the generation, recycling and reuse of C&D waste as part of an autonomous and functioning model that is feasible from an economic standpoint.

On the other hand, the paper presents an integrated simulation model based on two policy instruments (incentives and tax penalties) using systems dynamic methodology in the aggregates field. The use of simulation methodologies as a tool to deepen the dynamic consequences of implementing different policies 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 policy instruments. In our particular case of study, the findings reveal that a complete integration of recycled C&D wastes (30% as the total of aggregates) can be achieved in the dynamic process in just 12 years, regardless of the political instrument adopted. According to the results of the simulation, we conclude that the fulfilment of the goals of recycling and reusing of waste materials for construction—a key aspect in sustainable construction—requires the active participation of the administration in the short term. Government can boost the recycled market of C&D waste through policy instruments in a dynamic way to provide a better understanding of the interactions in the key areas of the C&D waste management process. Measures as economic incentives or tax penalties are options that will allow for the harmonization of the behavior of waste management and construction companies with the C&D waste management model proposed within a legal framework.

In particular, each policy instrument proposed in the simulation model aims towards the goal of increasing the use of recycled C&D waste (30% of the total aggregates) in construction. The first measure is based on economic incentives for construction companies so that they will use these aggregates, providing compensation for the difference in cost for using them instead of quarried aggregates. This measure will increase the percentage of C&D waste materials in these mixes in 12 years, but this policy will repay the cost of recycling to the public administration. The second measure is based on economic penalties (non-recycling tax) to help achieve the aforementioned goal of recycling C&D waste in only 10 years. Against the economic incentives, this might be considered a most profitable policy for the public administration in the short term according to the Spanish agenda. However, increasing the global cost of quarried aggregates will also boost the total cost of materials of all companies (the maximum distribution percentage between recycled C&D waste and quarried aggregates is 30%), reducing the competitive advantage of the companies subject to this fiscal framework in external markets. Finally, the novelty of this approach is to show how these policies provoke changes in the stakeholders' behavior over time. Further harmonization of these methods may be carried out across different feasible fields (not only in the case study of aggregates) in the future.

Supplementary Materials

Supplementary materials can be accessed at: http://www.mdpi.com/2071-1050/6/1/416/s1.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. II Plan Nacional de Residuos de Construcción y Demolición 2007–2015 (in Spanish). Available online: http://www.boe.es/boe/dias/2009/02/26/pdfs/BOE-A-2009-3243.pdf (accessed on 23 January 2013).
2. Hao, J.L.; Hills, M.J.; Huang, T. A simulation model using system dynamic method for construction and demolition waste management in Hong Kong. *Construct. Innov.: Inform. Process Manage.* **2007**, *7*, 7–21.
3. Lu, W.; Yuan, H. Exploring critical success factors for waste management in construction projects of China. *Resour. Conserv. Recy.* **2010**, *55*, 201–208.
4. Sroufe, R. Effects of environmental management systems on environmental management practices and operations. *Prod. Oper. Manag.* **2003**, *12*, 416–431.
5. Ortiz, O.; Pasqualino, J.C.; Castells, F. Environmental performance of construction waste: Comparing three scenarios form a case study in Catalonia, Spain. *Waste Manage.* **2010**, *30*, 646–654.
6. Del Río Merino, M.; Salto-Weis Azevedo, I.; Izquierdo Gracia, P. Sustainable construction: Construction and demolition waste reconsidered. *Waste Manage. Res.* **2010**, *28*, 118–129.
7. Llatas, C.; Ramírez, L.C.; Huetes, R. Una aproximación metodológica a la verificación en obra de la cuantificación de residuos de construcción en Andalucía. In Proceedings of the Sustainable building conference, Madrid, Spain, 28–30 April 2010; C025.
8. Yuan, H.; Chini, A.R.; Lu, Y.; Shen, L. A dynamic model for assessing the effects of management strategies on the reduction of construction and demolition waste. *Waste Manage.* **2012**, *32*, 521–531.
9. Manowong, E. Investigating factors influencing construction waste management efforts in developed countries: An experience from Thailand. *Waste Manage. Res.* **2012**, *30*, 56–71
10. Plan Nacional de Residuos de la Construcción y Demolición (PNRCD) 2000–2006 (in Spanish) Available online: http://www.boe.es/boe/dias/2001/07/12/pdfs/A25305-25313.pdf (accessed on 14 March 2013).
11. Kemp, R.; Pontoglio, S. The innovation effects of environmental policy instruments-A typical case of the bling men and the elephant? *Ecol. Econ.* **2011**, *72*, 28–36.
12. Vandecasteelo, C.; van der Sloot, H. Sustainable management of waste and recycled materials in construction. *Waste Manage.* **2011**, *31*, 199–200.
13. Saotome, T. Development of Construction and Demolition Waste Recycling in Ontario. Master's Thesis, MC Master University Engineering, Hamilton, Canada, 2007. Available online: http://msep.eng.mcmaster.ca/epp/publications/student/Development_of_C&D_recycling_in_Ontario.pdf (accessed on 12 May 2013).
14. Lu, W.; Yuan, H. A framework for understanding waste management studies in construction. *Waste Manage.* **2011**, *31*, 1252–1260.
15. Cooper, J.C. Controls and incentives: A framework for the utilization of bulk wastes. *Waste Manage.* **1996**, *16*, 209–213.

16. Lu, W.; Yuan, H.; Li, J.; Hao, J.J.L.; Hi, X.; Ding, Z. An empirical investigation of construction and demolition waste generation rates in Shenzhen city, South China. *Waste Manage.* **2011**, *31*, 680–687.
17. Hyder Consulting, Encycle Consulting & Sustainable Resource Solutions. *Construction and Demolition Waste Status Report. Management of Construction and Demolition Waste in Australia*; Department of Sustainability, Environment, Water, Population and Communities & Queensland Department of Environment and Resource Management: Melbourne, Australia, 2011. Available online: http://www.environment.gov.au/system/files/resources/323e8f22–1a8a-4245-a09c-006644d3bd51/files/construction-waste.pdf (accessed on 11 June 2013).
18. Rodríguez, G.; Alegre, J.; Martínez, G. The contribution of environmental management systems to the management of construction and demolition waste: The case of autonomous community of Madrid (Spain). *Resour. Conserv. Recy.* **2007**, *50*, 334–349.
19. Solís-Guzmán, J.; Marrero, M.; Montes-Delgado, M.V.; Ramírez-de-Arellano, A. A Spanish model for quantification and management of construction waste. *Waste Manage.* **2009**, *29*, 2542–2548.
20. Martínez Lage, I.; Martínez Abella, F.; Vázquez Herrero, C.; Pérez Ordóñez, J.L. Estimation of the anual production and composition of C&D debris in Galicia (Spain). *Waste Manage.* **2010**, *30*, 636–645.
21. *Management of Construction and Demolition Waste*; Working document no. 1; European Union: Brussels, Belgium, 2000. Available online: http://www.docstoc.com/docs/971611/Management-of-Construction-and-Demolition-Waste/ (accessed on 23 May 2013).
22. Marrero Meléndez, M.; Solís Guzmán, J. *A Blueprint for Sustainable Purchasing and Policy Development for Construction*; The Environment Centre: Southampton, UK, 2007.
23. De Guzmán Baez, A.; Villoria Sáez, P.; del Río Merino, M.; García Navarro, J. Methodology for quantification of waste generated in Spanish railway construction works. *Waste Manage.* **2012**, *32*, 920–924.
24. Stavins, R.N. Experience with market-based environmental policy instruments. In *Handbook of Environmental Economics*, 1st ed.; Karl-Göran, M., Vincent, J., Arrow, K., Intriligator, M., Eds.; Elsevier: Amsterdam, The Netherlands, 2003; Volume 1, pp. 355–435.
25. Bohne, R.A.; Brattebø, H.; Bergsdal, H. Dynamic eco-efficiency projections for construction and demolition waste recycling strategies at the city level. *J. Ind. Ecol.* **2008**, *12*, 52–68.
26. Guo, Y.; Baetz, B.W. Sizing of rainwater storage units for green building applications. *J. Hydraul. Eng.* **2007**, *12*, 197–205.
27. Aerts, K.; Schmidt, T. Two for the price of one? Additionality effects of R&D subsidies: A comparison between Flanders and Germany. *Res. Policy* **2008**, *37*, 806–822.
28. Sánchez, M.F.; Castro, J.G. *Gestión y minimización de residuos*, 2nd ed.; TAXUS, Gestión Ambiental, Ecología y Calidad S.L.: Madrid, Spain, 2011.
29. Forrester, J.W. *Industrial Dynamics*, 1st ed.; Pegasus Communications: Boston, MA, USA, 1961.
30. Stearman, J. Business Dynamics: Systems Thinking and Modeling for a Complex World, 1st ed.; Irwin McGraw-Hill: Boston, MA, USA, 2000.
31. Senge, P. The Fifth Discipline. The Art & Practice of the Learning Organizations, 1st ed.; Random House: Ann Arbor, MI, USA, 1990.

32. Reimer, M. Planning cultures in transition: sustainability management and institutional change in spatial planning. *Sustainability* **2013**, *5*, 4653–4673.
33. Pérez, I.; Toledano, M.; Gallego, J.; Taibo, J. Mechanical properties of hot mix asphalt made with recycled aggregates from reclaimed construction and demolition debris. *Materiales de Construcción* **2007**, *57*, 17–29.
34. Pérez, I.; Pasandín, A.R.; Gallego, J. Stripping in hot mix asphalt produced by aggregates from construction and demolition waste. *Waste Manage. Res.* **2012**, *30*, 3–11.