Dynamic Model for Comparing the Performance of Waste Management Strategies over Sustainability Dimensions

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Abstract

This paper aims to show a System Dynamics model proposed to evaluate and compare the impact of diverse waste management strategies on Construction and Demolition (C&D) debris over some environmental, ecological and economic aspects as dimensions for measuring sustainability. The model looks to promote systematic thinking about relations between strategic decisions over C&D waste management and its long term consequences over sustainability and also to provide a model that allows decision makers to simulate and study the potential impact of several waste strategies; those strategies were focused on two types, operational and regulative related. The model was run with some generic data contextualized in Bogotá D.C, Colombia, in order to show the expected results and behavior and also to provide a guideline for setting up the conclusions that were reached, those conclusion are concentrated on the methodological approach followed, instead of the behavior and analysis of the data set used.

Key Words: System Dynamics, Construction and Demolition Waste Management, Sustainability Performance Indicators.

Introduction

Understanding a strategy as a combination of ways and modes used to achieve the objectives of a system in the presence of uncertainty (Francés, 2006), the decision makers in different industries face a wide range of possibilities, each of them with different impacts over the dimensions and objectives of sustainability within the context in which those strategies would potentially be implemented.

The System Dynamic Model presented in this paper aims to provide an approach to evaluate and compare the impact over sustainability dimensions caused by some operational and regulatory strategies potentially implemented to manage C&D debris.

Firstly there is a brief definition of the problem and its background, after that; it is shown the way in which the model was conceived and structured, it included the development of four modules that are Generation and Waste Management, Logistics Strategies, Regulatory Strategies and a System of Indicators; then a set of scenarios were configured and simulated, and finally the conclusions reached as consequence of the design of the model are presented.

Brief Problem Background

The literature review shows us that some of the existing models of comparison of strategies on C&D debris management have been made by using Systems Dynamics. Taking advantage of the approach to represent dynamic and complex systems, this is the case of Calvo, Varela-Candamio, & Novo-Corti (2014) and Yuan (2012). Other authors such as Dantana, Touran, & Wang (2004), provide a framework of indicators to evaluate the performance of C&D industry in terms of its sustainability. Multicriteria analysis was proposed by Roussat, Dujet, & Méhu (2008). There are also authors focused on the assessment of specific factors like economic and environmental impact such as Kucukvar, Egilmez, & Tatari (2014), and Dantana, Touran, & Wang (2004).

Considering the performance measures proposed by the authors studied, it is evident that in several cases the most relevant sustainability dimension of study is environmental which is the case of Calvo, Varela-Candamio, & Novo-Corti (2014), Yuan, Chini, & Shen (2012), Wu & Yu (2014), and Kucukvar, Egilmez, & Tatari (2014).

Dantana, Touran, & Wang (2005) evaluate the economic impact. On the other side Yuan (2012), propouses a model focused on the social performance. Roussat, Dujet, & Méhu (2008) designed a system of indicators that contemplate the social, environmental and economic criteria.

In terms of the strategies to be compared and after considering a significant range of possibilities on C&D waste management strategies available in literature, it was decided to include within the framework and scope of the proposed model two generic operational strategies. Those are:

Conventional demolition, the buildings are demolished without sorting different components, after the demolition; the waste goes through a selection process in a collection center. After the classification of the different fractions of waste, the materials that can be used are reprocessed while there is capacity to do so. The non-usable ones will be disposed in a landfill as well as those that can be used but exceed the processing and storage capacity of the collection centers.

Selective demolition, also known as deconstruction, refers to the process of dismantling buildings in the reverse order from which they were constructed. The removed materials are stored for reuse or recycling and those that cannot be reused or recycled are discarded. (Dantana, Touran, & Wang, 2005). C&D waste is classified separating hazardous components (Roussat, Dujet, & Méhu, 2008).

For the development of the model it was assumed that only reusable C&D waste is flowing throw the system, leaving out the particular treatment of items like dangerous components since those must have a special handling and are not susceptible to being reused.

In terms of regulatory aspects, studies such as Calvo, Varela-Candamio, & Novo-Corti (2014), were taken as reference. Those emphasize the implementation of penalties, taxes and incentives as strategies that allow the Government to influence the behavior of the sector and thus the C&D waste recovering system. Consequently, penalties, taxes and incentives are regulatory strategies into the designed model.

Conceptualization and construction of the model

The dynamic model in reference is conceived from a modular perspective, which contemplates four modules integrated with each other, namely:

- ✓ Module 1: Generation and management of C&D waste
- ✓ Module 2: Logistics Strategies
- ✓ Module 3: Regulatory Strategies
- ✓ Module 4: Systems of indicators

Figure 1 displays the modular design proposed, the set of indicators offered is related to sustainability dimensions and it is shown in Table 1.

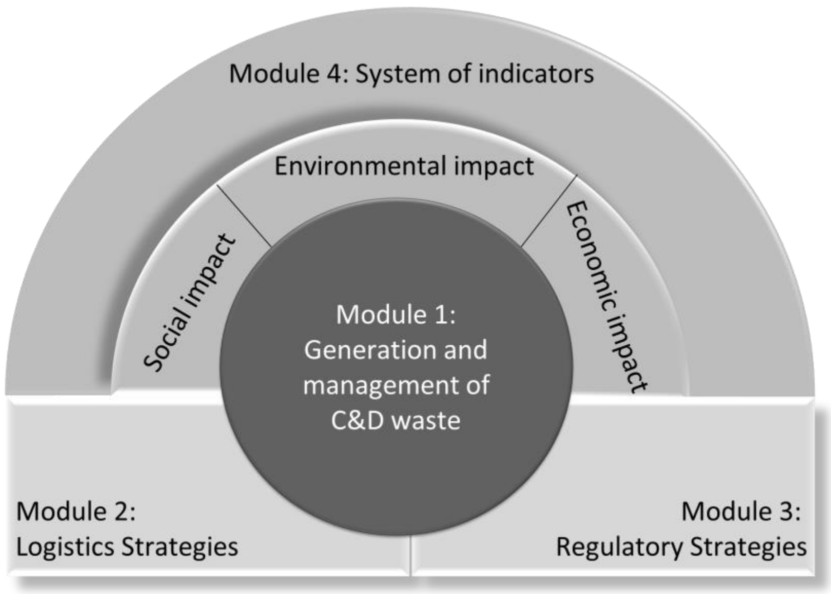


Figure 1. Modular composition of the dynamic model
Source: Own elaboration

Table 1. Performance indicators included in the designed model

Sustainability dimension	Indicator	Definition of the variable	Nomenclature / Units	References
Social impact	Employment generation	Estimation of jobs generated for the management of C&D waste during the planning horizon.	$SOIx1$ [Jobs]	Yuan (2012), Wu & Yu, (2014)
	Social perception of C&D waste management	Degree of satisfaction of the population in the perception of the management of C&D waste	$SOIx2$ [%]	Yuan (2012), Wu & Yu, (2014)
Environmental impact	Land use	Volume of landfill consumed by C&D waste, either by controlled or uncontrolled disposal	$ENIx1$ $[m^3]$	Yuan (2012), Wu & Yu (2014), Kucukvar, Egilmez, & Tatar (2014)
	Pollution of water sources	Volume of water sources affected by the C&D waste, it is associated with the uncontrolled disposal	$ENIx2$ $[m^3]$	Yuan (2012), Wu & Yu, (2014), Kucukvar, Egilmez, & Tatar (2014)
Economic impact	Recovery of economic value	Rate of recovery of economic value of C&D waste. It is measured as the equivalent fraction of C&D materials that are used in the industry from C&D waste treatment activities after discounting the costs of the related operations, also considering them as a fraction of C&D waste.	$ECIx1$ [%]	Yuan (2012), Wu & Yu, (2014)
	Cost of C&D waste treatment and recovery operations	Cost of treatment and recovery operations carried out during the planning horizon.	$ECIx2$ [$]	Yuan (2012)
	Transportation costs	Transport costs of C&D wastes generated during the planning horizon, these include those addressed to both the controlled and uncontrolled disposal	$ECIx3$ [$]	Yuan (2012)

Source: Own elaboration

Module 1: Generation and management of C&D waste

In the research article "*A system dynamics model for dynamic capacity planning of remanufacturing* in closed-loop supply chains" by Vlachos, Georgiadis, & Iakovou (2006), a system dynamics model is proposed, the model aims to establish an optimal strategy for the planning of remanufacturing capacities in a closed loop Supply Chain using as optimization criterion the Net Present Value of the total profit during the planning horizon.

A capacity strategy must take into account a large number of factors, including, but not limited to, demand patterns, cost of building and operating new facilities, new technologies and strategies of competitors (Fleischmann, *et all* 1997).

Capacity planning is a complex issue, even after deciding to expand capacity, a large number of expansion alternatives must be considered including where, when, and how much among other factors under the criterion of the two opposing objectives of capacity planning, such as maximization of market share and maximization of capacity utilization (Vlachos, Georgiadis, & Iakovou, 2006).

Given the similarities that the management of C&D debris present with the manufacturing processes studied by these authors and the relevance of their research, their dynamic model was taken as a frame of reference for designing the first module; adapting its variables and feedback loops to the problem and context in which the proposed model was placed.

According to that, Table 2 contains the denominations of the variables used for the construction of the first module of the dynamic model (Generation and Management of C&D waste), together with its definition, type and units for measurement. Figure 2 shows the causal loop diagram. Figure 3 shows the Forrester diagram proposed for this first module.

The causal diagrams, level diagrams and simulation presented in the next pages were made and performed by using Vensim ® PLE by Ventana Systems. Inc. software.

Table 2. Variables included for the Generation and Management of C&D waste module

Notation	Definition	Type	Dimension
$CDw\ Gen\ rt$	C&D waste generated per month	Rate	[kt/month]
$CDw\ Gen\ rt$ 0	C&D waste generated per month at moment 0	Cte.	[kt/month]
$rt\ de\ Inc\ Gen$	Percentage increment over C&D waste generated per month	Cte.	[1]
$CDw\ Gen\ Acum$	Total C&D waste generated during the simulation period	Level	[kt]
$CDw\ Lv$	Level of C&D waste in system	Level	[kt]
$rt\ RCL$	C&D waste flow rate in collection and inspection facilities	Rate	[kt/month]

Notation	Definition	Type	Dimension
$CDw\ RCL\ lv0$	Initial rate of waste C&D flow to collection and inspection facilities	Rate	[kt/month]
$Cap\ RCL$	Maximum volume of C&D waste that can be handled by collection facilities per unit of time	Level	[kt/month]
$Cap\ RCL\ 0$	Initial collection capacity	Cte.	[kt/month]
$Fact\ Cap\ RCL\ 0$	Factor used to calculate Cap RCL 0. Indicates the initial fraction of demolished C&D waste that is legally disposed.	Cte.	[1]
$rt\ Inc\ CapRCL$	Rate of increase of collection capacity	Rate	[kt/month]
$Obj\ Cap\ RCL$	Collection Capability Objective	Rate	[kt/month]
$Fact\ Obj\ Cap\ RCL$	Factor used to calculate the $Obj\ Cap\ RCL$ as a function of $CDw\ Gen\ rt$	Cte.	[1]
$Discr\ Obj\ Cap\ RCL$	Discrepancy between $Obj\ Cap\ RCL$ and $Cap\ RCL$	Aux.	[kt/month]
$Fac\ Inc\ Cte\ Cap\ RCL$	Constant increase factor of the$Cap\ RCL$, is activated when the target, $Obj\ Cap\ RCL$ has not been reached.	Aux.	[1/month]
$Fac\ Aux\ Inc\ Cap\ RCL$	Aux Factor. Of increase of the capacity of constant collection, originated by factors and policies external to the variables of the model	Cte.	[1/month]
$Inc\ CapRCL\ Dect$	Increased collection capacity for the implementation of selective demolition (deconstruction)	Aux.	[kt/month]
$rt\ \ disp\ NC$	It is the flow of C&D waste to be disposed of as a consequence of insufficient collection capacity (Cap_RCL), or industry players' preference for doing so	Rate	[kt/month]
$CDw\ disp\ NC$	Level C&D waste arranged in an uncontrolled manner	Level	[kt]
$Pref\ NC\ Reg$	The degree of preference of the companies of the sector to dispose their C&D waste in an uncontrolled (illegal) way, is a regulated value that varies between 0 and 1 corresponding to a fraction of C&D waste	Aux.	[1]
$Sink\ 1$	Disposal rate of C&D waste arranged in an uncontrolled manner	Rate	[kt/month]
$CDw\ RCL\ lv$	Level of C&D waste collected	Level	[kt]
$Fr\ CDw\ Acc$	Fraction of C&D waste collected accepted to be reused	Aux.	[1]
$Fr\ CDw\ Rej$	Fraction of C&D waste collected rejected for reuse	Aux.	[1]
$CDw\ accepted\ reuse$	Flow of C&D waste passing inspection and suitable for reuse	Rate	[kt/month]
$CDw\ rejected\ reuse$	Waste C&D flow that does not pass the inspection and should be discarded	Rate	[kt/month]

Notation	Definition	Type	Dimension
$CDw\ Reusable\ lv$	Level of C&D waste that meets the conditions to be reprocessed or recycled	Level	[kt]
$rt\ of\ disp\ SC$	C&D recoverable waste surplus inventory flow, which in order to prevent costly accumulation, should be discarded if there is not enough capacity for handling	Rate	[kt/month]
$CDw\ dis\ SC$	Level of C&D waste disposed in a controlled way	Level	[kt]
$Sink\ 2$	Final disposal rate of C&D waste disposed in a controlled way	Rate	[kt/month]
$Cap\ PR$	The maximum volume of C&D waste that can be reprocessed in the treatment facilities of the system	Level	[kt/month]
$Fact\ Cap\ PR\ 0$	Factor used to calculate initial processing capacity as a fraction of the C&D waste demand in the market	Cte.	[1]
$Fact\ Obj\ Cap\ PR$	Factor used to calculate the target of processing capacity as a function of C&D waste demand in the market	Cte.	[1]
$Discr\ Cap\ Obj$	Discrepancy between Cap PR and its objective	Aux.	[kt]
$PR\ rt$	Flow of C&D waste treated through recovery facilities	Rate	[kt/month]
$rt\ Inc\ CapPR$	Rate of increase of processing capacity (recovery)	Rate	[kt/month]
$Fac\ Inc\ CapPR$	Factor of increase of the processing capacity, is used to calculate the $rt\ Inc\ CapPR$ based on demand for C&D waste in the market	Aux.	[kt]
$Aux\ Inc\ CapPR$	Increase in processing capacity, used to calculate $Fac\ Inc\ CapPR$ based on C&D waste demand in the market	Cte.	[1]
$CDw\ PR\ Market$	Level of C&D waste processed and available to be reincorporated into the market	Level	[kt]
$CDw\ PR\ UsMarket$	Reinstatement rate in the processed C&D waste market	Rate	[kt/month]
$Acum\ CDw\ PR\ UsMarket$	C&D waste used in the market accumulated during the planning horizon	Level	[kt]
$Demand\ CDw\ PR\ Market$	Demand in the C&D waste treated market	Level	[kt]
$Pref\ dis\ NC$	Preference for uncontrolled disposal	Level	[1]
$Pref\ dis\ NC\ 0$	Initial preference for uncontrolled disposal	Level	[1]
$rt\ Inc\ Pref\ dis\ NC$	Rate of increase of preference for uncontrolled disposal	Rate	[1/month]
$MaTax\ Disp\ SC$	Marginal tax charged for disposal of C&D waste in landfills. This variable comes from the module of regulatory strategies	Aux.	[$/kt]

Notation	Definition	Type	Dimension
$Fac\ Inc\ Pref\ NC\ Tax$	An estimated factor that would increase the preference for the uncontrolled provision as a result of taxes for reported C&D waste generation	Aux.	[1/$/kt] [kt/$]
$CosMaTr\ NC$	Marginal cost of transportation to landfills or other illegal disposal sites	Aux.	[$/kt]
$CosMaTr\ SC$	Marginal cost of transportation to legal collection centers	Aux.	[$/kt]
$Rel\ CosMaTr\ NC/SC$	Cost Ratio $CosMaTr\ NC/CosMaTr\ SC$	Aux.	[1]
$Fac\ Inc\ Pref\ NC\ Cos\ NC\ /SC$	An estimated factor that would increase the preference for uncontrolled disposal as a consequence of the differences between transport costs by controlled and uncontrolled disposal	Aux.	[1]
$rt\ dec\ Pref\ dis\ NC$	Rate of decreasing preference for uncontrolled disposal	Aux.	[kt/month]
$Fac\ dec\ Pref\ NC\ Cos\ NC\ /SC$	Estimated decreasing factor in preference for uncontrolled disposal as a consequence of differences between transportation costs by controlled and uncontrolled disposal	Aux.	[1]
$Fac\ dec\ Pref\ NC\ PeMa$	Estimated decreasing factor in preference for uncontrolled disposal as a consequence of marginal penalty for illegal disposal	Aux.	[1]
$P\ Pe\ disp\ NC$	Probability of assigning penalties by uncontrolled disposal. This variable comes from the module of regulatory strategies	Aux.	[1]
$PeMa\ disp\ NC$	Marginal penalty for uncontrolled disposal. This variable comes from the module of regulatory strategies	Aux.	[$/kt]
$Obj\ Pref\ dis\ NC$	Target in preference for uncontrolled provision	Aux.	[1]
$Discr\ Obj\ Pref\ dis\ NC$	Discrepancy between preference for uncontrolled disposal and its target value	Aux.	[kt/month]

Source: Own elaboration

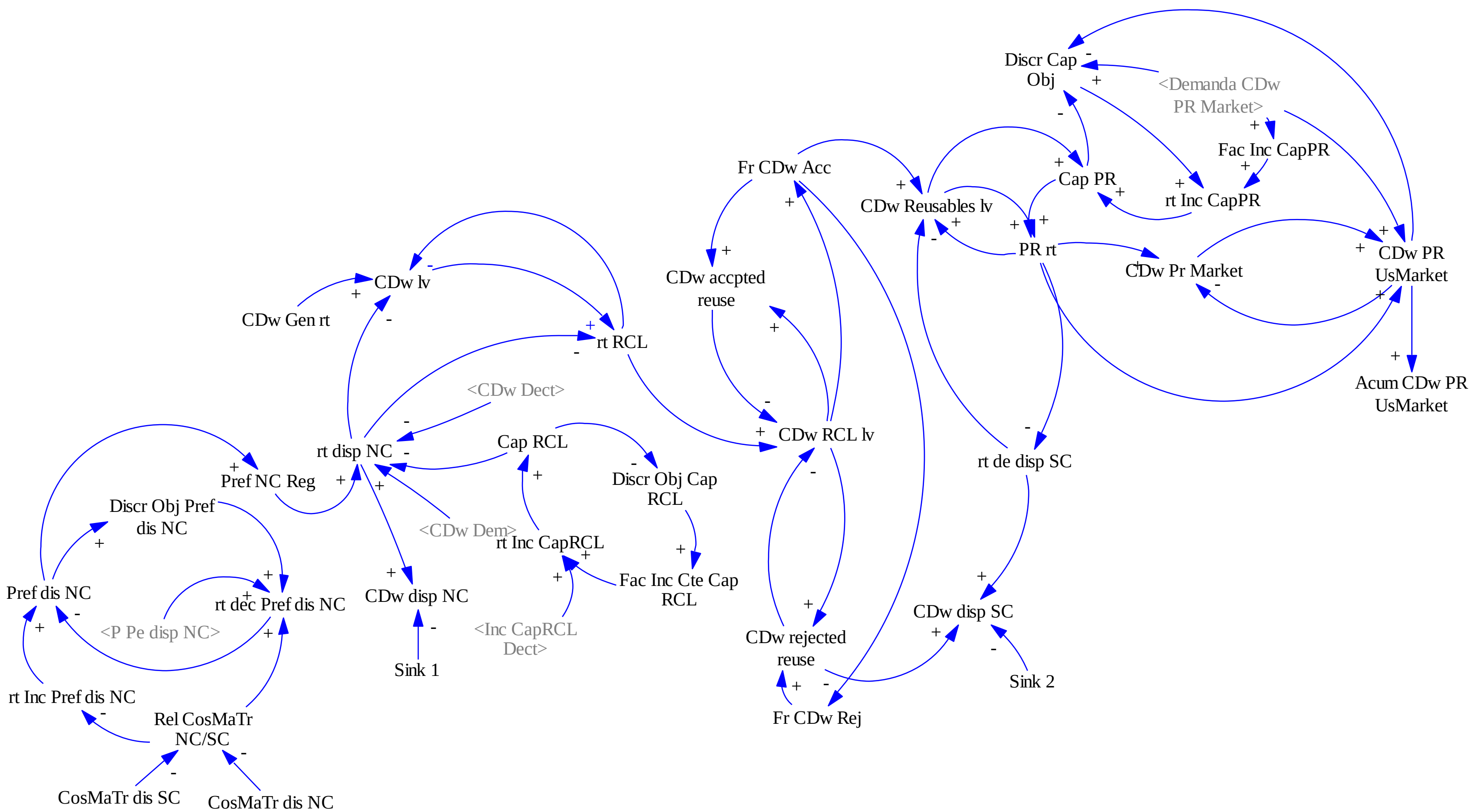


Figure 2. Causal loop diagram for module 1
Own elaboration

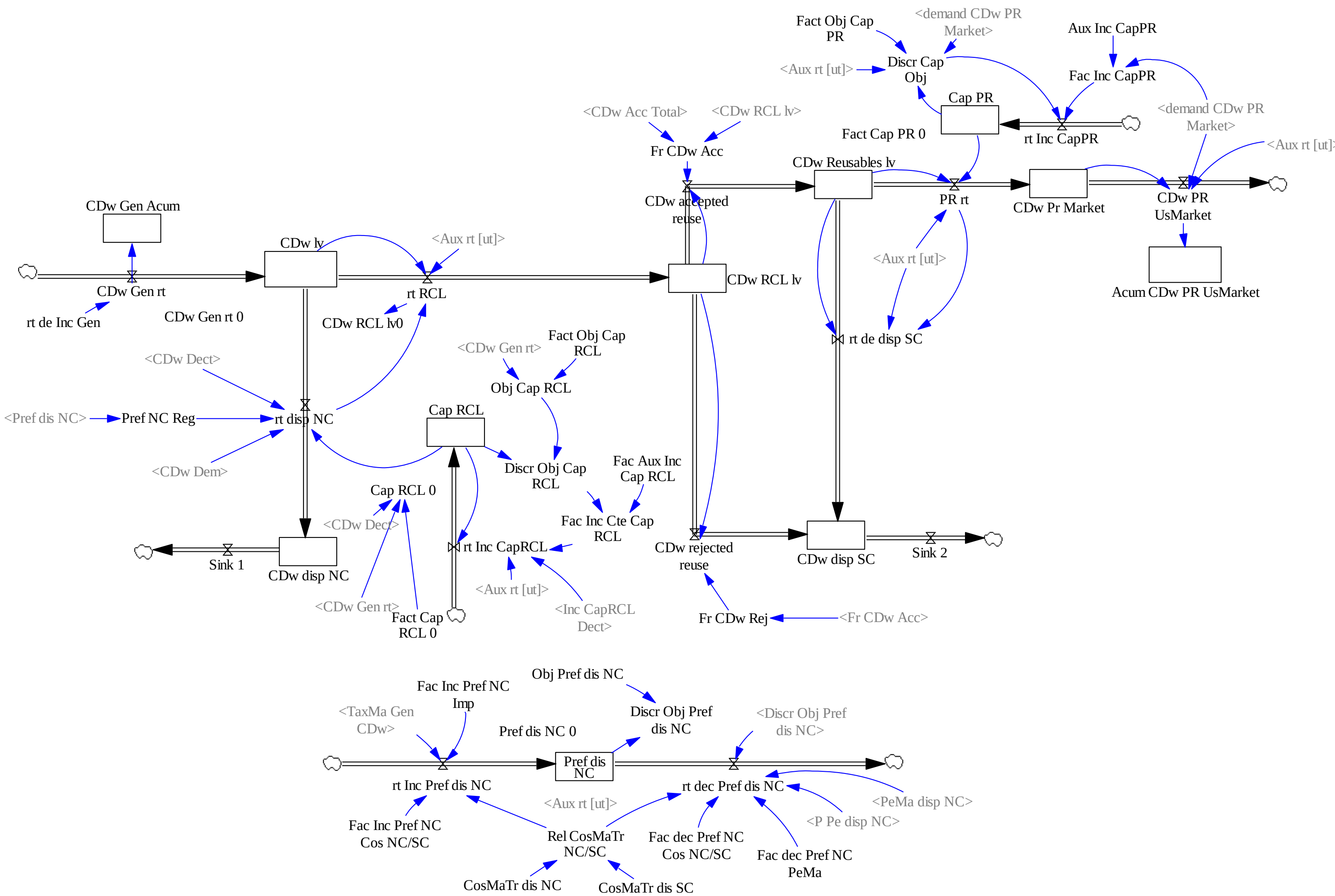


Figure 3. Forrester diagram for module 1
Own elaboration

Module 2: Logistics strategies

According to what was exposed before, the scope of the model considers the evaluation of two types of logistic strategies:

- ✓ Conventional Demolition (Classification in collection center)
- ✓ Selective Demolition (Deconstruction)

In order to incorporate the logistic strategies within the model, and their expected impact over the systems variables shown in Table 3 were included.

Table 3 Variables include for logistics strategies module

Notation	Definition	Type	Dimension
$Fr\ CDw\ Dect$	Fraction of C&D waste to be deconstructed	Cte.	[1]
$Fr\ CDw\ Dect\ 0$	Initial fraction of C&D waste to be deconstructed	Cte.	[1]
$Fr\ CDw\ Dem$	Fraction of C&D waste to be conventionally demolished	Cte.	[1]
$Fr\ CDw\ Dem\ 0$	Initial fraction of C&D waste to be conventionally demolished	Cte.	[1]
$rt\ Inc\ CDw\ Dect$	Rate of increase of fraction of C&D waste to be deconstructed	Cte.	[1]
$Grad\ Inc\ CDw\ Dect$	Degree of constant increase over the rate of deconstruction	Cte.	[1/month]
$Obj\ Fr\ CDw\ Dect$	Objective fraction of C&D waste to be deconstructed	Cte.	[1/month]
$Discr\ Obj\ Fr\ CDw\ Dect$	Discrepancy between $Fr\ CDw\ Dect$ and $Obj\ Fr\ RCD\ Dect$	Aux.	[1/month]
$Aux\ rt\ [ut]$	Auxiliary variable used to convert by equivalence rates to units of 1 / month	Aux.	[1/month]
$Inc\ CapRCL\ Dect$	Increase in the collection rate expected by the implementation of deconstruction strategy	Aux.	[kt/month]
$CteInc\ rtRCLDect$	Constant increase in collected CDw to be deconstructed	Cte.	[1]
$rt\ Dec\ RCD\ Dem$	Decrease of C&D waste demolished	Cte.	$[1/mes^2]$
$CDw\ Dect$	C&D waste coming from deconstruction	Aux.	[kt/month]
$CDwDem$	C&D waste coming from demolition	Aux.	[kt/month]
$CDwDect\ RCL$	C&D waste from deconstruction collected	Aux.	[kt/month]
$CDw\ Dem\ RCL$	C&D waste from demolition collected	Aux.	[kt/month]
$Fr\ Acc\ Dect$	Fraction of C&D waste from deconstruction that is accepted for treatment	Cte.	[1]
$Fr\ Acc\ Dem$	Fraction of C&D waste from demolition that is accepted for treatment	Cte.	[1]
$CDw\ Dect\ Acc$	C&D waste from deconstruction accepted for treatment	Aux.	[kt/month]
$CDw\ Dem\ Acc$	C&D waste from demolition accepted for treatment	Aux.	[kt/month]
$\%Inc\ Costo\ Oper\ Dect$	Constant percentage of increase of operating costs for moving from conventional demolition to deconstruction	Cte.	[1]

Notation	Definition	Type	Dimension
Inc Cost Oper CDw Dect	Percent increase in operating costs for moving from conventional demolition to deconstruction	Aux.	[1]

Source: own elaboration

A logistics strategy would be configured by defining the variables shown in Table 4

Table 4. Variables that make up a logistics strategy

Variable	Description
Obj Fr RCD Dect	Objective fraction of C&D waste to deconstruct
Grad Inc de RCD Dect	Degree of constant increase that brings the deconstruction rate

Source: own elaboration

Figure 4 shows the causal diagram and Figure 5 the Forrester diagram for module 2, this is focused on the decision of how much of the C&D waste generated in the system should be deconstructed, and how fast that transition, form demolition to deconstruction is expected to be.

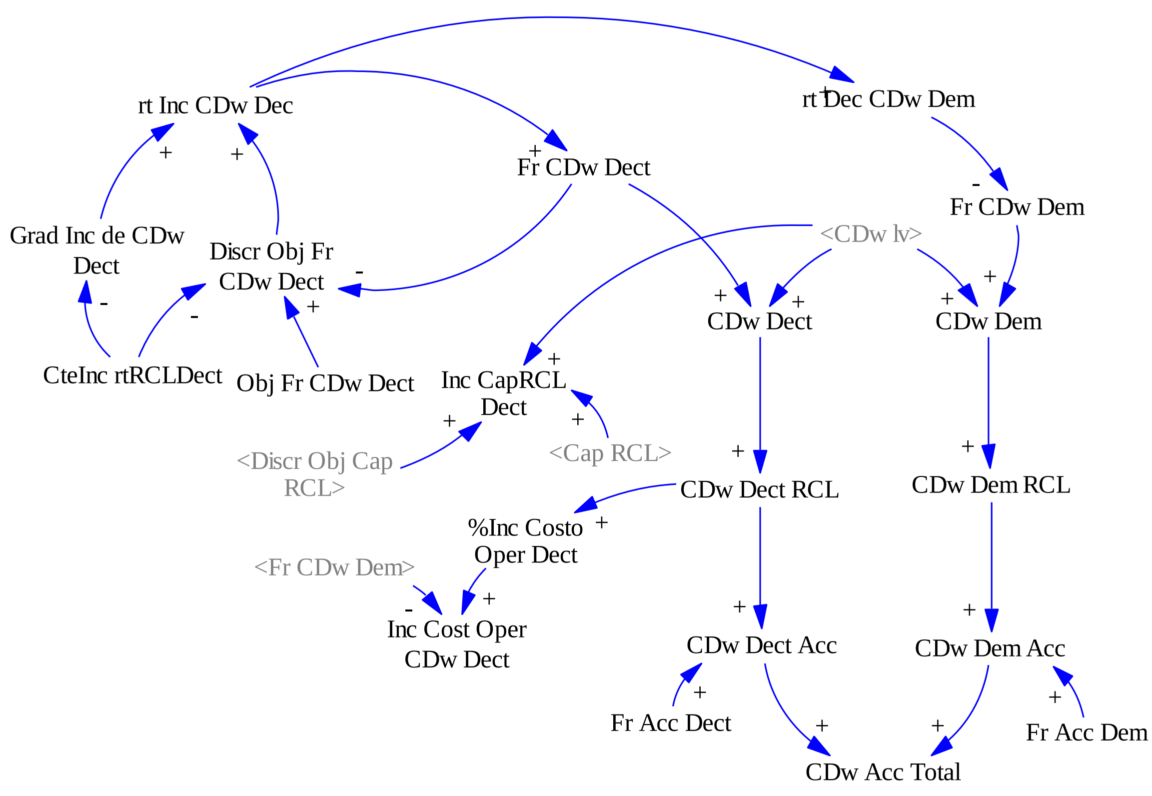


Figure 4. Causal loop diagram for module 2
Own elaboration

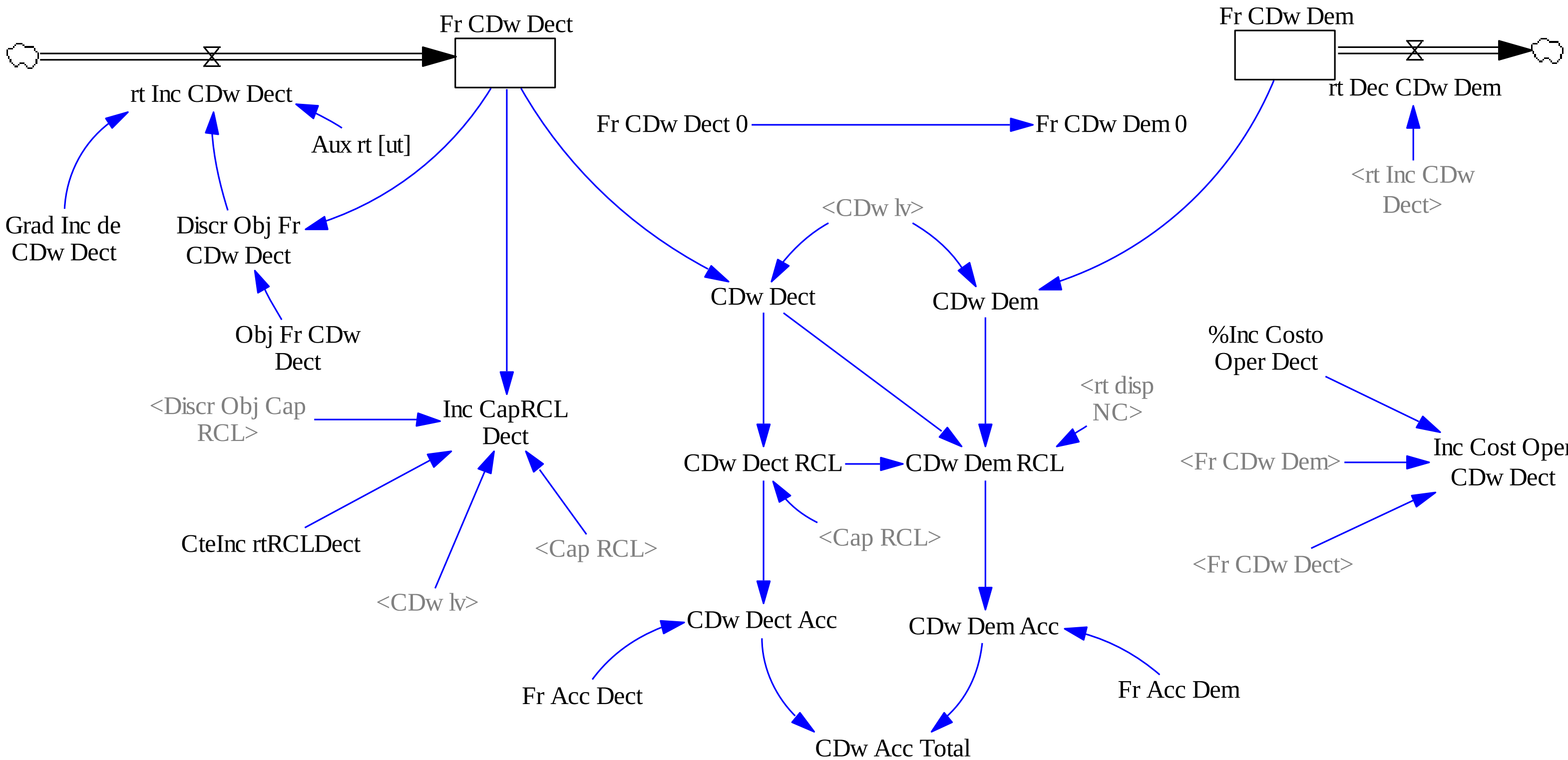


Figure 5. Forrester diagram for module 2
Own elaboration

Module 3: Regulatory Strategies

According to Karavezris (2007), cited by Yuan (2012), governments play a crucial role in promoting C&D waste management practices through the strengthening of industry-wide regulations, in various regions such as Shenzhen, China, Governmental regulations have been identified as the most important factor driving the management of C&D waste, Lu & Yuan (2010).

The search for economic efficiency through the inclusion of external costs in the productive system has generated different environmental policy instruments (Rodríguez Camargo, 2008), those are classified as legal instruments (environmental conditioning or standards) and market economy oriented instruments (emission taxes, emissions certificates, offsets), a third classification consisted of the combination of those instruments (emissions trading).

As for the case of logistic strategies, the regulatory strategies to be studied were basically delimited to:

- ✓ Penalty policies aiming to promote 3R actions (reduce, reuse and recycle), in the management of waste C&D or environmental taxes with tax penalties that increase collection (ER1)

- ✓ Incentive or regulatory policies aimed at promoting 3R or incentive taxes created to change the behavior of producers and / or consumers (ER2)

To incorporate the impact of regulatory strategies within the system, variables shown in Table 5 were included.

Table 5. Variables included for the regulatory strategies module

Notation	Definition	Type	Dimension
$ER\ 1$	Degree in which the regulatory strategy is implemented 1, Three levels are proposed for the model (High: 1, Medium: 1/3: Null: 0)	Cte.	[1]
$ER\ 2$	Degree in which regulatory strategy is implemented 2, Three levels are proposed for the model (High: 1, Medium: 1/3: Null: 0)	Cte.	[1]
$Cos\ Pe\ disp\ NC\ Nv$	Level of penalties paid for uncontrolled provision accumulated during the planning horizon	Level	[$]

Notation	Definition	Type	Dimension
$Imp\ RCD\ gen\ Nv$	Level of taxes paid by C&D waste generation accumulated during the planning horizon	Level	[$]
$Pe\ ExcLimRCL$	Level of penalties paid for exceeding the acceptable limits of cumulative disposal during the planning horizon	Level	[$]
$Ts\ Acum\ Cos\ Pe\ dis\ NC$	Rate of accumulation of penalty costs by uncontrolled disposal	Rate	[$/month]
$Ts\ Acum\ Imp$	Rate of accumulation of cost of taxes by generation of C&D waste	Rate	[$/month]
$Ts\ Acum\ Pe\ Exc\ LimRCL$	Rate of accumulation of cost of penalties for exceeding acceptable limits of disposal	Rate	[$/month]
$Costo\ Pe\ disp\ NC$	Costs of penalty by uncontrolled provision	Aux.	[$/month]
$PeMa\ Disp\ NC$	Marginal penalties for uncontrolled disposal	Aux.	[$/kt]
$P\ Pe\ disp\ NC$	Probability of assigning penalties for uncontrolled (unlawful)		
$PeMa\ NC\ smmlv$	Random variable that defines the marginal cost of penalty by uncontrolled	Aux.	[1/kt]
$Oper\ Control\ dNC$	Control operations carried out to find illegal disposal of C&D waste	Level	[operativo]
$Oper\ Control\ dNC0$	Control operations carried out at the initial moment to find illegal disposal of C&D waste	Cte.	[operativo]
$Ts\ Inc\ Oper\ Control$	Rate of increase of realization of control operations	Rates	[operativo /mes]
$Ts\ Reinv\ Oper\ Control$	Rate of investment of the payment of penalties that is invested in increasing the number of operations per month	Aux.	[operativo /mes]
$OpEr/smmlv$	Factor in which the control operations increase for each smmlv (Minimum monthly salary) that is paid through penalty for illegal disposal	Cte.	[1]
$smmlv$	Minimum Monthly Legal Salary Effective in Colombia for 2017, in millions of COP	Cte.	[$]

Notation	Definition	Type	Dimension
$Fac\ P\ Pe\ OpCon$	Factor in which the probability of assigning penalties to Non-Controlled provisions increase for each control operation performed	Cte.	[1/operative]
$MaTax\ Gen\ RCD$	Marginal tax for C&D waste	Aux.	[$/kt]
$Fac\ MaTax$	Factor used to calculate the $ImpMa\ Gen\ RCD$ consistent with the degree of implementation of the regulatory strategy ER 1	Cte.	[$/kt]
$LimRCL$	Acceptance limit accepted by regulation	Cte.	[kt/month]
$PeMa\ exc\ LimRCL$	Marginal penalty for exceeding the acceptance limit established by regulation established for ER1	Aux.	[kt/month]
$Fac\ PeMa\ LimRCL$	Factor used to calculate $PeMa\ exc\ LimRCL$ consistent with the degree of implementation of the regulatory strategy ER1	Cte.	[$/kt]
$IncenMa$	Marginal incentive for the use of treated C&D waste	Aux.	[1]
$FacIncenMa$	Marginal incentive factor for the use of C&D waste used to calculate the IncenMa depending on the degree of ER2 implementation	Cte.	[1]
$InMa\ Inc\ Ts\ Us\ RCD\ PR$	Percentage of IncenMa evaluated as a function of the discrepancy between the use of waste C&D treated in the market and its target value	Aux.	[1]
$\%Obj\ Us\ RCD\ Pr$	Percentage of consumption of processed C&D waste in relation to the generated C&D waste	Cte.	[1]
$Obj\ Us\ RCD\ Pr\ Mdo$	Net consumption target of C&D waste processed against C&D waste generated	Aux.	[kt/month]
$Discr\ UsMdo\ Obj\ \%$	Discrepancy between the use of waste C&D treated in the market and its target value	Aux.	[1]
$Inc\ Ts\ Us\ RCDRP\ ER2$	Increase in the rate of use of C&D waste treated in the market as a consequence of the incentives provided by ER2	Aux.	[kt/month]

Notation	Definition	Type	Dimension
$Fac\ UsMin\ RCD\ PR$	Percentage of minimum use of reprocessed C&D waste in the market	Cte.	[1]
$Ts\ Inc\ UsMdo$	Rate of increase of consumption of waste C&D treated in the market	Aux.	[kt/month]
$Inc\ Ts\ Us\ RCDRP\ OF$	Increase in the rate of use of C&D waste treated in the market as of other factors	Aux.	[kt/month]
$Fac\ Inc\ Ts\ Inc\ Us\ RCD\ Pr\ OF$	Factor of increase in waste C&D consumption treated by market conditions external to regulatory strategies	Cte.	[1]
$Demanda\ RCD\ PR\ Mdo$	Demand for processed C&D waste treated	Level	[kt]
$Demanda\ RCD\ PR\ Mdo\ 0$	Initial demand for processed C&D waste	Cte.	[kt]

Source: Own elaboration

Penalty policies are expected to affect mainly the rate of uncontrolled disposal, as there are fines associated with the illegal dumping of waste.

Law 1333 of 2009 in Colombia establishes the environmental sanction procedure; it defines penalties to those responsible for environmental infractions that include fines of 5000 smmlv, closure of establishments, and even demolition at the expense of the offender (Congreso de la República de Colombia, 2009). The uncontrolled provision refers specifically to the unlawful disposal, so the evaluation of penalty strategies would be directly related to this rate. Figure 7 shows the Forrester diagram conceived for the inclusion of this module into the model.

A regulatory strategy would be configured by defining the variables shown in Table 7.

Table 6. Variables that make up a regulatory strategy

Variable	Description
$ER\ 1$	Implemented degree of regulatory strategy 1: Taxes / Penalties
$ER\ 2$	Implemented degree of regulatory strategy 2: Incentives

Source: own elaboration

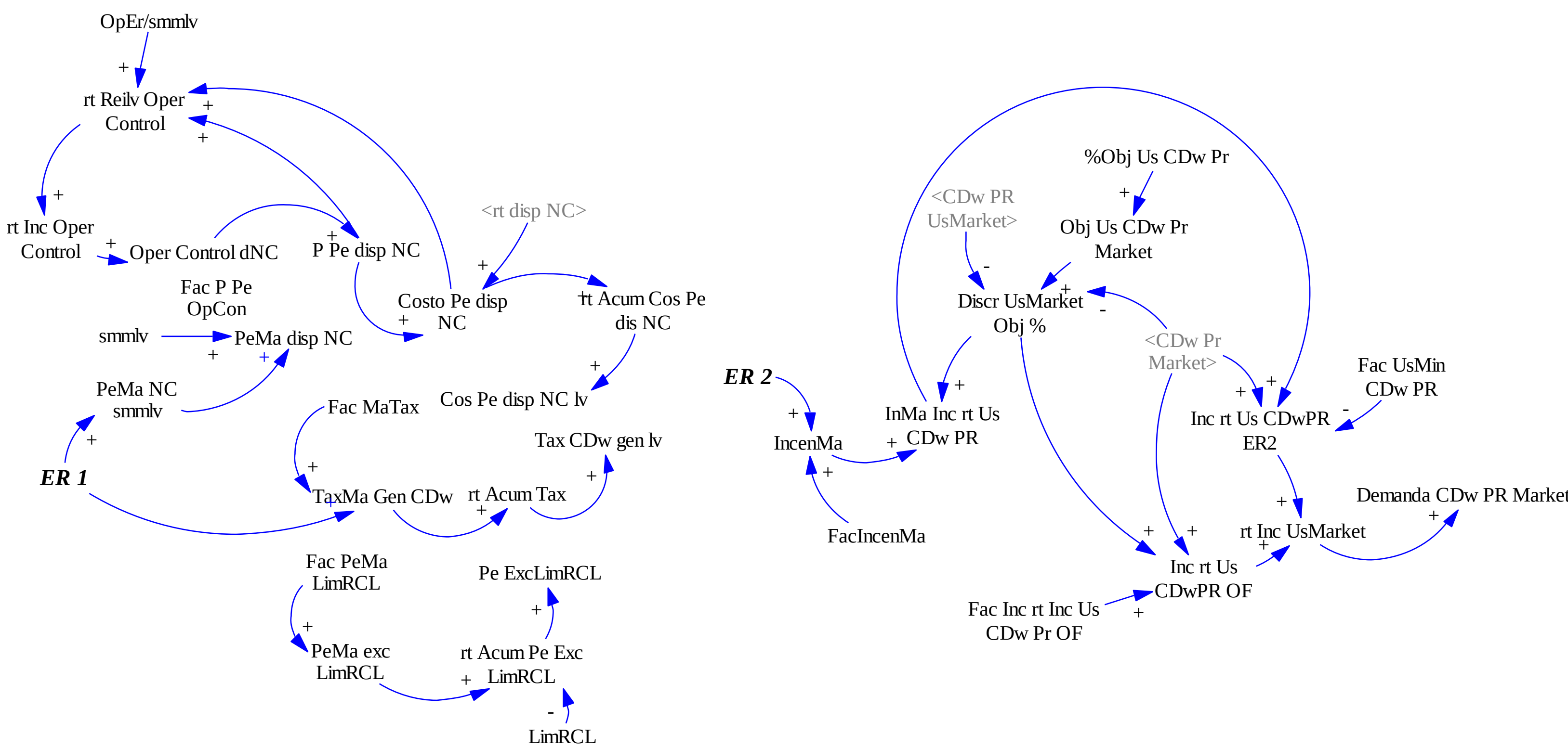


Figure 6. Causal loop diagram for module 3

Own elaboration

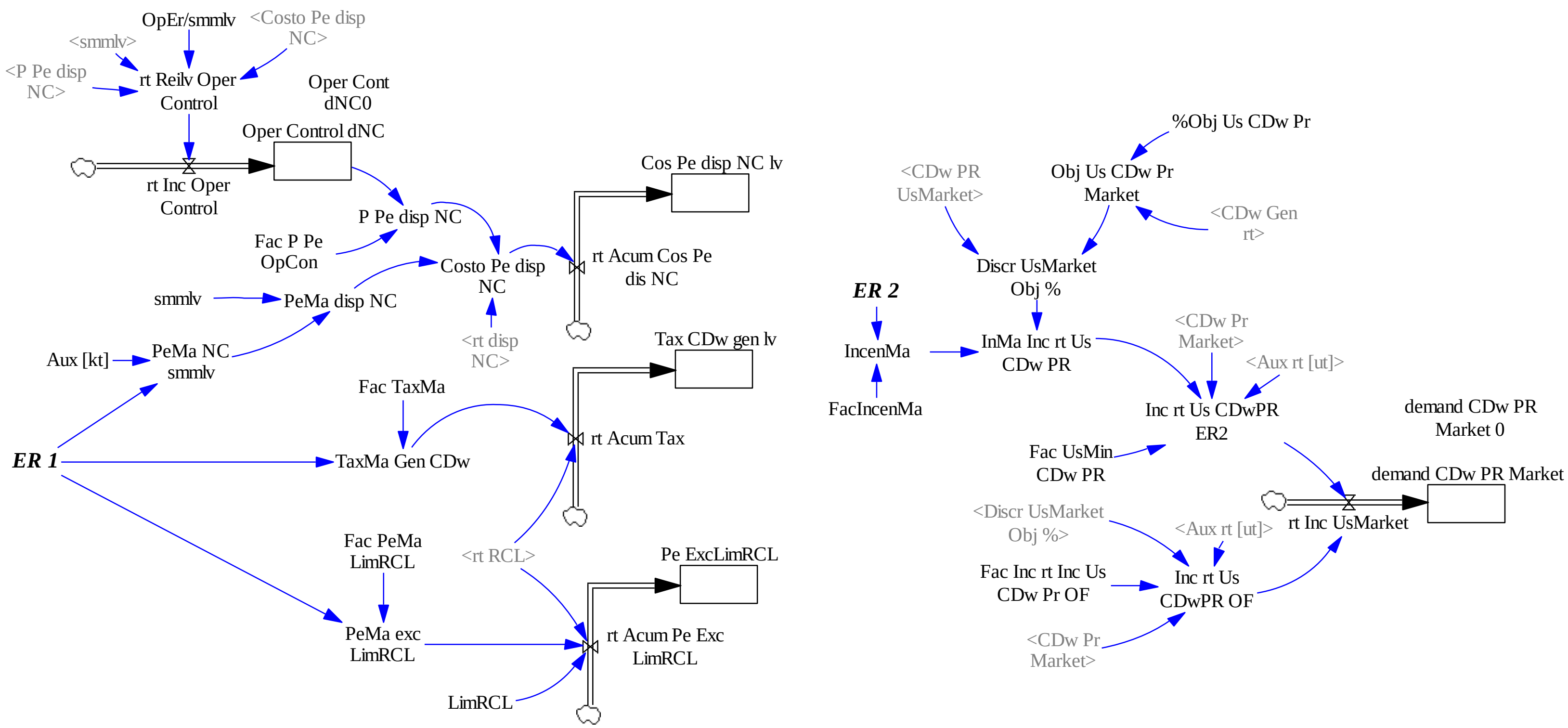


Figure 7. Forrester diagram for module 3
Own elaboration

Module 4: System of indicators

The development System of indicators module is based on several authors. In particular the studies of Yuan, H., Chini, A., Lu, Y., Shen, L. (2012), Calvo, Varela-Candamio, & Novo-Corti (2014), and Yuan (2012), were taken as framework. The indicators included in the model were previously shown in Table 1.

The articulation of these indicators with the central module of generation and management of waste C&D gives rise to new variables, interrelations and causal loops. Those variables are presented in Table 7, while the Forrester diagram associated with the module is shown in Figure 9.

Table 7. Variables included for the system of indicators module

Notation	Definition	Type	Dimension
$SOIx1$	Estimation of jobs generated for the management and management of waste C&D during the planning horizon (simulated period)	Aux.	[jobs]
$SOIx2$	Degree of satisfaction of the population in terms of the perception of the management of waste C&D in the City	Aux.	[%]
$ENIx1$	Volume of landfill consumed by disposal of C&D waste, either by controlled or uncontrolled disposal	Aux.	$[m^3]$
$ENIx2$	Volume of water sources affected by the disposal of C&D waste, is associated with the uncontrolled disposal	Aux.	$[m^3]$
$ECIx1$	Economic recovery of C&D waste. It is measured as the equivalent fraction of C&D materials that are used in the industry from waste C&D treatment activities after discounting the costs of the related operations, also considering them as a fraction of C&D waste.	Aux.	[%]
$ECIx2$	Cost of treatment and recovery operations carried out during the planning horizon. It consists of demolition costs and deconstruction costs considered in a generic way	Aux.	[$]
$ECIx3$	Cost of transportation of waste C&D generated during the planning horizon, these include those addressed to both the controlled and uncontrolled disposal	Aux.	[$]
$Emp\ RCD\ RCL$	Jobs generated to handle the controlled collection of C&D waste	Cte.	[jobs/kt]
$Emp\ RDC\ PR$	Jobs generated to handle the processing capacity available in the system	Cte.	[jobs/kt]
$Emp\ Opr\ Dect\ Dem$	Jobs generated by demolition and deconstruction activities	Aux.	[jobs]
$EmpMa\ Cap\ RCL$	Jobs generated per unit of C&D waste collected	Cte.	[jobs/kt]

Notation	Definition	Type	Dimension
$EmpMa\ Cap\ PR$	Jobs generated for per unit of processed C&D waste	Cte.	[jobs/kt]
$EmpMa\ Opr\ Dect$	Jobs generated per unit of C&D waste conventionally demolished	Cte.	[jobs/kt]
$EmpMa\ Opr\ Dem$	Jobs generated per C&D waste unit deconstructed	Cte.	[jobs/kt]
$vv\ disp\ SC$	Volume of landfill used per C&D waste unit in its controlled disposal	Aux.	[m^3]
$vt\ disp\ NC$	Volume of land used per C&D waste unit in its uncontrolled disposal	Aux.	[m^3]
$Fr\ RCD\ disp\ NC\ FH$	Fraction of water sources affected by uncontrolled disposal per waste C&D unit	Cte.	[1]
$Fac\ RecEC\ PR$	Recovery factor of C&D waste by equivalence with recovery of economic value per kt processed with exit to the market	Cte.	[1]

Source: Own elaboration

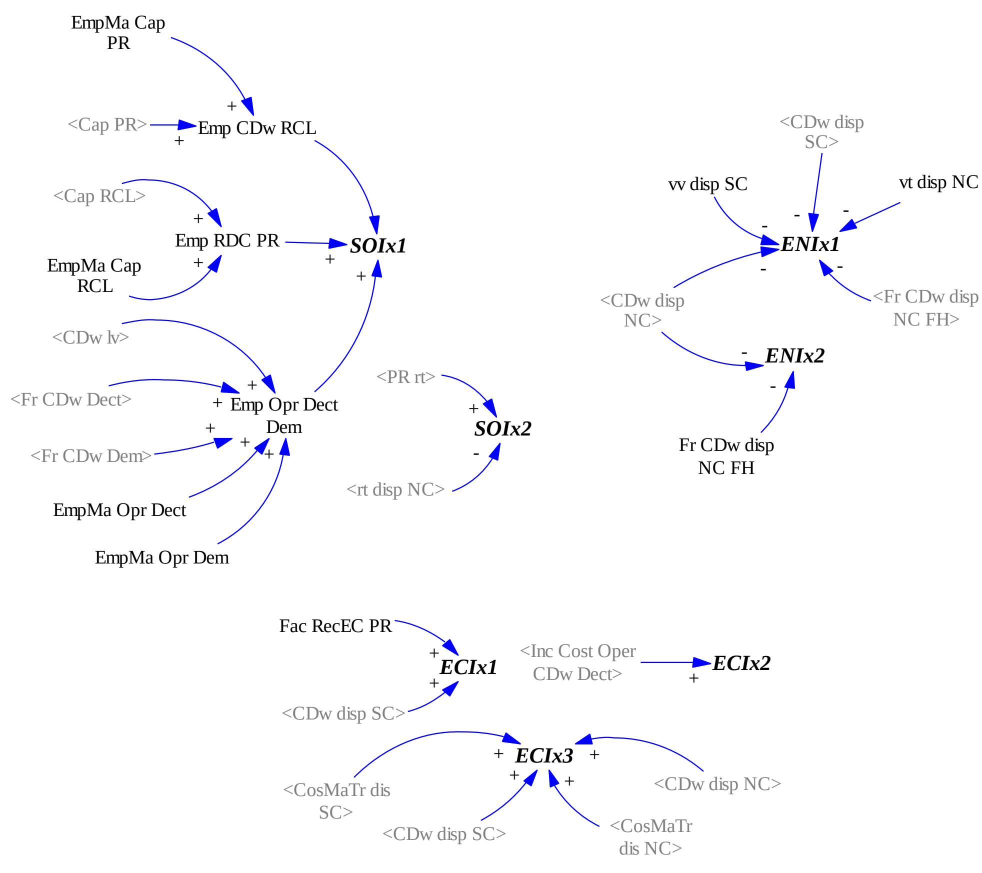


Figure 8. Causal diagram for module 4
Own elaboration

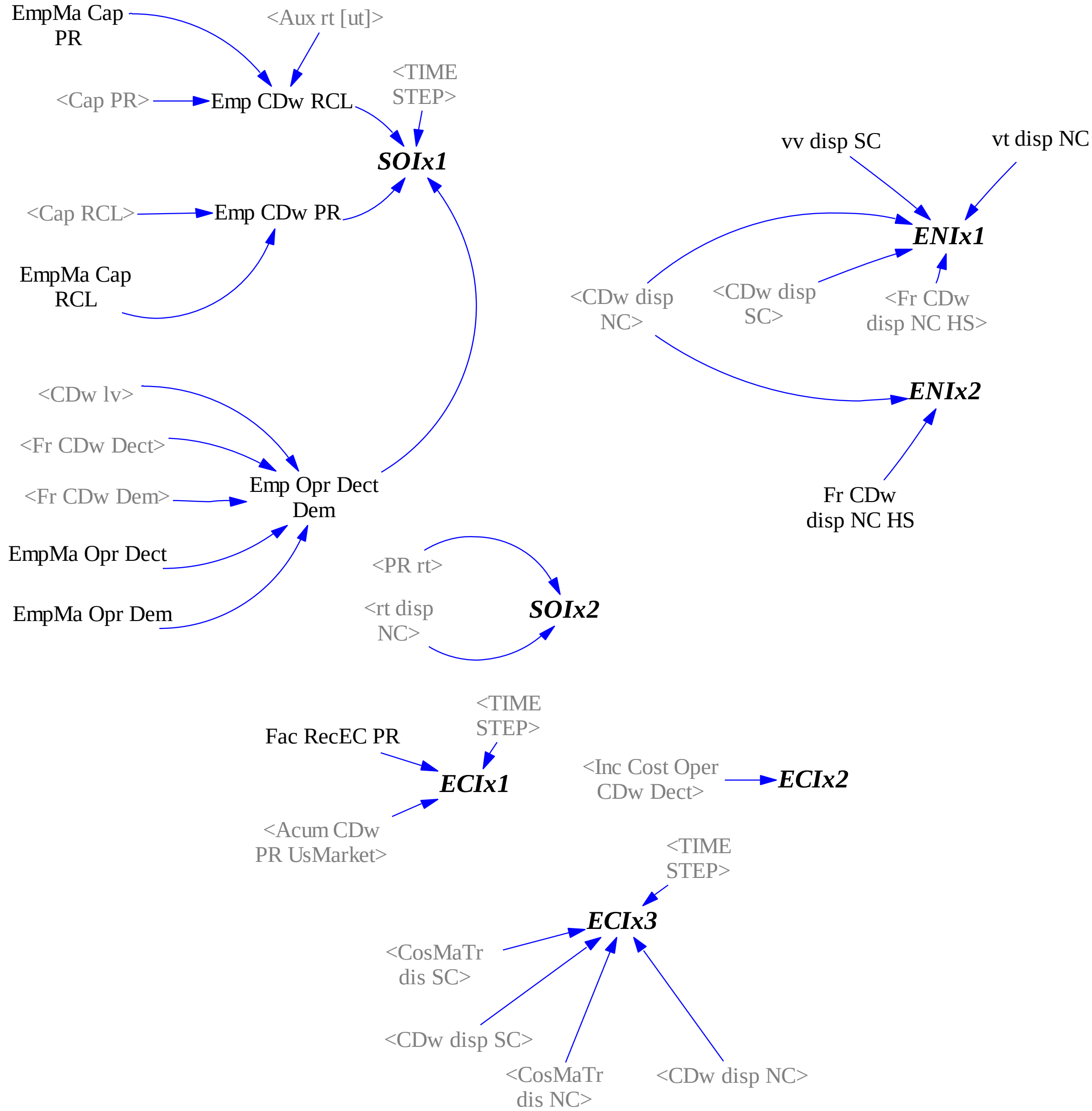


Figure 9. Forrester diagram for module 4
Own elaboration

Simulated scenarios

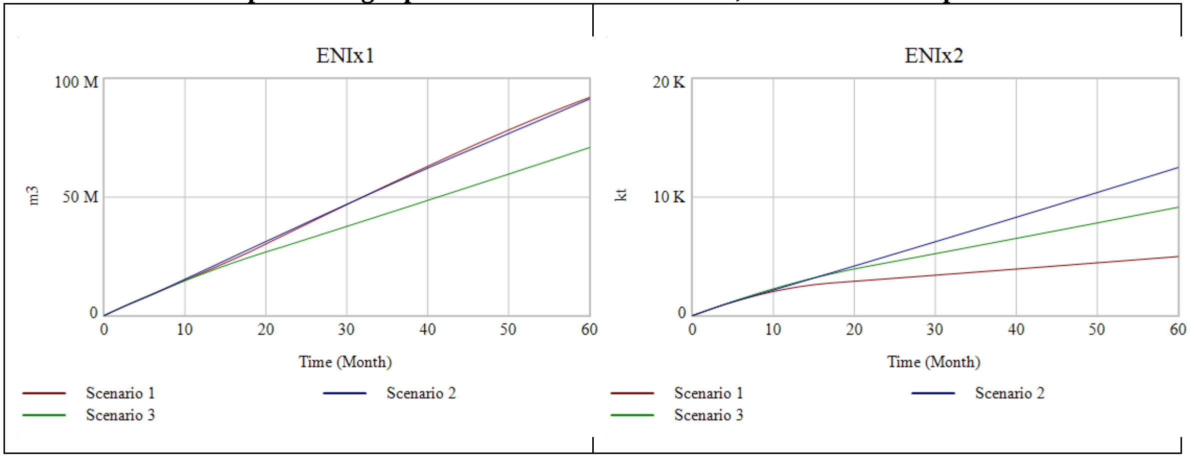
The first of the simulated strategies consists of a scenario in which a 33% degree of implementation of taxes and penalties policy is fixed, which leads to relatively low values in those aspects. The strategy of deconstructing is privileged by setting up its target value in 80% and its gradual implementation rate at 5% per month. No incentives were considered.

The second of the simulated strategies consists of a scenario in which a degree of 100% implementation of tax and penalties policy is established. Deconstruction strategy is fixed in a low value of 20% and its gradual implementation rate at 5% per month. No incentives were considered.

The third one consists of a scenario with a 33% degree implementation of taxes and penalties. Deconstruct strategy is set up in a medium value of 50% and its gradual implementation rate at of 2.5% monthly. Incentives were set up at a degree of 100% of their maximum values stablished.

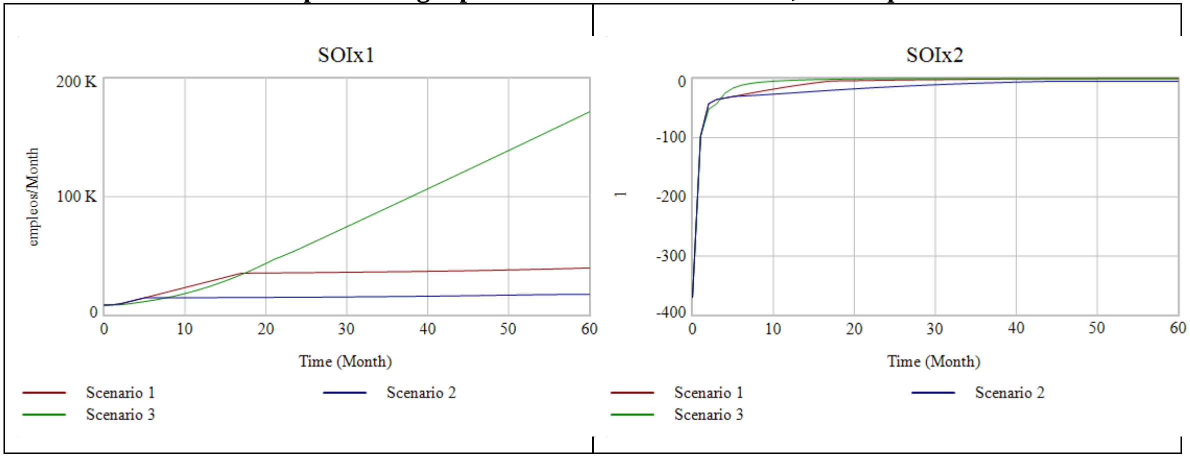
The results obtained after running a 60 month length simulation of this scenarios are shown in the graphs included in Tables 8, 9 and 10.

Table 8. Comparative graphs of simulated scenarios, environmental performance



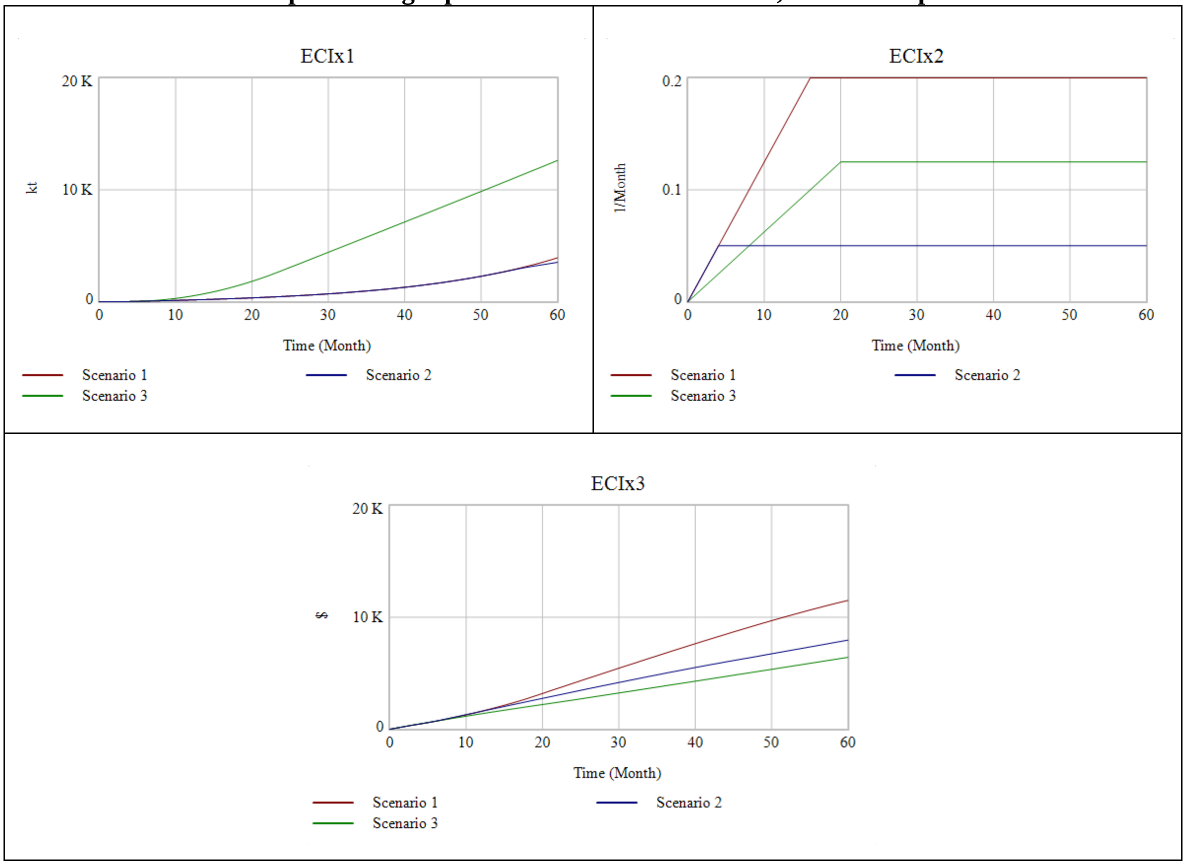
Own elaboration

Table 9. Comparative graphs of simulated scenarios, social performance



Own elaboration

Table 10. Comparative graphs of simulated scenarios, economic performance



Own elaboration

Conclusions

The dynamic model for contrasting management strategies of Construction and Demolition Waste was proposed articulating four modules interrelated with each other, one of the modules integrates the system of indicators to contrast the performance of the strategies to be evaluated.

The review of the literature allowed us to identify that there is an interest to provide different performance management frameworks for waste management, with special emphasis on one or more of the component dimensions of sustainability. They are presented from different disciplines or approaches and were an essential input for the integration of the proposed model.

Within the strategies studied for waste management, it is possible to speak of two broad categories, some of which include logistical or operational aspects conceived within the industry and its component links and others of an external nature, which are usually established by Governments, such as regulation and normative, that includes incentive strategies or penalties for the results of waste management in the construction and demolition sector.

Since the impact of construction and demolition waste management is likely to be categorized in the environmental, economic and social areas, it was possible to define a system of indicators that would include indexes specific to each of these. Integrative indicators for each dimension were proposed to evaluate the strategies in terms of its sustainability performance.

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