The importance of feedback loops designing environmental policies for sustainable development

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This article examines the impact of environmental legislation on sustainability that manifests through the conservation of natural resources and landfills. The developed model is implemented to a real world closed-loop supply chain with recycling activities of electrical equipment in Greece. The motivation behind this research is to examine whether the environmental legislation should be considered as an endemic process of the system under study or introduced without considering the "Limits" issues. We adopt System Dynamics methodology applied to many environmental systems. Numerical analysis illustrates that the consideration of the endemic process and the expansion of the environmental regulations in order to include also measures for the products' recyclability and recycled content improves significantly the efficiency of the environmental legislation on sustainability.

Keywords: Sustainable Development; Environmental Legislation; Closed-Loop Supply Chains; System Dynamics

1 Introduction

In 1970 Forrester presented the ''equilibrium run'' of his world model (Forrester, 1971) to members of the Club of Rome. He stated that stabilizing production at levels compatible with the limited environmental capacity of our planet is essential to avoid overshoot and subsequent decline in the world system. Later, the Brundtland commission changed Forrester's "equilibrium" into "sustainable development" (Angell and Klassen, 1999).

Nowadays the development of technology has enabled the industry to produce a plethora of products resulting in the depletion of natural resources and indiscriminate disposal habits (Gupta, 1995). Furthermore, ecological problems such as the climate change, global warming, acid rain, diminishing raw material resources and overflowing landfills are realities of our modern life; hence sustainability is emerging as one of crucial topics. This article deals with two specific aspects of sustainability, the conservation of natural resources and landfills.

To prevent the extinction of both available natural resources and landfills, environmental legislation has been introduced forcing the producers to take-back their products after their end-of-use and to recover the value still incorporated. The

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environmental regulations usually impose minimum collection and recycling percentages. However, the introduction of the regulatory measures occurs usually externally without considering the rates of natural resources' usage and used products' disposal; would sustainability be promoted if the environmental legislation was introduced as internal variable by taking into consideration these two rates? It is also noteworthy that the environmental regulations are confined to take-back and recovery measures ruling out any measures regarding the Design for Environment (DfE) practices (e.g., the products' easy disassembly) (Directive, 2002, Bloemhof-Ruwaard *et al.*, 2004).

Due to the enforcement of environmental regulations and the consumers' pressures for the greening of the industry, many firms have asserted sustainability as one of their main strategic priorities (González *et al.*, 2003) and they are going "green" by developing closed-loop supply chains activities, designing "green" products and using recycled materials rather than natural resources. The tremendous interest on sustainability resulted in the development of several models focused on the optimization of firms' green operations. However, only few authors have holistically dealt with the concept of reverse logistics (RL) and DfE (Carter and Ellram, 1998). For example, Krikke *et al.* aim at the cost and waste minimization produced by the supply chain's operations (Krikke *et al.*, 2003). Biehl *et al.* simulate a carpet closed-loop supply chain to analyze the impact of the products' recyclability (percentage defining how recyclable a product is) and legislation affecting the system's operational performance (Biehl *et al.*, 2007). It is remarkable that the existing environmental regulation does not impose separate measures for recycling percentage and recyclability or a minimum limit of recycled content (percentage of recycled materials found in one kilogram of finished product). To investigate whether these omissions decrease the policy's efficiency, their impact on sustainability should be examined.

In this article we propose a model of a single product closed-loop supply chain with DfE and recycling activities that operates under the pressure of environmental regulations. The motivation behind this research is twofold: first, to examine whether the environmental legislation should be considered as an endemic process of the system under study or introduced externally without taking into consideration the rates of the natural resources' usage and the used products' disposal and second, to examine the efficiency of different types of environmental legislation on sustainability in order to direct the policy at the right mix of regulatory measures.

The analysis tool used here is System Dynamics (SD) methodology. In the 1960's Forrester includes a model of supply chain as an early example of the SD methodology (Forrester, 1961). Towill uses SD in supply chain redesign (Towill, 1995). Gonçalves *et al.*'s model incorporates endogenous demand (Gonçalves *et al.*, 2005). Sterman presents two case studies to model RL problems (Sterman, 2000). Georgiadis and Vlachos evaluate the effect of environmental issues on RL activities (Georgiadis and Vlachos, 2004). Van Schaik and Reuter's model reveals that the realization of the legislation targets imposed by European Union (EU) depends on the cars' design (van Schaik and Reuter, 2004). SD has been also used for long-term decision-making of environmental systems. By 2003, 10% of the SD publications have dealt with environment or resources (Cavana and Ford, 2004). The number of publications increased in the 1970's due to the tremendous interest of "World Dynamics" (Forrester, 1971) and "Limits to Growth" (Meadows *et al.*, 1972). Then Acharya and Saeed developed a model based on the original "Limits" study (Acharya and Saeed, 1996), which includes regeneration of resources. Jones *et al.* studied the resource unsustainability of commodity systems in the forest ecosystem of the Northeastern US (Jones *et al.*, 2002). The Sustainability Institute's Report in 2003 deals with commodity systems to insure their long-term sustainability (Sustainability Institute, 2003).

Section 2 presents the structural elements of the system under study, while section 3 presents the comprehensive SD model. In section 4 the model is tested empirically by implementing it to a real world closed-loop supply chain of electrical equipment in Greece. Numerical analyses reveal the importance of feedbacks for the introduction of efficient environmental legislation (section 5). In section 6 sensitivity analyses investigate the impact of different types of environmental legislation on preserving natural resources and landfills. Finally, in section 7 we present our conclusions.

2 The System under Study

Figure 1 depicts the system under study that incorporates the following activities: procurement of natural resources, production, distribution, product use, collection of used products, recycling and disposal.

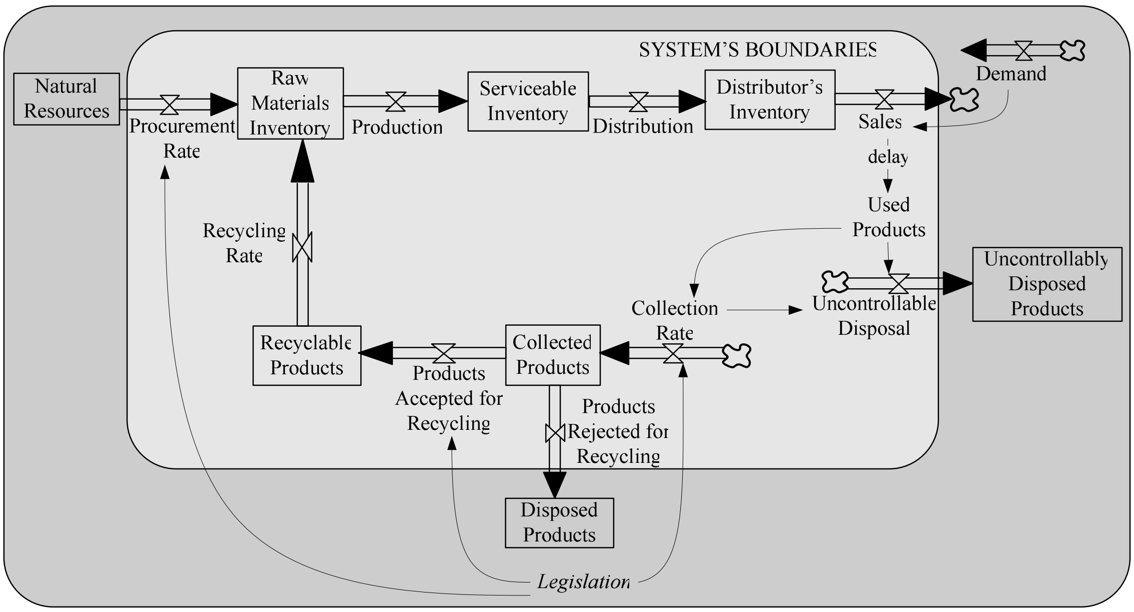

Figure 1: Structure of the Closed-Loop Supply Chain

The forward supply chain comprises two echelons: producer and distributor. The producer's demand for raw materials is satisfied with a mix of natural resources (procurement rate), provided by external suppliers, and recycled materials deriving from the firm's recycling operations (recycling rate). Production increases the serviceable inventory, and distribution depletes the serviceable inventory and increases the distributor's inventory. The distributor's inventory is depleted to satisfy demand. Sales turn into used products after their usage time and they are either collected or uncontrollably disposed. The collected products are inspected and they are either accepted for recycling (recyclable products) or rejected (disposed products). White goods (like refrigerators and dryers), tires and photo films (Vlachos *et al.*, 2007), vehicles (Gupta, 1995), bumpers (Gupta, 1995), batteries (Pappis *et al.*, 2004), sand (Barros *et al.*, 1998) and household waste (Chang and Wei, 2000) are representative examples of products that fit the above description.

The inventories in the system of Figure 1 are managed by a "pull-push" policy. We adopt a "pull" policy in the forward channel to maintain better stock control (van der Laan *et al.*, 1999), while we use a "push" policy in the reverse channel to express the pressure of local governments on manufacturers to reduce the used product flows going into landfills (Biehl *et al.*, 2007).

In Figure 1 the material flows are the outcome of corresponding decision-making processes. Collection, recycling and natural resources' procurement rates are determined by a decision-making process also influenced by environmental legislation. We assume that the environmental legislation imposes minimum limits for collection percentage, recycling percentage, recyclability and recycled content. Specifically, it urges a) the increase of the collected products' amount, b) the increase of the recycled products' amount and c) to produce products using recycled materials with priority compared to the original raw materials. The firms develop collection activities to achieve the legislative collection percentage. However, to increase the amount of recycled products the firms should both develop recycling activities (legislative recycling percentage) and design recyclable products (legislative limit of recyclability). Finally, the firms can achieve the legislative limit of recycled content only if the recycled materials are sufficient for the production.

2.1 Conceptual Modeling of Sustainable Development

A system's feedback structure in SD is captured by causal-loop diagrams (Sterman, 2000). For the remaining paper variable names are shown in italics using terms with underscore; this is the requirement of the employed SD commercial software package (Powersim®2.5c).

Figure 2 displays the causal-loop diagram of sustainable development comprised by the conservation of natural resources and landfills. The diagram consists of four balancing feedback loops. Loop1 and Loop2 focus on the preservation of *Landfills_Availability*, while Loop3 and Loop4 focus on the preservation of *Availability_of_Resources*.

Specifically, in Loop1 an increase in *Uncontrollable_Disposal* decreases *Landfills_Availability*, forcing governments to impose stringent *Legislation* through increased collection percentage of used products (*Collection_Percentage*). The *Collection_Percentage* then increase the company's *Collection_Rate* leading to a decrease in *Uncontrollable_Disposal*. The feedback loops Loop2 (*Products_Rejected_for_Recycling→Landfills_Availability→Legislation→Recycling_Percentage→Products_Accepted_for_Recycling*), Loop3 (*Procurement_Rate→ Availability_of_Resources→ Legislation→Limit_of_Recyclability→Products_Accepted_for_Recycling→Available_Recycled_Materials→Procurement_Rate*) and Loop4 (*Procurement_Rate→Availability_of_Resources→Legislation→Limit_of_Recycled_Content→Procurement_Rate*) are built similarly with Loop1.

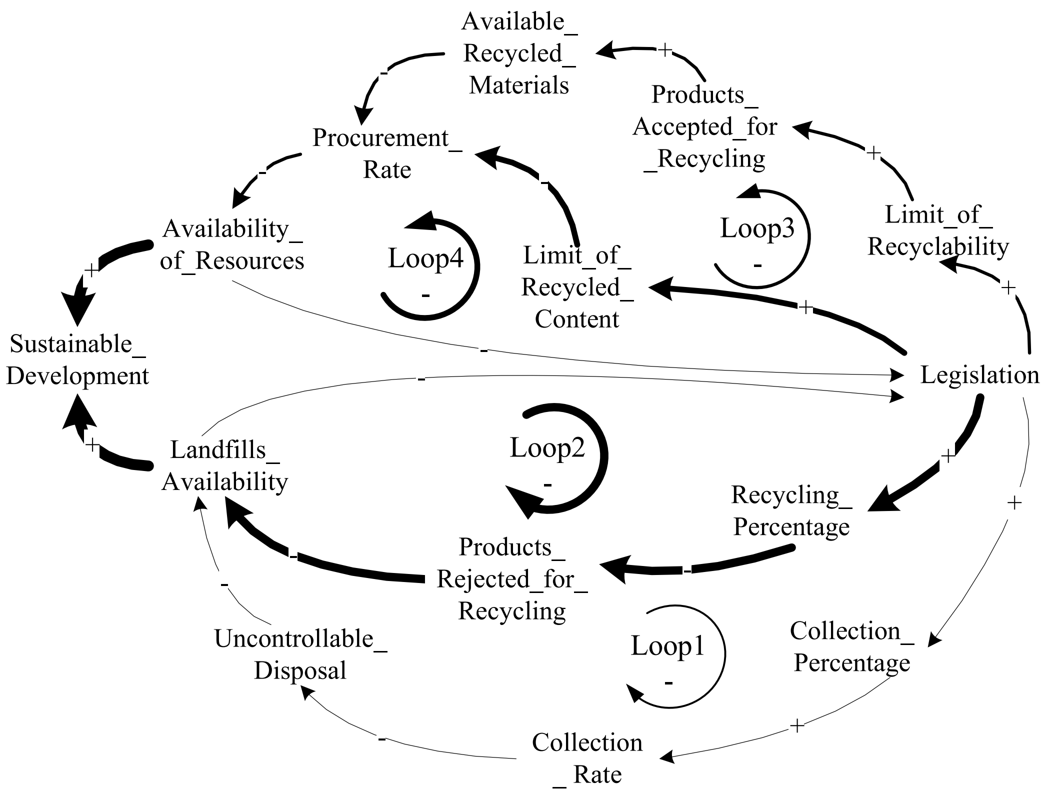

Figure 2: Causal-Loop Diagram of *Sustainable_Development*

3 Model Structure

In this section we present the structure of the SD model. Subsection 3.1 maps the generic causal-loop diagram of the closed-loop supply chain. Because of its importance, the causal links of *Legislation* are presented in the subsection 3.2. Finally, we present the mathematical formulation of the model in the subsection 3.3.

3.1 Generic Causal-Loop Diagram

Figure 3 depicts the causal-loop diagram of the system under study. Variables expressing inventory levels are shown in capital letters, forecasts in small italics and the flow, auxiliary variables and constants in small plain letters. The variable *Legislation*, whose structure is studied in subsection 3.2, is shown in a box.

The forward supply chain begins from the upper left corner of Figure 3. The *Procurement_Rate*, which depletes *Natural_Resources*, and the *Recycling_Rate*, which depletes *Recyclable_Products*, increase the *Raw_Materials_Inventory*. *Procurement_Rate* results from combining the *Expected_Producer's_Orders* and the *Expected_Recycling_Rate* with an adjustment that brings *Raw_Materials_Inventory* aligned with its desired value (stock management structure suggested by Sterman (Sterman, 1989)). The same control rule is used for the rates of *Producer's_Orders* and *Distributor's_Orders*. *Usage_Rate* depletes *Raw_Materials_Inventory*. *Procurement_Rate*, *Recycling_Rate*, *Raw_Materials_Inventory* and *Usage_Rate* are

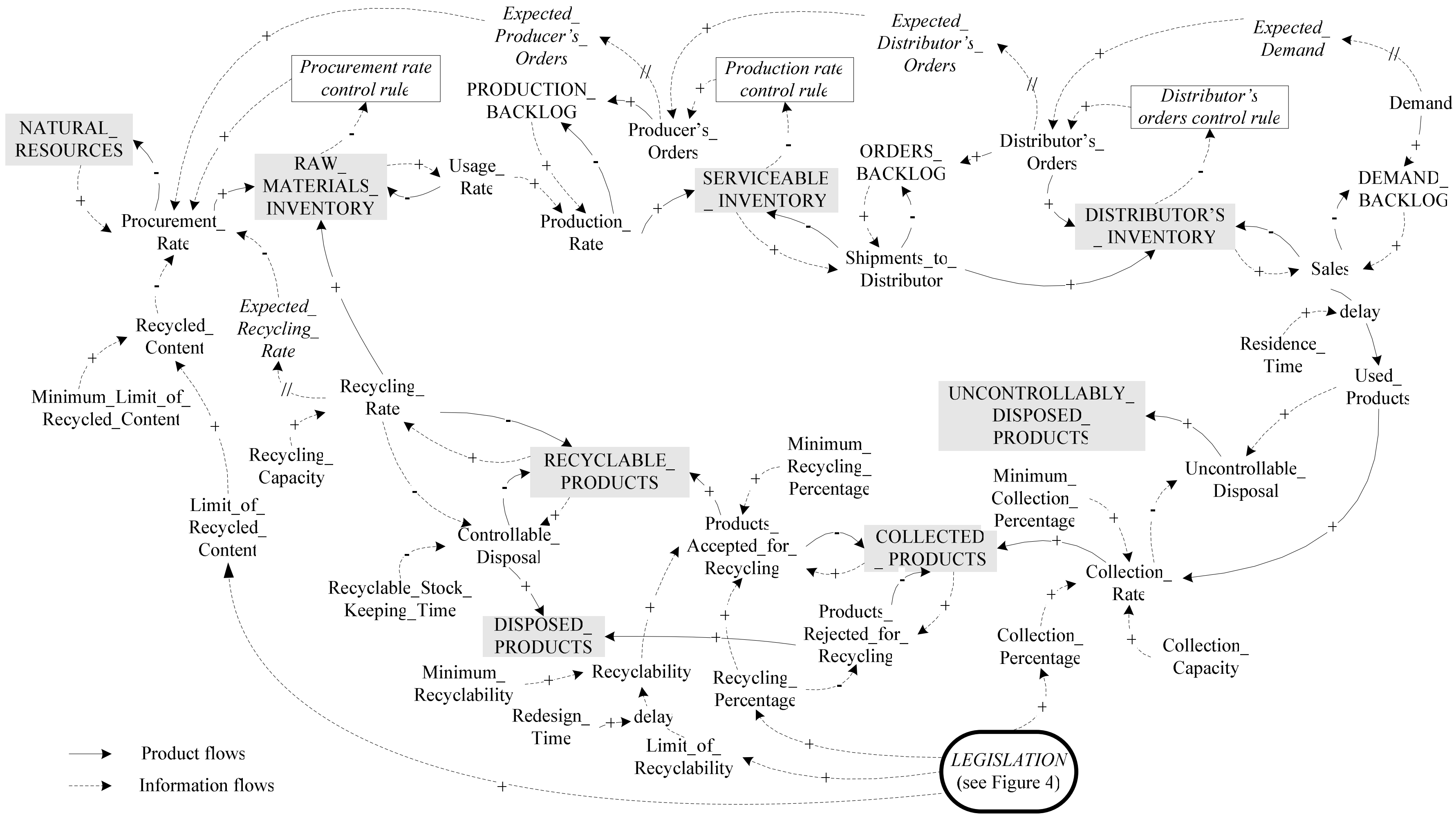

Figure 3: Causal-Loop Diagram of the Closed-Loop Supply Chain

array variables comprising of two dimensions. The two index variables concern the original raw materials (from natural resources) and the recycled materials respectively.

Production_Rate increases *Serviceable_Inventory*. *Shipments_to_Distributor* increase *Distributor's_Inventory*, which is depleted to satisfy *Demand*. *Demand_Backlog*, *Orders_Backlog* and *Production_Backlog* are satisfied in a future period. *Sales* turn into *Used_Products* after *Residence_Time*, which is the time a product stays with the customer before its end-of-use (Geyer *et al.*, 2007).

The reverse channel starts with the collection activities (*Collection_Rate*). The flows and the stocks can be derived from the Figure 3 in the way discussed for the forward channel. *Controllable_Disposal* drains the *Recyclable_Products* if they remain unused for more than *Recyclable_Stock_Keeping_Time* to prevent an endless accumulation. *Legislation* affects the *Collection_Rate*, the *Products_Accepted_for_Recycling* and the *Procurement_Rate* through *Collection_Percentage*, *Recycling_Percentage*, *Limit_of_Recyclability* and *Limit_of_Recycled_Content*. These influences will be discussed in subsection 3.2.

The achievement of the *Limit_of_Recyclability* requires *Redesign_Time* (time needed to redesign the product to comply with the legislation's requirements), assuming as a minimum value the *Minimum_Recyclability*. The *Procurement_Rate* of *Natural_Resources* depends on the *Recycled_Content*, assuming the *Minimum_Limit_of_Recycled_Content* as a minimum value.

3.2 The influence of Legislation

Figure 4 exhibits the causal links of the *Legislation* with the supply chain activities.

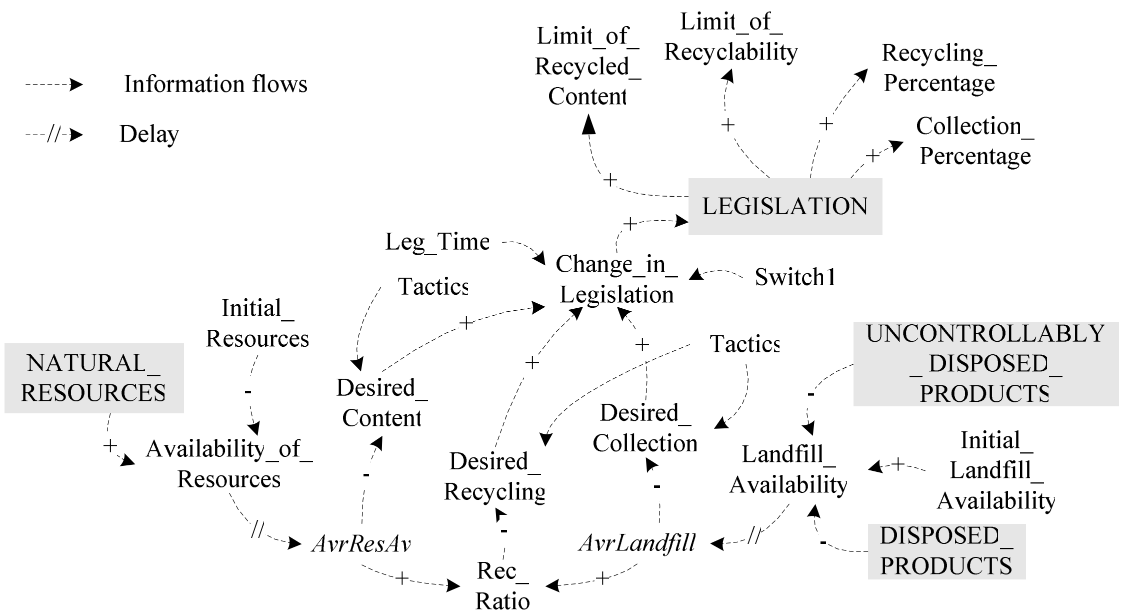

Figure 4: Causal-Loop Diagram of *Legislation*

Legislation modeling is an endemic process (Angell and Klassen, 1999). Especially, when the "Limits" issues grow there is need for stringent *Legislation*. *AvrLandfill* (average landfill availability) and *AvrResAv* (average resources availability) express the sustainability threats (minimization of available landfills and natural resources); the values of these two parameters are determined by smoothing and delaying past values of *Landfill_Availability* and *Availability_of_Resources* respectively.

Landfill_Availability reflects how much the initial available landfills have shrunk (*Initial_Landfill_Availability*) due to the accumulation of *Disposed_Products* and *Uncontrollably_Disposed_Products*. To decrease the shrinking of available landfills more *Used_Products* must be collected and reused through recycling activities. So, the *AvrLandfill* must affect the collection (*Desired_Collection*) and the recycling operations (*Desired_Recycling*). The *Desired_Collection* results from *AvrLandfill* according to the impact of the qualitative variable *Tactics*, which reflects the political tactics introducing new regulatory measures. These tactics depend on the political beliefs on environmental issues and the ecological influences coming from the society. To incorporate different tactics, we use four alternative curves (Figure 5). The relation for the first tactic (T1) is proportional. In T2 the politicians and therefore *Desired_Collection* responds quickly for low levels of *AvrLandfill* (environmental sensitive tactic), while in T3 the response becomes more acute for high levels of *AvrLandfill*. Finally, T4 combines T2 and T3; the relation has the form of an S-curve.

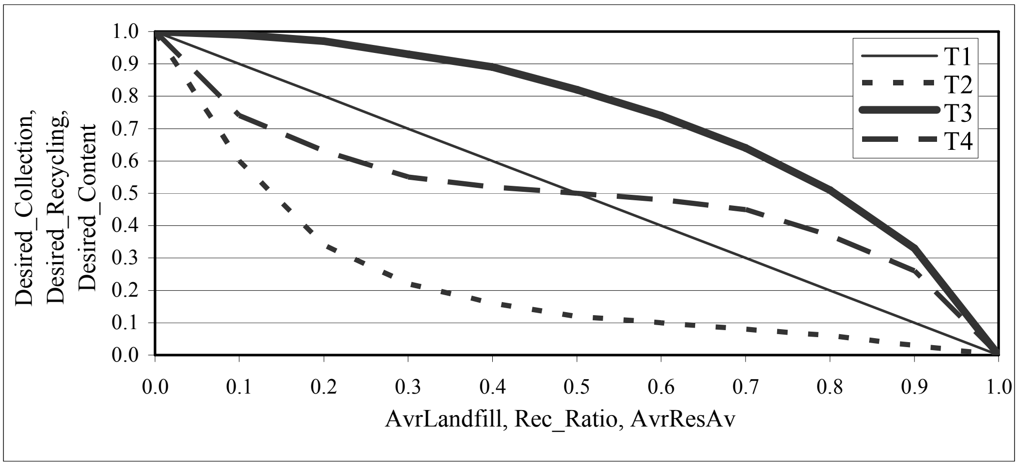

Figure 5: Relationship between *Desired_Collection* (*Desired_Recycling, Desired_Content*) and *AvrLandfill* (*Rec_Ratio, AvrResAv*) for various tactics

Availability_of_Resources reflects the decrease of *Natural_Resources* compared to their initial value (*Initial_Resources*). To decrease the *Procurement_Rate* more *Collected_Products* must be recycled and used in the production. Thus, the *AvrResAv* must affect the recycling operations (*Desired_Recycling*) and the inventory of recycled materials used in production (*Desired_Content*). Since *AvrLandfill* and *AvrResAv* must have a positive influence on *Desired_Recycling*, we model the joint influence using *Rec_Ratio* (the product of *AvrLandfill* and *AvrResAv*). Moreover, since both the *Recycling_Percentage* and the *Recyclability* affect the recycling activities, we use one variable (*Desired_Recycling*) to formulate both the *Recycling_Percentage* and the *Limit_of_Recyclability*. The *Desired_Recycling* results from *Rec_Ratio* according to the impact of *Tactics* (similarly with *Desired_Collection*, Figure 5). Furthermore, the

Desired_Content results from *AvrResAv* according to the impact of *Tactics* (similarly with *Desired_Collection*, Figure 5).

We assume that the new environmental policies can be introduced (*Change_in_Legislation*) in time periods. This time period is captured by a variable named *Leg_Time*. Moreover, we use a switch variable (*Switch1*). When *Switch1*=1, the endemic process of new regulatory measures' introduction is activated; when *Switch1*=0, the environmental legislation remains constant through time.

3.3 Mathematical Formulation

The next step of the SD methodology is the development of the mathematical model; the causal-loop diagram is translated into a system of differential equations. The stock-flow diagram of our model has been developed using Powersim®2.5c software. *Change_in_Legislation* and *Legislation* are array variables comprising of four dimensions. The four index variables concern the *Collection_Percentage*, the *Recycling_Percentage*, the *Limit_of_Recyclability* and the *Limit_of_Recycled_Content*.

4 Empirical Testing

The proposed model describes relationships already known; a full exploration of all interactions has not been published. Therefore it is necessary to assess whether the individual relationships can operate among each other simultaneously (Forrester, 1961).

Firstly, we tested the model against a particular real world application, that of a closed-loop supply chain of electrical equipment in Greece. To statistically estimate the model's interactions we used data from a Greek municipality (subsection 4.1). Finally, we conducted a variety of tests to check the model's validity (subsection 4.2).

4.1 Description of the case-study

In Europe, the main environmental drivers for sustainability are limited natural resources and limited landfill capacities. Increasingly, EU regulations force manufacturers to introduce recovery activities. Such a representative example is the Directive 2002/96/EC on waste electrical and electronic equipment (WEEE) (Directive, 2002). The Directive 2002/96/EC imposes an aggregate recycling percentage of 75%; should separate measures for recycling percentage and recyclability be introduced to increase the policy's efficiency? It is remarkable that the Directive 2002/96/EC imposes neither a collection percentage, nor a limit of recycled content; should both of them be introduced to increase the policy's efficiency? Hence we suppose that *Collection_Percentage*=80% (stated as recovery percentage) and *Limit_of_Recycled_Content*=0% (by an average weight per appliance). Moreover, we suppose that both *Recycling_Percentage* and *Limit_of_Recyclability* are equal to 87%, so as their product complies with the Directive's aggregate recycling percentage of 75%.

We examine a real world closed-loop supply chain of electrical equipment developed by a Greek municipality in Western Greece. The municipality has about 65,000 inhabitants and 10,000 households. It is a pioneer municipality in recycling activities in Greece aiming also to innovative actions, characteristics that could be found in other small European towns. The collected WEEE are transferred to the collection facilities, where dismantling activities also take place. For the recycling activities the used products are carried to external contributors. Data collected by the authors included (1) interviews with collection and recycling activities' managers; (2) archival data, such as the collected WEEE amounts per month. We focused our study on refrigerators. The related data date since 2003.

We also used data from Electrolux presentation in 2005 to estimate the *Residence_Time* of refrigerators (Klassen, 2005). Furthermore, using the results from a field survey on WEEE (Karagiannidis *et al.*, 2003), we estimated the refrigerators' annual *Demand* with an average value of 1,590 refrigerators and a random variation of 60 refrigerators between 1989-1995. Karagiannidis *et al.* present that all households in Greece possess fridges (Karagiannidis *et al.*, 2003). Using *Residence_Time* we calculated the average demand, considering the municipality's population increase relying on data from the Greek National Statistical Service.

In Figure 6 we present the actual amount of collected fridges between 1/1/2003-1/1/2006 and their trend line.

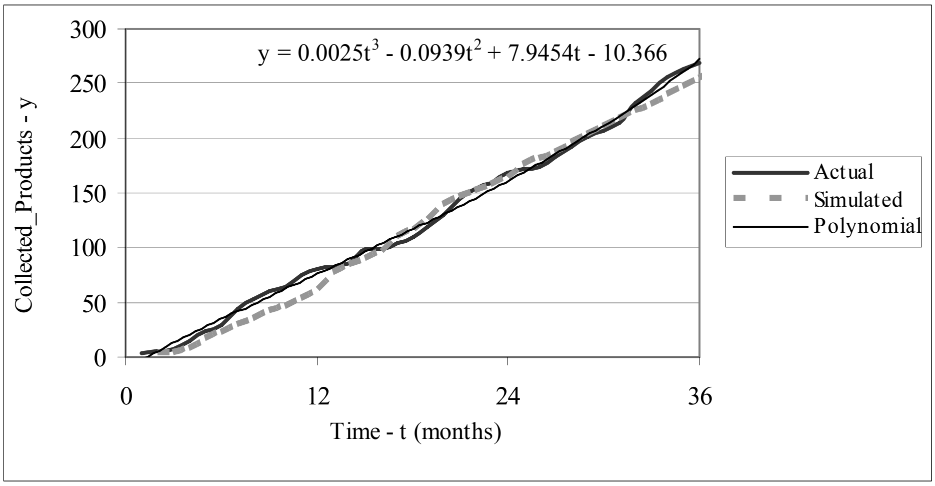

Figure 6: Actual *Collection_Products*, its trend line and comparison of Simulated and Actual Data

4.2 Model Testing

A wide variety of tests has been developed in SD for the models' improvement (Forrester and Senge, 1980, Barlas, 1996, Sterman, 2000). Firstly, we tested the structural validity of the model starting from its dimensional consistency. Then we conducted extreme-condition tests checking whether the model behaves realistically even under extreme policies. For example we checked that if no *Used_Products* return at the reverse channel, no inventory at the reverse channel drops below zero and for the production *Natural_Resources* are used exclusively. If there is no *Demand*, the production ceases. If *Production_Capacity* or *Collection_Capacity* or *Recycling_Capacity* is set to zero, *Serviceable_Inventory* or *Collected_Products* or the inventory of recycled materials are vanished respectively.

Integration error tests were subsequently conducted. We used the numeric method Euler; the integration method Runge-Kutta should be avoided in models with random disturbances (Sterman, 2000). Moreover, since the model's shortest time constant is set to one week and standard practice in SD suggests that the integrating time step (DT) should be maximum ¼ of the shortest time constant in the model, we set the DT initially at ¼week and ran the model. Then we cut the DT in half and ran the model again. The results did not significantly change, so we chose DT=¼week.

The ability of partial model structure to replicate data series with plausible parameters, constitute test of the model's structural validity. To examine whether the model can replicate the observed behavior, we simulated the model driven by the data series of the amount of *Collected_Products*. In Figure 6 we also present the simulated values of *Collected_Products*, which refer between 1/1/2003-31/12/2005. The mean absolute percent error (MAPE) between the simulated and actual level of *Collected_Products* is less than 0.6% (Table 1). The low bias and variation components of the Thiel inequality statistics indicate that the errors are unsystematic meaning that the model can replicate the observed behavior (Thiel, 1966).

Table 1: Historical fit (1/1/2003-31/12/2005)

	Theil's Inequality Statistics					
Parameter	MAPE	Bias	Unequal Variation	Unequal Covariation	R^2	N
Collected_Products(items)	0.005	0.0013	0.054	0.9447	0.993	36

5 Importance of Feedbacks for Sustainability

In this section we examine whether the environmental legislation should be considered as an endemic process of the system under study or introduced as external variable without considering the natural resources' usage and the used products' disposal rates.

For simplification we assume that the stocks' initial values are equal to zero except for *Natural_Resources*, which we assume to suffice for 180 years if their usage rate is 10,000 items/week, *Collected_Products*, which are equal to 3 items, and the inventory of recycled materials, which are equal to 100 items. We also assume that the *Minimum_Recyclability* is 0.2, implying that even if there are no rules imposing DfE the product should be recyclable by 20%, and that the *Minimum_Limit_of_Recycled_Content* is 0.2, implying that the percentage of recycled materials that must be used in the production is 20%. For the basic scenario we use the T4 tactic (Figure 5). The simulation horizon is 40 years (2000 weeks) and DT is ¼week. The simulation period starts in 1/1/2003.

To investigate the effects of *Legislation* on natural resources' and on landfill availability, we simulated the model firstly in case that the environmental legislation is introduced as internal variable by taking into consideration the rates of the natural resources' usage and the used products' disposal (*Switch1*=1) and secondly in case that the environmental legislation is fixed through time (*Switch1*=0). In case that the environmental legislation is considered as an endemic process a preservation of 4,537 items of *Natural_Resources* and a reduction of 4,536 disposed products is achieved. Since the total demand (during the simulation horizon) for new products is 68,286 items, the preservation of 4,537 items of *Natural_Resources* and of 4,536 disposed products prolongs the lifetime of *Natural_Resources* and of landfills respectively by about 6.64%.

6 Sensitivity Analysis and Discussion

In this section we demonstrate the conduct of variables' sensitivity analyses along with few interesting managerial insights.

Specifically, we conducted sensitivity analyses to investigate the impact of the current legislative measures, namely the collection and the recycling percentage, on the sustainability. We also examined whether the omission of the recyclability and the recycled content as legislative measures is significant. Hence, we concentrated on the effects of *Collection_Percentage*, *Recycling_Percentage*, *Limit_of_Recyclability* and *Limit_of_Recycled_Content* on *Natural_Resources* and on *Sum_Disposal* (*Sum_Disposal* equals with the sum of *Uncontrollably_Disposed_Products* and *Disposed_Products*), using Analysis of Variance (Anova). We also assumed that the environmental legislation does not change through time (*Switch1*=0).

Each of these parameters is examined at two levels (Table 2). The number of all possible combinations of these 4 parameters is 2^4=16; each combination was simulated thrice to test for alternative generators of random numbers concerning *Demand*, leading to $3*2^4$=48 simulations.

Table 2: Levels of model parameters

Parameter	(1)	(2)
Collection_Percentage	80%	90%
Recycling_Percentage	87%	97%
Limit_of_Recyclability	87%	97%
Limit_of_Recycled_Content	0%	10%

Table 3 contains the P-values for each of the significant influences, i.e. the lowest significance levels to reject the null hypothesis that the control factor does not affect *Natural_Resources* or *Sum_Disposal*.

The results of the Anova tests revealed that the *Collection_Percentage*, the *Recycling_Percentage*, the *Limit_of_Recyclability* and its interaction with the *Recycling_Percentage* and the *Limit_of_Recycled_Content* have significant influence on *Natural_Resources*. Moreover, the *Collection_Percentage*, the *Limit_of_Recyclability*, the *Recycling_Percentage* and its interaction with the *Limit_of_Recycled_Content* have significant influence on *Sum_Disposal*.

Table 3: Results of ANOVA tests (P-values) for the significant effects of *Legislation* on *Natural_Resources* and *Sum_Disposal*

Factor-Interaction	*Natural_Resources*	*Sum_Disposal*
Collection_Percentage	0.000*	0.000*
Recycling_Percentage	0.000*	0.000*
Limit_of_Recyclability	0.000*	0.000*
Limit_of_Recycled_Content	0.808	0.936
*(Recycling_Percentage*Limit_of_Recycled_Content)*	0.169	0.095*
*(Recycling_Percentage*Limit_of_Recyclability *Limit_of_Recycled_Content)*	0.022*	0.769

*P-value<0.1

To further understand the influence of *Collection_Percentage*, *Recycling_Percentage*, *Limit_of_Recyclability* and *Limit_of_Recycled_Content* on *Natural_Resources* and on *Sum_Disposal* we conducted 11^4 simulations (at total 14,641 simulations) at the system under study for constant generator of random numbers and increasing *Collection_Percentage*, *Recycling_Percentage*, *Limit_of_Recyclability* and *Limit_of_Recycled_Content* by 10% starting from 0% and ending to 100%. The results of these simulations confirmed that if policy-makers/regulators are interested in conserving the landfill availability, it will be more efficient to increase the *Collection_Percentage*, the *Recycling_Percentage* and the *Limit_of_Recyclability* rather than the *Limit_of_Recycled_Content*. Furthermore, to conserve the *Natural_Resources*, it will be more efficient to increase the levels of all of the above four parameters of *Legislation*. Hence, it is evident that to increase the policy's efficiency, legislative measures of *Collection_Percentage*, *Recycling_Percentage*, *Limit_of_Recyclability* and *Limit_of_Recycled_Content* should be introduced.

Due to the simulations' results of the Anova tests we converted the causal-loop diagram of *Legislation* (Figure 4) to a new one that contains all the significant impacts of the "Limits" issues on the introduction of new regulatory measures. Figure 7 presents the new causal-loop diagram of *Legislation*. The only difference between Figure 4 and Figure 7 is that both the *AvrLandfill* and the *AvrResAv* affect the *Desired_Collection* and not just the *AvrLandfill*. Hence the direct influence of *AvrLandfill* on *Desired_Collection* (strikethrough arrow in Figure 7) is replaced by the influence of *Rec_Ratio* on *Desired_Collection* (thick arrow in Figure 7).

To investigate the improvement of the "Limits" issues for the case of the new causal-loop diagram, we simulated the model again. The simulation results revealed a preservation of just 0.01 items of *Natural_Resources* and a reduction of just 0.01 disposed products. Hence, the improvement of the "Limits" issues is not significant.

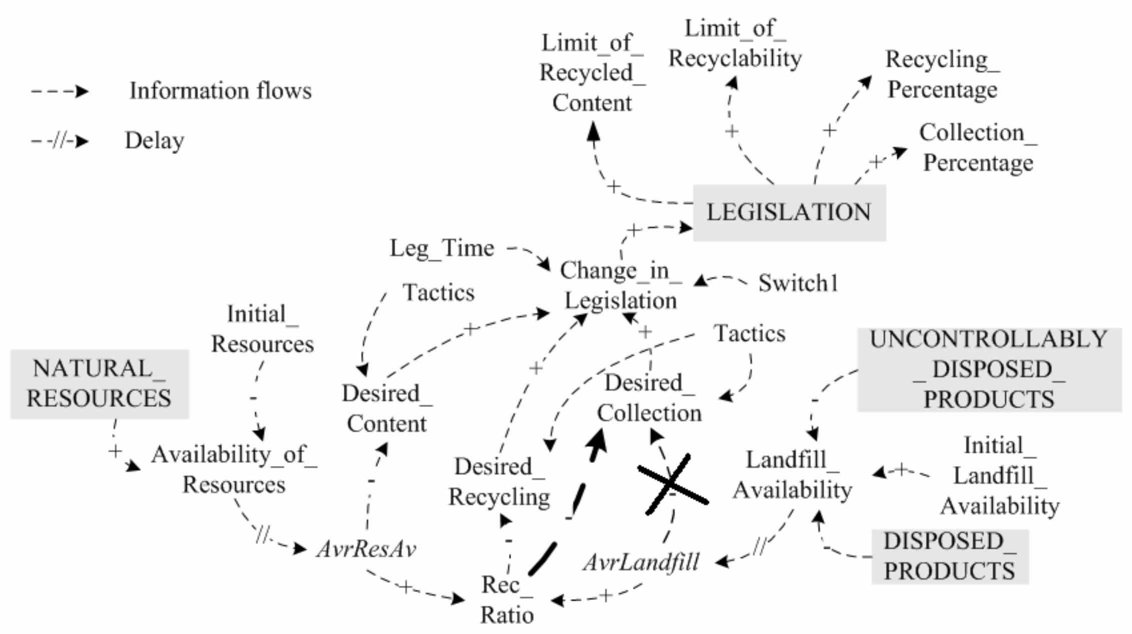

Figure 7: New Causal-Loop Diagram of *Legislation*

7 Conclusions

In this manuscript we presented the development of a SD model for a single product closed-loop supply chain with recycling activities applied to a real-world application. The numerical examples provided insights according to the environmental policies expected to perform best. Specifically, we came to the conclusion that the collection percentage, the recycling percentage and the recyclability affect the preservation of natural resources, whereas all the above three parameters and the recycled content affect the availability of landfills. Hence, it is evident that the environmental regulations should expand and impose minimum values for collection percentage, recycling percentage, recyclability and recycled content. Moreover, the environmental legislation should be introduced as internal variable by taking into consideration the rates of natural resources' usage and used products' disposal.

The developed model can be used as a methodological tool for the conduct of sensitivity analyses on issues such as the firms' compliance to regulatory measures. Furthermore, it can be extended from the narrow boundaries of a specific geographical state to that of a country or even to receive global dimensions depending on the availability of the necessary data. Finally, the model could prove helpful to researchers in the area of environmental management along with decision-makers and policy-makers/regulators dealing with closed-loop supply chain management issues providing a tool to compare the effects of alternative policy options. Further refinements of the model may provide insights into other important features of environmental management such as the investigation of the impact of products' price and the economical profit on the environmental management.

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