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DECISION MAKING IN REVERSE LOGISTICS USING SYSTEM DYNAMICS

P. GEORGIADIS, D. VLACHOS

Department of Mechanical Engineering
Aristotle University of Thessaloniki
541 24, Thessaloniki, Greece

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Abstract: Reverse logistics is a modern field of consideration, research and study, providing helpful information on the operation of the closed-loop supply chain. Although the starting point of this field is traced back to the early 90's, no standard method has been suggested, neither prevailed. The purpose of this paper is to introduce a new approach on the study of reverse logistics. It is actually a review on how System Dynamics (SD) can be a helpful tool when it is used in the reverse logistics field. The paper explains the basic theory of the system modelling and next it utilizes the reverse logistics model. Finally, an illustrative example shows how SD modeling can be used to produce a powerful long-term decision-making tool.

Keywords: Reverse logistics, supply chain management, system dynamics.

1. INTRODUCTION

In the world of finite resources and limited capacities of disposal facilities, recovery of used products and material is a key to support a growing population at an increasing level of consumption. The "reuse" opportunities of both used products and materials give rise to a new material flow from the user back to the producers. The management of this material flow opposite to the traditional supply chain flow is the concern of the recently emerged field of "reverse logistics". [5] [6] [10] [19]

Several definitions are given for reverse logistics. Stock [19] and Kopichi et al. [10] define reverse logistics as "the term often used to refer to the role of logistics in recycling, waste disposal, and management of hazardous materials; a broader perspective includes all issues relating to logistics activities carried out in source reduction, recycling, substitution, reuse of materials and disposal". Pohlen and Farris [15] reverse logistics define as "the movement of goods from a consumer towards a producer in a channel of distribution". More recently, Rogers and Tibben-Lembke [16] define reverse logistics as "the process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods, and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal".

The recovery of used products and materials consists of four main reuse options [6] [21]: "direct reuse, repair, remanufacturing, and recycling." The *direct reuse* refers to the activities that aim to reuse items without prior repair operations. Examples are reusable packages such as bottles, pallets or containers. The *repair* option refers to the activities that aim to return used products to "working order". Examples are domestic appliances, industrial machines, and electronic equipment. The *remanufacturing* option aims to get the used products into an "as good as new" condition. Examples are remanufactured aircraft engines, machine tools, and copy machines. *Recycling* denotes material recovery without conserving any product structures. Examples are metal, glass, paper, and plastic recycling. Each of the above product recovery options involves collection of used products and components, reprocessing, and redistribution.

Numerous case studies have been carried out in order to study the different approaches to reverse logistics options. Carpet recycling logistics networks are addressed by Ammons et al. [1] and Louwers et al. [13]. Barros et al. [2] report on a network for sand recycling in the Netherlands. Spengler et al. [17] examine the recycling of industrial by-products in German steel industry. Thierry et al. [21] report on the recovery of copy machines. Jayaraman et al. [9] analyzes the logistics network of an electronic equipment remanufacturing company. Berger and Debaillie [3] address the situation of recovery of used products. Krikke et al. [11] study the reverse logistic network for durable consumer products. Kroon and Vrijens [12] analyze a logistic system for reusable transportation packages. We refer to Fleischmann et al. [5] for a detailed discussion of this field.

The planning and control tasks arising in the context of reverse logistics from an Operational Research point of view are reviewed by Fleischmann et al. [6]. Linear programming, dynamic programming, networks theory and Markov theory algorithms are used for the mathematical formulation and the solution of specific problems. As a concluding remark they report that as a scientific field, reverse logistics is still rather young. The results published to date are rather isolated. Comprehensive approaches are rare. They also note that research on reverse logistics has been confined to rather narrow views on single issues. The influence of return flows on supply chain management is a topic that deserves further research efforts. No standard methodology is yet in common use; neither a general framework has been suggested.

Long-term strategic management issues on reverse logistics systems have not been adequately analyzed in the past, possibly because of the difficulty in handling the variety of involved factors in forward and reverse flow channel and the complexity of their interdependencies. A notable exception is the work of Thierry et al. [21], which systematically describes the implementation steps of a copier recovery strategy. Although the contribution of Thierry et al. is valuable, it does not delineate a specific formal quantitative analysis. The purpose of this paper is to introduce how the methodological tool of System Dynamics (SD) can be employed to assist the reverse logistics modelling to develop integrated forward/reverse dynamic logistic models that include both quantitative and qualitative variables (e.g. users' environmental consciousness), time delays for each activity (e.g. collection time, delivery time), and uncertainty in variables (e.g. the timing of return of used products). The objective of this modelling approach is twofold. The first objective is to understand the dynamic behaviour of an integrated forward/reverse logistics network, by evaluating the effects of shocks imposed by the external environment to the system (e.g. a new state regulation), or the magnitude of influences between internal elements of the system (e.g. the effect of collection rate to remanufacturing capacity). The second objective is to develop a powerful simulation tool for long-term policy design and evaluation in a real closed-loop supply chain. The investigation of new decision rules, strategies and structures that might be applied in the real world can be performed from the point of view of a single company, a joint venture, or an industry sector. It is also possible to design and evaluate public policies aiming at securing the viability of reverse channels.

The remaining of the paper is organized as follows: Section 2 contains a literature review on system dynamics modeling. Section 3 describes the system dynamics methodology, including all the necessary information needed in order to design a model for both the forward and the reverse supply chain. Section 4 consists of a comprehensive description of the closed loop logistics network. Numerical investigation for a single producer-single product is presented in Section 5. Finally, section 6 summarizes some conclusions and guidelines for future research.

2. SYSTEM DYNAMICS MODELING

Forrester [7] introduced the SD approach in the early 60's as a modelling and simulation methodology for analysis and long-term decision making in dynamic industrial management problems. Since then, SD has been applied to various business policy and strategy problems. There are already some publications using SD in supply chain modelling, but all of them refer to forward logistics. Forrester [7] included a model of a supply chain as one of his early examples of applying SD methodology. Towill [22] uses SD in supply chain redesign to gain additional insight into system dynamics behaviour and particularly into the underlying causal relationships. The output of the proposed approach is a collection of effective industrial dynamics models of supply chains. Minegishi and Thiel [14] use SD to improve the knowledge of the complex logistic behaviour of an integrated food industry. They present a generic model and some practical simulation results applied to the field of poultry production and processing. Hafeez et al. [8] describe the analysis and modelling of a two-echelon industry supply chain that services the construction industry, using an integrated System Dynamics framework. Simulation results are used to compare various re-engineering strategies. Sterman [18] presents two case studies where SD methodology is used to model reverse logistics problems. In the first one, Zamudio-Ramirez [23] analyzes part recovery and materials recycling in the US auto industry to assist the industry think about the future of enhanced auto recycling. In the second one, Taylor [20] concentrates on the market mechanisms of paper recycling, which usually lead to instability and inefficiency in flows, prices, etc.

The application of SD in all these papers shows that System Dynamics can indeed be a useful tool for long term analysis of traditional (forward) supply chains. It remains to be seen in the subsequent paragraphs how this tool can be applied to supply chains involving reverse logistics as well.

3. SYSTEMS DYNAMICS METHODOLOGY

The structure of a system in SD modelling is described using causal-loops or influence diagrams. A causal-loop diagram consists of variables connected by arrows denoting the causal influences among the variables. The involved variables and the system boundaries are identified according to the system objectives. The major feedback loops are also identified in the causal-loop diagram. These loops are either positive feedback (reinforcing) or negative feedback (balancing) loops. In a positive feedback loop an initial disturbance leads to further change, suggesting the presence of an unstable equilibrium. Figure 1 represents the causal loops for a simplified inventory planning and control system. Actual serviceable inventory and production rate are the variables that determine the internal environment of the system, while sales determine the external environment. Loop 1 that consists of production rate, the actual serviceable inventory, the desired serviceable inventory, and sales is a positive feedback loop. An increase in the production rate will increase the actual serviceable inventory, which may in turn increase sales. Increased sales will cause an increase in the desired serviceable inventory, which leads to an increase in the production rate. If the system consisted of only this loop, the production rate would grow indefinitely. Of course, this cannot be true in the real world. Negative feedback loops limit such growth. A negative feedback loop exhibits goal-seeking behaviour: after a disturbance, the system seeks to return to an equilibrium state. In the previous example an increase in sales will decrease the actual serviceable inventory, which may in turn decrease sales (loop 2). In addition, an increase in the production rate will increase the level of actual serviceable inventory, which will lead to a decrease in the production rate (loop 3).

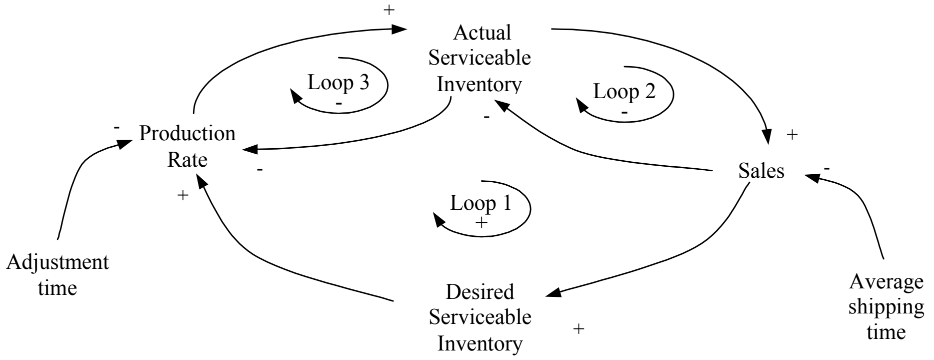

Figure 1: An example of causal loop (influence) diagram

Causal loop diagrams play two important roles in system dynamics studies. First, during model development, they serve as preliminary sketches of causal hypotheses. Second, causal loop diagrams can simplify the representation of a model. The structure of a dynamic system model contains level and rate variables. The level (state) variables are the accumulations within the system and their values over time describe the state of the system. The rate variables represent the flows, which alter the state of the system. For example, the actual serviceable inventory in figure 1 is a level variable, while the production rate and sales are rate variables. The embedded mathematical equations are divided into two main categories: the level equations, defining the accumulations within the system through the time integrals of the net flow rates, and the rate equations, defining the rate of change of the levels. The rate equations are the output of the embedded decision making mechanisms. For example, the mathematical form of the actual serviceable inventory at time *t* is the following:

$$\text{Actual serviceable inventory (t)} = \int_0^t [\text{Production rate(t) - Sales(t)}]\, dt + \text{Actual serviceable inventory(0)}$$

The production rate at time t, in the previous example, could be determined using the following decision rule, which adjusts the actual level of serviceable inventory until it is equal to the desired level:

$$\text{Production rate}(t) = \{\text{desired level of inventory}(t) - \text{actual level of inventory } (t)\}/\text{adjustment time}$$

In this decision rule the adjustment time is a decision variable, which refers to the time required to close the gap between the desired and the actual inventory levels. Aggressive correction actions require small values of adjustment time, while more conservative actions require greater values.

The causal loop diagrams lead to the development of the dynamic simulation model using specialized software. Nowadays, high-level graphical simulation programs (such as i-think® and Powersim®) support this phase. Then, the simulation model is verified and validated. During that step it is likely to return to and correct the conceptual modelling in order the model to accurately represent the system. Then, we run the model and log the dynamic behaviour of the variables. The final step is to use the model to design and evaluate new decision rules and strategies that might be applied in the real system. This can be done by analyzing the sensitivity of the model and examining the results of what-if scenarios.

4. CLOSED-LOOP SUPPLY CHAIN MODELLING

The integration of the forward and reverse flow channels transforms the 'one-way' structure of the traditional supply chain networks to closed-loop networks. For the different forms of reuse (direct reuse, re-manufacturing, repair, recycling), the main flows and the major loops of such closed-loop logistic networks are depicted in figure 2. The solid lines represent the forward channel while the dashed lines represent the reverse channel. Four loops characterize the structure of the system. The first loop refers to the direct reuse. *Reusable packages* such as bottles, pallets or containers are transported back to the *original producer* and possibly after a cleaning and minor maintenance are reused for packaging purposes. The second loop refers to the added value recovery process that includes the re-manufacturing and the repair forms of reuse. *Used products* are transported to producers and after an *added value recovery process*, *reusable products* that include good as new products or B class products are produced. The last two loops refer to recycling. Recyclable material is transported to the recyclers and after a material recovery process they are used by the *original producers* (loop 3 - the outer loop) or the producers in the *added value recovery process* (loop 4).

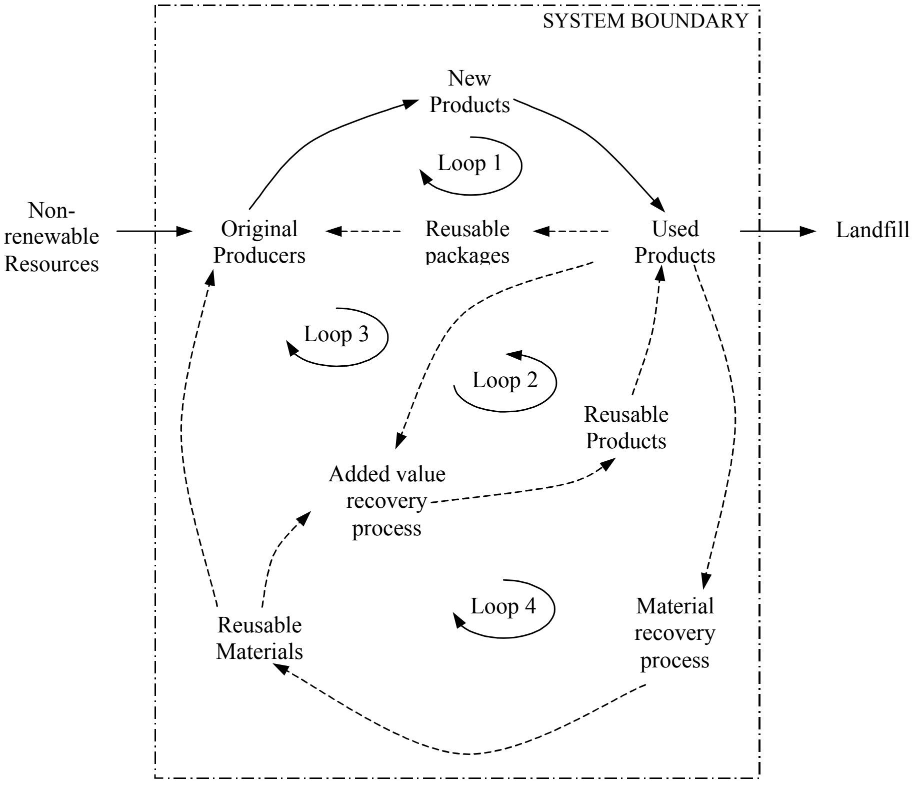

Figure 2: Major causal loops in a closed-loop logistics network

Several actors are involved in the above closed-loop system: suppliers, original producers, value added recovery producers, distributors, users, collectors, and recyclers [6]. Actors may be members of the forward channel (e.g. manufacturers, retailers, and logistics service providers), private third parties (e.g. secondary material dealers, material recovery facilities, and added value recovery facilities), or members of the public sector (e.g. government, municipality). The motivation for the participation of original producers and/or specialized third parties in an integrated closed-loop logistics network may be economical, ecological or both. Reverse inbound flows are economically attractive when the value gain, i.e. the value still incorporated in a used product minus the cost of the required reverse activities, is positive. Ecological motivation is expressed via state environmental legislation, holding for example the original producers responsible for the entire product life cycle or imposing a percentage of recycling. The goal is to reduce both the disposal rate of the used products and the usage rate of non-renewable resources. Moreover, customer expectations urge companies to reduce the environmental burden of their products and a 'green' image has become an important marketing element that forces the original producers to take environmental aspects into account.

A more detailed causal-loop diagram of the close-loop logistics network is presented in figure 3. Specifically, the diagram involves all the actors participating in the forward and reverse channel and the flows among them. The actors involved in the forward channel are the suppliers, the producers, the distributors and the market. The reverse flow channel involves actors participating in disposing, repairing, remanufacturing, recycling, and reuse activities.

Referring to the main flows in the forward and reverse channel and starting from the non-renewable resources, raw materials fulfill the suppliers' inventory. These materials are transported to the producers' facilities and new products are produced. According to the order rate, distributors come in and provide the market with these products. The life cycle of the product ends after its use. Used products are either collected or uncontrollably disposed. Uncontrollable disposal of used products by end users is not an environmental friendly option. Collection of used products is the starting point of the reverse channel. At the inspection station each product is marked as product for controllable disposal, direct reuses, remanufacture, repair or recycle. The controllable disposal feature includes useless unserviceable products, which are rejected after the inspection. The option of reuse refers to reusable packages. It is actually a "direct reuse", as the products can be used again without any further process. Products for remanufacturing include a new process in order to become "as good as new products" or B class products. B class products are ready to use after a repair. Finally, recycled products can be reused first directly, as raw materials, second, as materials in remanufacturing activities, and third, as materials in repairing of reused products.

The reverse flow is in use when even one of the following loops is active:

↺ Loop 1: Reusable packages return to the serviceable inventory in new products
↺ Loop 2: Products after remanufacturing return to the serviceable inventory in " as good as new" products
↺ Loop 3: Products after repair return to the serviceable inventory in new products
↺ Loop 4: Recycled products provide raw materials to the inventory in materials.

The motivation for each one of these flows can be economical or ecological or both. The points where such a motivation is needed to activate the specific loop is illustrated in figure 3. Therefore if someone wishes to reinforce the reverse channel flow, he must ensure the economical profitability of the associated flows. The environmental profitability cannot be the major reason for business investments unless it is combined with the economical profit.

The model includes two decision points, where decision rules must be applied. The first one is after the end-of-use of used products, where we must decide if these products will be uncontrollably disposed or properly collected. The second is at the inspection facilities where we decide if a specific item will be reused or not. Such decision rules are examined in section 5 for the case of a single producer-single product, activating only the loop 2.

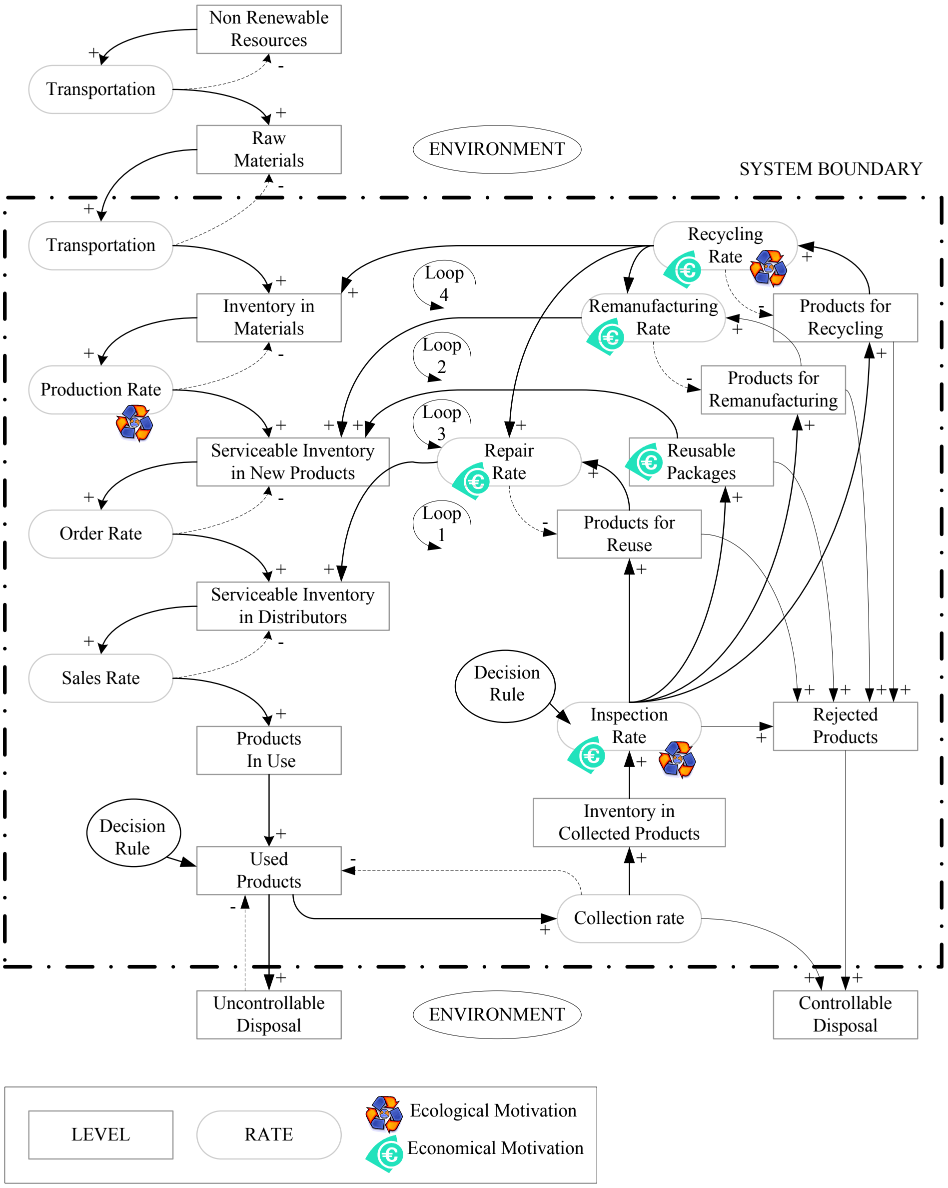

Figure 3: Detailed causal-loop diagram of the close-loop logistics network.

5. NUMERICAL INVESTIGATION

The causal loop diagram of the single producer-single product case includes only the remanufacturing loop (loop 2) of the influence diagram of figure 3. The assumptions that rule this case are the following:

- There is no need to disassemble the product in order to remanufacture it. (e.g. tyres)
- We study a product with two quality classes. A-class refers to high quality products, while B-class refers to products, which are sold only to secondary markets. A-class products may be remanufactured after inspection at the end of their life cycle for a finite number of times. Remanufacturing leads to as good as new products. Alternatively A-class returns can be used as B-class, which cannot be reused.
- The demand per time unit (three months period) is constant both for A-class and B-class products.
- The demand is satisfied from an inventory of new and remanufactured products.
- Used products are either collected or disposed uncontrollably.
- The collected items are inspected and then remanufactured, or used in a secondary market or are disposed /incinerated.
- All production rates are limited from specific capacities.
- The capacity of controllable disposal or incineration is infinite which seems not valid but we handle it assuming that the associated cost increases exponentially.

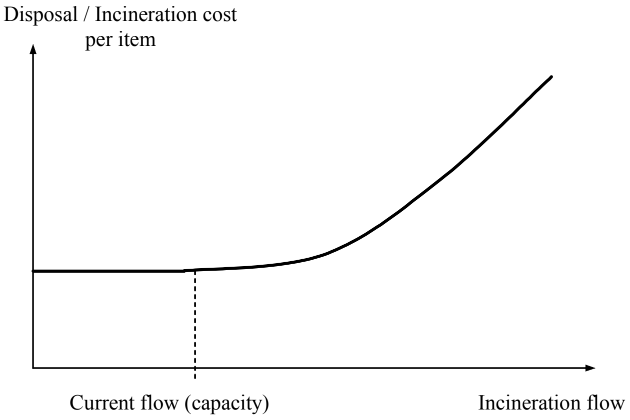

Figure 4: Unit cost for controllable disposal

The cost structure of our model includes production cost, collection and inspection cost, remanufacturing cost, disposal/incineration cost and uncontrollable disposal cost. The last one may be a take back fee or penalty imposed from environmental legislation. We assume that the first two costs are constant (independent from the related flows). The incineration cost will increase if the demand for incineration increases. The graph of figure 4 shows this dependency.

To model the remanufacturing cost we assume that the current remanufacturing capacity will increase in the future as a result of scheduled investments. The remanufacturing cost up to current capacity is assumed constant. The cost for larger remanufacturing rates is shown in figure 5. The cost is higher when the system operation is far from the new maximum capacity. The cost is lower as we approach maximum capacity. This cost includes both fixed and variable costs.

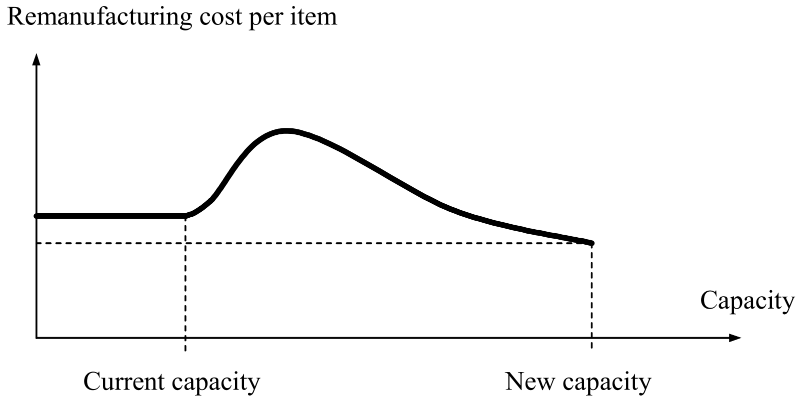

Figure 5: Unit remanufacturing cost

As shown in figure 3 there are two points where a decision rule must be set in our model. The first decision is made by the user who decides whether to dispose the used product in the appropriate collection point or not. The second decision is made by the collector who has to decide to send inspected products to a remanufacturer or not. The criterion for these decisions is mainly economical. The user or the collector has to decide what is more profitable for him based on the cost of the alternative options. To model these decisions making procedures, we used the following sigmoid functions:

$$\text{Percentage of uncontrollable disposal} = \frac{1}{1+e^{L}}$$

$$\text{Percentage of collected products to be remanufactured} = \frac{1}{1+e^{M}}$$

where L and M are control variables that express the normalised cost difference of the alternative flows for the two cases. Specifically,

$$L = a_1 \frac{c_{\text{uncontrollable disposal}} - \min\left(c_{\text{disposal / incineration}}, c_{\text{remanufacturing}}\right)}{c_{\text{production}}}$$

$$M = a_2 \frac{c_{\text{remanufacturing}} - c_{\text{disposal / incineration}}}{c_{\text{production}}}$$

We study an environmental policy where the manufacturer pays a penalty for the used products that are not properly collected and handled. And since the manufacturer never pays for such things, the cost will be transferred to the user as a take back fee included in the price which the user will be paid back if he returns the product to specific collection points. This policy limits the uncontrollable disposal.

We examined the above system under 9 scenarios for the remanufacturing capacity. All of them have a current capacity equal to 15% of the demand, which increase to 30%, 40% or 50% within a period of 3, 6 or 9 years. We run the above capacity scenarios for 7 different penalty levels (expressed as percentage of the production cost) and we logged the dynamic change of flows and costs per time unit. All simulations run in the Powersim 2.5c environment.

Figure 6 shows the transient change in flows when penalty is imposed. Two levels of penalty are depicted in figure 6, a low penalty level (5% of the production cost) and high penalty level (30%). We assumed that the penalty is imposed at year 1. We notice that the uncontrollable disposal is eliminated when high penalty is imposed and of course the incineration flow increases respectively. Figure 7 depicts the transient change in the same flows when new remanufacturing capacity is added (year 1) after the penalty imposition. The transition period is long for both levels of penalty because the initial investment cost is significant and the uncontrollable disposal seems less costly.

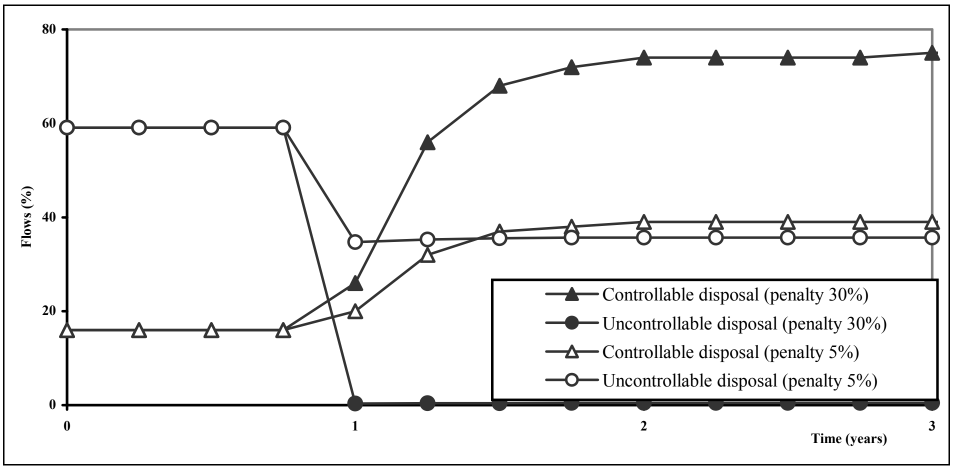

Figure 6: Change in flows when penalty is applied

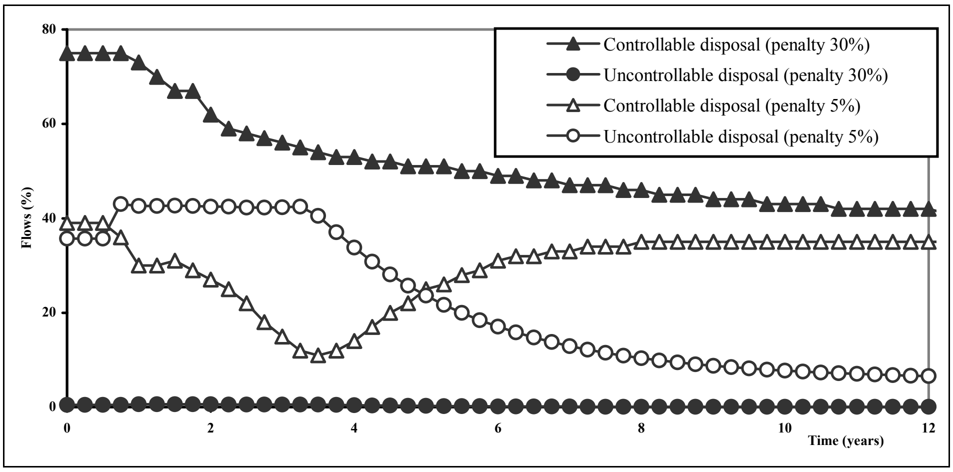

Figure 7: Flows change when remanufacturing capacity is added

The main costs in our scenarios are the production and remanufacturing costs. From Figures 8 and 9 we can see that the increased total cost because of the penalty imposition further increases when we add remanufacturing capacity because the associated cost is higher due to the initial investments. When remanufacturing reaches its final capacity the cost per item decreases. The situation is similar for different penalty levels.

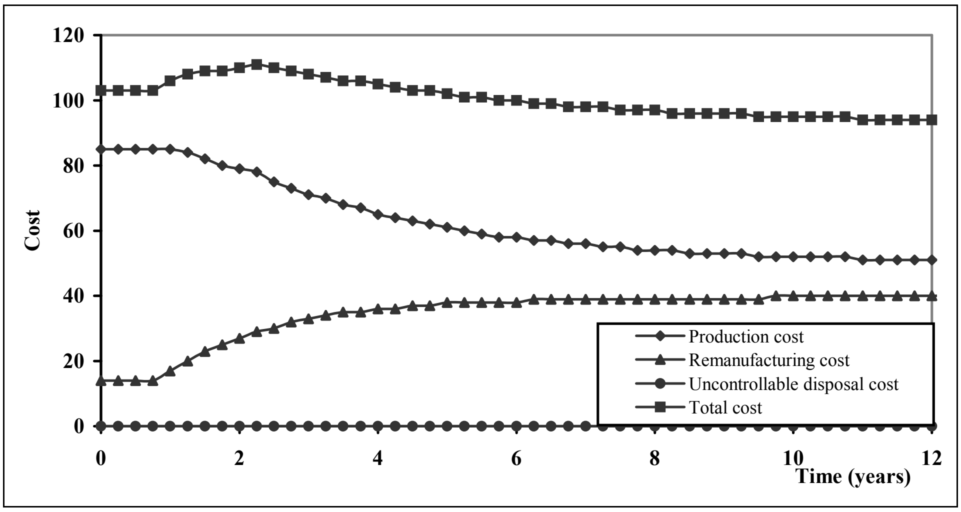

Figure 8: Costs during the remanufacturing adding period (penalty 30%)

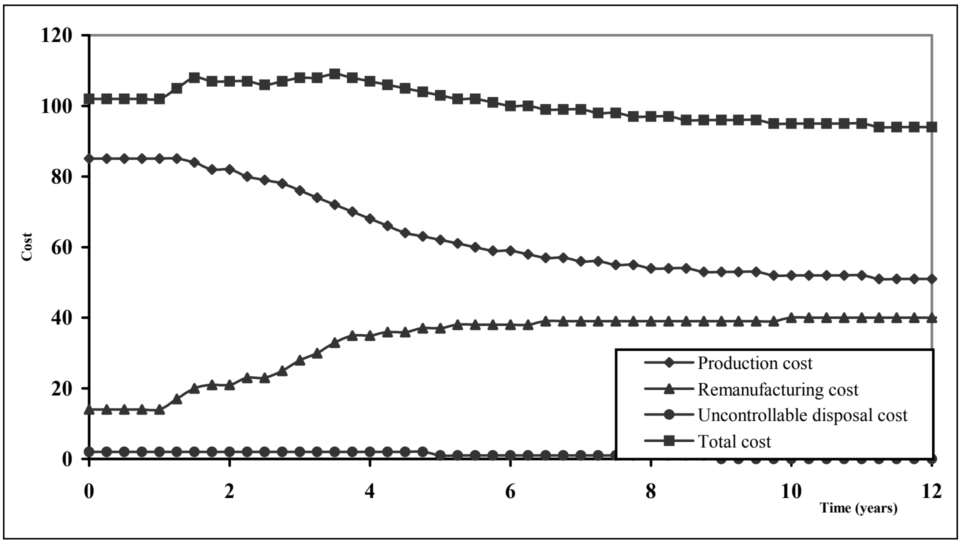

Figure 9: Costs during the remanufacturing adding period (penalty 5%)

6. CONCLUSIONS

This research analyses the Reverse Logistics network using SD methodology. After a well work-out of the reverse logistics model, we come up with the impression that the study of this field must continue. It is important to understand the necessity of the reverse channel and the economical and ecological profits from it. We believe that in the next years the industries that wish to come up with the competition and the environmental legislations should operate a new section in their production, the reverse channel. Furthermore, as no standard tool has been yet suggested, we propose the use of system dynamics. Its advantages make it a powerful tool and its applications provide support for long term decision making and environmental policy design.

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