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Ecological Motivation and Sustainability for Reverse Logistics: A System Dynamics Modeling Approach

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Abstract: - Sustainable development, along with technological and economical trends have led to the development of efficient "closed-loop supply chains". In this context, "ecological motivation" is a strategic issue of increased importance for the profitability of reverse supply chains due to companies' concerns about their "green image" and environmental legislation. In this paper we examine the impact of the ecological motivation on the long term behavior of a simple system that can be encountered on a variety of real-world cases, namely that of a single producer and a single product chain with recycling activities. Ecological motivation manifests through a variety of issues that are investigated, including the take-back obligations, lower limits of recycling imposed by legislation, green consumerism and design for environment (DfE). We develop a novel modeling approach that captures these issues comprehensively by exploiting the principles of the system dynamics (SD) theory. The dynamic model provides a simulation tool, which can be used for the conduct of various "what-if" analyses, by evaluating the impact of various regulatory measures and green consumerism on system performance. Finally, we discuss the potential value of the proposed modeling procedure in managing real world cases.

Key-Words: - Reverse Logistics; Closed-Loop Supply Chains; Sustainable Development; Recycling; System Dynamics, Ecological Motivation; Dynamic Simulation

1 Introduction

Sustainable development as has been emerged and developed manifests through the enforcement of environmental regulations, the relocation of severely polluting activities from the developed countries to the emerging market economies, the "greening" of the industry, and the corporate strategy of increasing profitability through socially sensitive policies [1, 13].

Specifically for the European Union, Germany (with its taking-back, packaging and electronic devices' regulations) and the Netherlands (with its stringent automobile laws) have emerged as the pioneers in strict regulatory policies [2]. Today, the EU's environmental policies have set the targets of minimizing the usage of dangerous substances, while promoting design for recycling, making producers responsible for the "End of Life" phases of their products, introducing regulations for take-back obligations and recovery quotas of the used products. Further, the recent directive 2002/96/EC of the European Parliament on Waste Electrical and Electronic Equipment (WEEE), which came into effect in August 2004, has as its main objectives the reuse, recycling and other forms of recovery of such wastes so as to eventually reduce the waste disposal. The Restriction of Hazardous Substances (RoHS) legislation (that will be effective in July 2006) limits products to contain only trace amounts of hazardous substances like lead, mercury and cadmium. At the same time regulatory interventions keep on proliferating on the other side of the Atlantic, as well. In the U.S. the amount of environmentally related regulatory interventions has increased five-fold in the last decades up to 1995, from nine major acts and laws to well over forty-five [16].

Sustainable development and several economical trends have further contributed in the increasing relevance of "reverse logistics" in the two last decades. The European Group of Reverse Logistics, REVLOG (1998-2003) defines reverse logistics as "the process of planning, implementing and controlling backward flows of raw materials, in process inventory, packaging and finished goods, from a manufacturing, distribution or use point, to a point of recovery or point of proper disposal" [6]. Reverse logistics concentrates on sustainability, when the classical supply chain management in forward and backward channels aims at profitability with reduced sources of waste and resource utilization [7]. Sustainability requires closing the loop of material and product flows thus leading to the development of closed-loop supply chains.

In such closed-loop systems the distinct, although interrelated, environmental pressures from governments, investors, consumers, suppliers, environmental groups, employees [16] and other community stakeholders, do not affect just the corporate strategies but also the operational practices throughout the supply chain. Moreover, pressures enforced by environmental legislation have profound ramifications on corporate strategies. Companies have to be cognizant of their environmental reputation, namely their “green image” [11], and further should be “ecologically motivated”, recognizing that they are responsible for their products throughout their life cycles [8]. Companies then have to identify more cost-effective opportunities to minimize the environmental impacts of both their manufacturing processes and their products during their life cycle. A prerequisite for achieving this is the early involvement of the supply function in the product design process. Design for Environment (DfE), otherwise known as “green product design” or “green engineering”, is thus emerging as an important factor, which must be integrated with other design tools along the supply chain [14]. The targets of DfE span the minimization of the usage of materials, whose acquisition is environmentally damaging, the maximization of the usage of recycled materials, renewable resources and recyclability, and finally the reduction of material use and waste [14, 17].

While up to date, there can be found a number of publications related to the sustainable development of closed-loop supply chains, there is clearly a lack of methodological approaches that adress the impact of critical environmental parameters on the operations of closed-loop supply chains. It is this void that the modeling approach that we present in this paper attempts to fill in. More specifically, we consider a generic single producer closed-loop supply chain with recycling activities and we present the development of a methodology based on the principles of System Dynamics (SD). The contribution of this methodological approach is that we model the influence of both take-back obligations imposed by regulations and green consumerism on the DfE, and then study the impact of DfE on the system’s behavior. Using the model a policy-maker can conduct various “what-if” analyses about the dynamic behavior of the system by evaluating the effects of abrupt changes imposed by the external environment (e.g. the enforcement of a new regulation), while having modeled comprehensively constraints as lower limits of recycling, take-back obligations, green consumerism and DfE.

The next section presents a brief SD literature review. The conceptual modeling of the ecological motivation is presented in section 3. In section 4 we present the comprehensive SD model and the issues that can be investigated using the proposed methodology. Finally, in section 5 we wrap-up with a summary and the conclusions of our study.

2 SD Literature Review

The primary modeling and analysis tool used in this research is System Dynamics (SD) methodology. It is a powerful methodology for obtaining useful insights into problems of dynamic complexity and policy resistance. Forrester [10] introduced SD in the early 60’s as a modeling and simulation methodology for long-term decision-making in dynamic industrial management problems. Since then, SD has been applied to various business policy and strategic problems [19]. There are already a few publications using SD in supply chain modeling, but most of them refer to forward logistics. Towill [21] uses SD in supply chain redesign to provide added insights into SD behavior and particularly into its underlying casual relationships. The outputs of the proposed model are industrial dynamics models of supply chains.

It is noteworthy that very few strategic management problems in closed-loop supply chains have been analyzed and are reported in the literature [9]. Sterman [19] presents two case studies where SD is used to model reverse logistics problems. The first one analyzes part recovery and material recycling in the US auto industry to provide insights about the future of enhanced auto recycling. The second one concentrates on the market mechanisms of paper recycling, which usually lead to instability and inefficiency in flows, prices, etc. Berends and Romme [4] examine the cyclicality of paper sale prices, of profit and of existing productive capacities for the entire paper industry, using a SD approach. Spengler and Schroter [18] use a system-oriented approach based on SD to develop a tool for strategic spare-parts management in Agfa-Gevaert. They model an integrated production and recovery system for supplying spare parts to evaluate possible strategies for meeting spare-parts demand for electronic equipment in the end-of-life service period. Tang and Naim [20] study the system dynamics of a hybrid system with reverse logistics flows. They model a simple combined manufacturing/remanufacturing system and investigate its dynamic behavior. Mathematical and simulation analyses of the system indicate that the greater the degree of information transparency, the greater the robustness of the hybrid system is. Georgiadis et al. [12] present the major influence loops for the different forms of product reuse and systematically introduce how SD methodology can be applied to supply chains involving reverse logistics as well to develop strategic decision–making tools. Georgiadis and Vlachos [11] apply this methodology to develop a dynamic model in a first attempt to evaluate the effect of environmental issues on long-term decision-making in collection and remanufacturing activities.

3 Conceptual Modeling of "Ecological Motivation"

The structure of a system in SD methodology is described by causal-loop or influence diagrams. Causal-loop diagrams play two important roles. First, during model development, they serve as preliminary sketches of causal hypotheses and secondly, they describe the major feedback mechanisms [19]. The causal-loop diagrams' variables are connected by arrows, known as causal links, indicating the causal influences among the linked variables. The direction of a causal link represents the direction of the impact. The polarity (+) or (-) at the upper end of the causal links indicates how a dependent variable changes (in the same or in opposite direction) when the independent variable changes too.

The major feedback loops that exist in a causal-loop diagram can be either positive (reinforcing) or negative (balancing). In a negative feedback loop, after a disturbance, the system seeks to return to an equilibrium (balanced) situation, while a positive feedback loop exhibits the presence of an unstable equilibrium. In a feedback loop a change in a given variable traverses the entire loop and comes back to affect the same variable. The polarity of a feedback loop is obtained by the algebraic product of causal links polarities around the loop and is represented by (+) and (-) polarities. If an initial increase (or decrease) in a variable in a feedback loop eventually results in an increasing (or decreasing) effect on the same variable, then the feedback loop is identified as a positive feedback loop. If an initial increase in a variable eventually results in a decreasing effect on the same variable or vice versa, then the feedback loop is identified as a negative feedback loop. For the rest of the paper, when discussing the system's variables we will present them in italics.

Ecological motivation is expressed via environmental protection policies, for example imposing a percentage of recycling, and via customers' preferences to environmental friendly products. Fig.1 displays the causal-loop diagram of the described "ecological motivation". The diagram consists of three major negative feedback loops. Specifically, in Loop#1 an increase in *Uncontrollable Disposal* forces governments (*Environmental Protection Policies*) to impose stringent *Take-back Obligations* of reused products. *Take-back Obligations* then increase the *Collection Rate* of used products leading to a decrease in *Uncontrollable Disposal*.

In Loop#2, an increase in *Raw Materials Usage Rate* leads stricter limits of percentage of recycling (*Environmental Protection Policies*). However, products' designers (DfE activities) usually can not react in a timely manner about any increases on the percentage of recycling imposed by regulations. According to our experience with industrial firms in Northern Greece with product reuse activities, this is due either to negligence or even due to the belief of corporate executives that it is more cost-effective for the firm to pay fines due to its indifference to imposed regulations, than to redesign its products. As a consequence of this practice there is a significant time lag between the time that regulations are imposed and when designers are ready to react on legislative modifications (captured by the delay in Fig.1). The latter from now on will be captured in our SD model by a variable named *Legislation Perceived by the Firm*. An increase in *Legislation Perceived by the Firm* causes an increase in *DfE* and in *Recyclability*.

In Loop#3, an increase in *Collection Rate* causes an increase in the green image factor (*GIF*), in *DfE* and in *Recyclability*. An increase in *Recyclability* leads to a decrease in *Raw Materials Usage Rate* that leads to less stringent *Take-back Obligations* and to a decrease in *Collection Rate*.

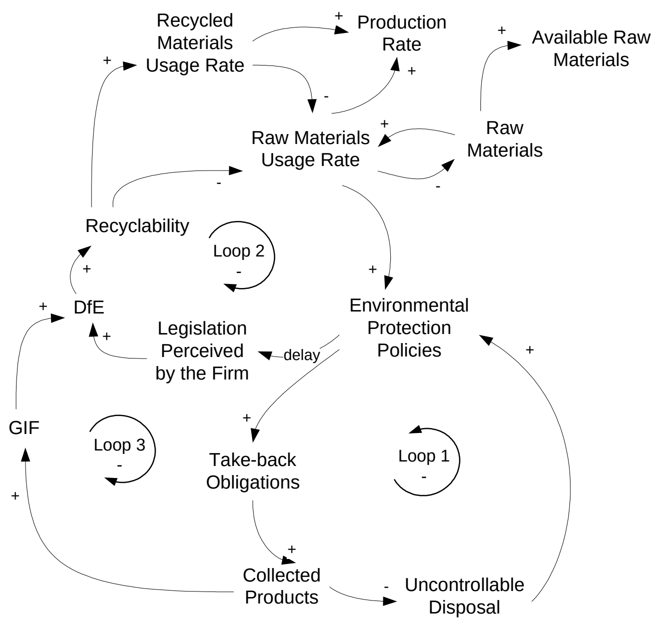

Fig.1. Causal-loop diagram of the ecological motivation

Apart from the three loops, in Fig.1 it is clear that an increase in *Raw Materials Usage Rate* leads to a decrease in *Available Raw Materials*. The *Available Raw Materials* are measured in years, representing the remaining life time of a specific type of raw material.

4 Modeling of the System under Study

The trends, briefly described in section 1, are further exacerbated as technological innovation has led to constantly shrinking product life cycles and an ever increasing number of product offerings; this is particularly true in IT, where Moore's Law still reigns. A variety of consumable products that their recycling is extensive includes cell phones, white goods (like washers and dryers), tyres and photo films [23], automobiles, batteries [15], and generic products such as sand [3] and household waste [5].

One of the simplest generic manifestations of an ecologically motivated closed-loop supply chain with recycling appears in Fig.2. The system under study includes a single producer closed loop supply chain (with a forward and a reverse component) that consists of the following distinct operations: supply of original raw materials, production, use, collection, recycling and disposal. Systems like this are encountered quite often in Greek Small-Medium Enterprises (SMEs) that make up 85-90% of the country's companies. The same trend can be observed in other relatively small EU member countries.

The forward supply chain begins from the upper left corner of Fig.2. The forward supply chain includes only one echelon (producer). In the reverse channel we assume that the only reuse activity is that of recycling. *Raw Materials* (original raw materials) are provided by external suppliers. The *Raw Materials Usage Rate* that depletes the *Raw Materials*, and the *Recycled Materials Usage Rate* that reduces *Recycled Materials*, compose the *Production Rate*. The *Recycled Materials* are the outcome of the firm's recycling operations. The *Production Rate* increases the *Serviceable Inventory* that is then depleted to satisfy *Demand* through *Sales*.

The product sales at the end of their usage period turn into *Used Products*, which can be either uncontrollably disposed (*Uncontrollable Disposal*) or collected for recycling (*Collection Rate*). The *Collected Products* are transferred to the recycling centers (*Shipments to Recycling Centers*) increasing the stock of *Recyclable Products*. The *Recycling Rate* depletes the *Recyclable Products* and increase the stock of *Recycled Materials*. The recycled materials are used as raw materials in producing new products thus "closing" the loop. In the production process, all the *Recycled Materials* are used; in case they do not suffice to satisfy the production needs, *Raw Materials* are then used. The input of *Raw Materials* and the Demand shape the external environment of the system. The inventories in the system of Fig.2 are managed by means of a combined "pull-push" policy; we adopt a "pull" policy in the forward channel to maintain better stock control, while we use a "push" policy in the reverse channel to achieve faster system response [22].

In Fig.2 the material flows are the outcome of corresponding decision-making processes. In this research the following flows: *Collection Rate*, *Recycled Materials Usage Rate*, *Raw Materials Usage Rate* and *Production Rate*, as documented in section 3, are determined by a decision-making process that is additionally influenced by the "ecological motivation", as this is manifested with environmental legislation and green consumerism. Specifically, take-back obligations imposed by the *Environmental Protection Policies* increase the *Collection Rate* and the *Recycled Materials Usage Rate* and decrease the *Raw Materials Usage Rate* and *Uncontrollable Disposal*. As customers' expectations motivate companies to further produce environmental friendly products of increased recyclability, the *GIF* has emerged as an issue of significant corporate value since it can increase revenue streams [11].

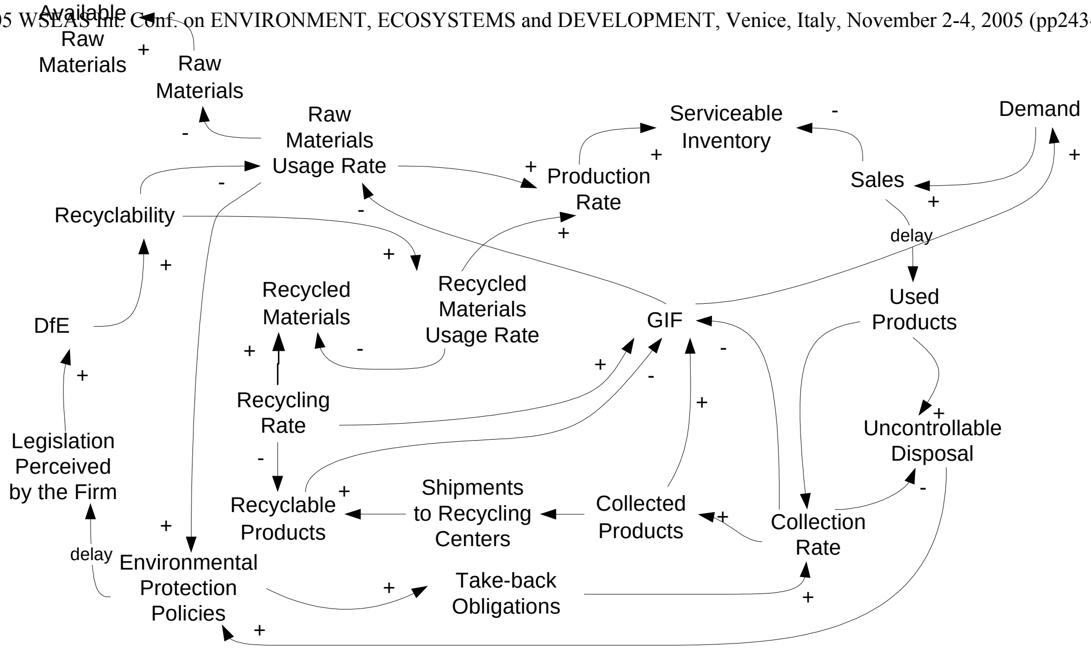

Fig.2. Causal loop diagram of the Closed-Loop Supply Chain under study

Thus, the developed model can be used by a decision-maker and/or a regulator to conduct a number of "what-if" analyses regarding strategic decision-making. Issues that can be investigated using the model include the following examples of strategic decisions:

• What is the transient response of recyclability for various levels of lower limits of recycling imposed by legislation?

• What is the transient response of recyclability for various levels of GIF?

• What is the environmental protection policies' impact on reverse flows, raw materials usage rate and recycled materials usage rate?

What is the GIF's impact on reverse flows, raw materials usage rate and recycled materials usage rate?

• How different environmental protection policies and levels of green consumerism affect the stock of available raw materials?

We developed an SD model using the Powersim® commercial software and then ran a number of "what-if" analyses on a test case example. Due to the limited length of the paper we do not present the detailed modeling and the quite extensive numerical investigations. Instead, we summarize below the main intuitively sound conclusions. First, in case policy-makers/regulators are interested in decreasing the consumption rate of non-renewable resources, it is more efficient to increase the regulatory take-back obligation levels than to increase the collection percentage level. Secondly, the more environmentally sensitive the market is, the more pressure is imposed to industry to adopt DfE initiatives (that is exhibited by the system attaining its equilibrium quicker). Thus, fully understanding GIF emerges as an important corporate competitive practice.

5 Conclusions

We proposed a SD modeling methodology for a single producer and a single product closed-loop supply chain with recycling activities. The model can be used for obtaining a comprehensive understanding of the long-term system behavior under a wide range of alternative environmental issues that give rise to "ecological motivation", such as take-back obligations, collection percentage level, green consumerism and design for environment (DfE). The developed model can further be used as a methodological tool for the conduct of various sensitivity analyses evaluating the impact of various regulatory measures and green consumerism on system performance. Finally, the model could prove helpful to decision-makers and policy-makers/regulators dealing with closed-loop supply chain management issues along with researchers in the area of environmental management.

References:

[1] L.C. Angell, R.D. Klassen, Integrating Environmental Issues into the Mainstream: An Agenda for Research in Operations Management, *Journal of Operations Management*, Vol.17, No.5, 1999, pp. 575-598.

[2] G., Azzone, G., Noci, Identifying effective PMSs for the deployment of "green" manufacturing strategies, *International Journal of Operations & Production Management*, Vol.18, No.4, 1998, pp. 308-335.

[3] A.I., Barros, R., Dekker, V, Scholten, A two-level network for recycling sand: A case study, *European Journal of Operational Research*, Vol.110, No.2, 1998, pp. 199-214.

[4] P.A.J., Berends, A.G.L., Romme, Cyclicality of capital - intensive industries: A system dynamics simulation study of the paper industry, *Omega*, Vol.29, No.6, 2001, pp. 543-552.

[5] N.-B. Chang, Y.L. Wei, Siting recycling drop-off stations in urban area by genetic algorithm-based fuzzy multiobjective nonlinear integer programming modeling, *Fuzzy Sets and Systems*, Vol.114, No.1, 2000, pp. 133-149.

[6] M.P., De Brito, R., Dekker, A Framework for Reverse Logistics, in R., Dekker, M., Fleischmann, K., Inderfurth, L.N., van Wassenhove (Eds.), *Reverse Logistics: Quantitative Models for Closed-Loop Supply Chains*, Springer/Verlag, Berlin, pp. 3-27, 2004.

[7] I., Fernandez, *Reverse Logistics Implementation in Manufacturing Companies*, PhD thesis, Universitas Wasaensis, 2004.

[8] M. Fleischmann, J.M. Bloemhof-Ruwaard, R. Dekker, E. van der Laan, J.A.E.E., van Nunen, L.N. van Wassenhove, Quantitative Models for Reverse Logistics: A Review, *European Journal of Operational Research*, Vol.103, No.1, 1997, pp. 1 - 17.

[9] M. Fleischmann, *Quantitative models for reverse logistics*, PhD thesis, Erasmus University, 2000.

[10] JW. Forrester, *Industrial Dynamics*, MIT Press, 1961.

[11] P. Georgiadis, D. Vlachos, The Effect of Environmental Parameters on Product Recovery, *European Journal of Operational Research*, Vol.157, No.2, 2004, pp. 449 - 464.

[12] P. Georgiadis, G. Tagaras, D. Vlachos, Long-term Analysis of Closed-loop Supply Chains, in R. Dekker, M. Fleischmann, K. Inderfurth, L.N. van Wassenhove (Eds.), *Reverse Logistics: Quantitative Models for Closed-Loop Supply Chains*, Springer/Verlag, pp. 313-331, 2004.

[13] S.L. Hart, Beyond Greening: Strategies for a Sustainable World, *Harvard Business Review*, Vol.75, No.1, 1997, pp. 66-76.

[14] M. Lenox, A. King, J. Ehrenfeld, An assessment of design-for-environment practices in leading US electronics firms, *Interfaces*, Vol.30, No.3, 2000, pp. 83-94.

[15] C.P. Pappis, S.E. Daniel, G.T. Tsoulfas, LCA for Evaluating End-of-life Options of Spent Products, in R. Dekker, M. Fleischmann, K. Inderfurth, L.N. van Wassenhove (Eds.), *Reverse Logistics: Quantitative Models for Closed-Loop Supply Chains*, Springer/Verlag, pp. 333-356, 2004.

[16] J., Sarkis, Manufacturing Strategy and Environmental Consciousness, *Technovation*, Vol.15, No.2, 1995, pp. 79-97.

[17] S.J. Schvaneveldt, Environmental performance of products. Benchmarks and tools for measuring improvement, *Benchmarking: An International Journal*, Vol.10, No.2, 2003, pp. 136-151.

[18] T., Spengler, M., Schroter, Closed-Loop Supply Chains-A System Dynamics Approach, *Interfaces*, Vol.33, No.6, 2003, pp. 7-17.

[19] J.D. Sterman, *Business Dynamics: Systems Thinking and Modeling for a Complex World*, McGraw-Hill, 2000.

[20] O., Tang, M.M., Naim, The Impact of Information Transparency on the Dynamic Behavior of a Hybrid Manufacturing/ Remanufacturing System, *International Journal of Production Research*, Vol.42, No.19, 2004, pp. 4135–4152.

[21] D., Towill, Industrial dynamics modeling of supply chains, *International Journal of Physical Distribution & Logistics Management*, Vol.26, No.2, 1995, pp. 23-42.

[22] E., Van der Laan, M., Salamon, R., Dekker, An investigation of Lead-Time Effects in Manufacturing/Remanufacturing Systems under Simple Push and Pull Control Strategies, *European Journal of Operational Research*, Vol.115, No.1, 1999, pp. 195-214.

[23] D. Vlachos, P. Georgiadis, E. Iakovou, A System Dynamics Methodology for Dynamic Capacity Planning of Remanufacturing Reverse Supply Chains, *Computers & Operations Research*, to appear, 2005.