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Dynamic System Modeling for Closed Loop Supply Chains System

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Abstract. The need for holistic modeling efforts for returns that capture the extended closed loop supply chain (CLSC) system at strategic as well as operational level has been clearly recognized by the industry and academia. Strategic decision-makers need comprehensive models that can guide them in efficient decision-making to increase the profitability of the entire forward and return chain. Therefore, determination of a near optimal design configuration, which includes the environmental, economical and technological capability factors, is important in strategic decision-making effort that affect the profitability of the closed loop supply chain. In this paper, we adopted an improved system dynamics methodology to tackle strategic issues that affect various performance measures, like market, time/cost, environment etc., for closed loop supply chains. After studying real life implementation issues in CLSC design, we presented guidelines for the PBM (Participative Business Modeling) methodology and presented its extension for the strategic dynamic system modeling of return chains. Finally, we demonstrated the measurement of operational performance by extending SD (system dynamic) application to closed loop supply chain management.

Keywords: Reverse Logistics, Closed Loop Supply Chain, Dynamic Modeling, And Business Modeling

1. INTRODUCTION

Closed loop supply chain and reverse logistics management are just two paradigms of how environmental and economical issues related to management of product returns have been incorporated into an academic context. However, these research areas can still be considered as fairly young. Several authors have spoken of ‘reverse supply chains’, a topic which was mainly discussed in practitioner circles (e.g. Cruz, 2000; Morrell, 2001; Serant, 2001). However, a clear definition of closed-loop supply chain only seems to have emerged thereafter. In general, a closed loop supply chain system can be defined as the process of moving goods from their typical final destination for the purpose of capturing value, or proper disposal (Rogers and Tibben-Lembke, 1998).

A closed loop supply chain system incorporates a supply chain that has been redesigned to manage the flow of products or parts destined for remanufacturing, repairing, or disposal and to effectively use resources (Dowlatshahi, 2000). The first contributors in designing a closed-loop supply chain were probably Thierry *et al.* (1995) with their model of an ‘integrated supply chain’. This integrated supply chain has been defined as a supply chain, which is comprised of service, product recovery, and waste management activities. Figure 1 is a generic illustration of a product return network, or so called integrated supply chain, where the retailers, collection stations, and evaluation point serve as decision-making nodes for opting reverse manufacturing facilities. This figure attempts to incorporate entire possible facilities and transportation links in a forward and reverse logistics network. It also demonstrates how all of these reprocessing facilities, along with involvement of third party and local remanufacture, are integrated. Then, depending upon market, environmental, legislative conditions etc., one can route the products to various nodes

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of reverse logistics. This can also be further viewed as a type of routing problem which is dynamic. In this direction Wadhwa and Browne (1989) have shown the benefits of routing flexibility in a manufacturing system. These flexibility concepts can also be discussed in multiple entity flows (Wadhwa and Rao, 2003; Wadhwa *et al.*, 2006) from an enterprise synchronization perspective in the context of reverse logistics. It can be suggested that routing flexibility can play a vital role in designing an RLS.

Besides this, strategic and operational decision-makers need comprehensive decision models that can guide them to capture the dynamics and profitability of the return chain. Products after return must be moved promptly to the reprocessing station in order to avoid loss in value (Davey, S., 2001). During the years, several definitions have been developed and tried to communicate to managers how, when, where and what product return occurs in a firm and which factors affect the outcome or if the process is effectively and efficiently managed (Sundong *et al.*, 2003). These definitions come from different perspectives that either focus on management, economic or social sciences. The factors that are relevant to CLSC, as they are presented in the literature, however, create a complex net. Product recovery operations in CLSC are often characterized by a high variety of products, uncertain product condition after usage, and hence result in high levels of uncertainties when it comes to making decisions that determine the destiny of the product at its end-of-life. Uncertainties prevalent in product recovery management are broadly classified in the literature as (i) quantity uncertainty-uncertainty with respect to the number of products returned at any time, (ii) timing uncertainty-uncertainty

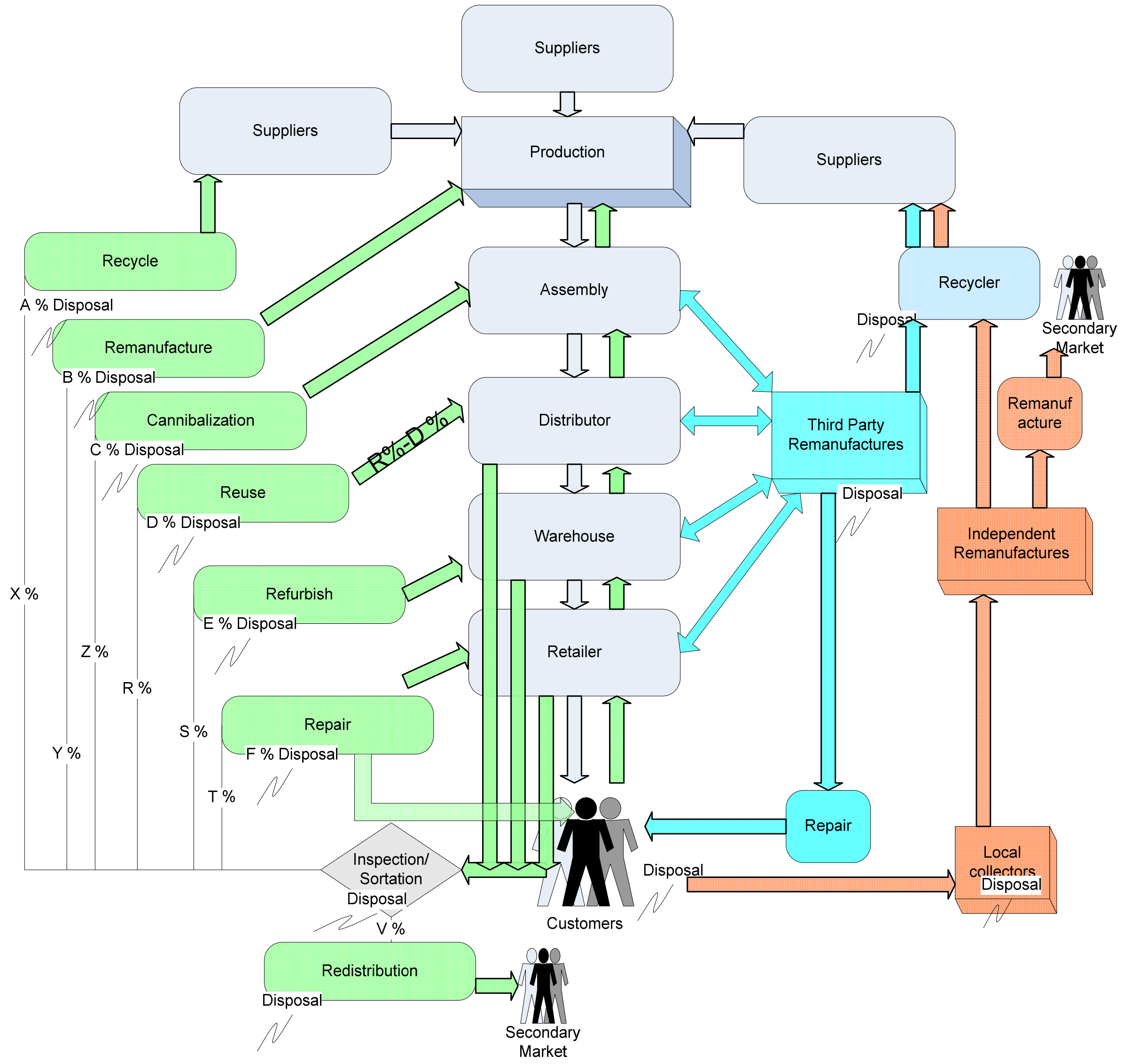

Figure 1. Generic View of Closed loop Supply Chain

with respect to the time at which a product will be returned, and (iii) quality uncertainty-uncertainty with respect to the quality of the returned product (Guide *et al.*, 1999; Toffel, 2004). These complexities pose difficulties in planning and controlling collection processes. This is detrimental to design the integrated forward and reverse distribution networks of CLSC. In addition, legislative, R&D and marketing issues for the product return issues have profound ramifications on the design of the closed loop supply chain. For instance, proper monitoring and response to problems require the ability to trace back lots, from retailer to reprocessing station, and sending it back to the forward chain. All these characteristics, along with the dynamically evolving framework, further hinder the task of efficiently managing closed loop supply chains. An SD model, both at strategic level (design) and operational level (system performance measurement), is developed to study this dynamics of product returns based on various criteria, e.g. cost/time, market, environment, quality, legislation, etc. The key motivation for this paper is the evaluation impact of these criteria on the model and to calculate approximate level of returns at various collection centres in return chain under different circumstances. The objectives of this paper are to capture dynamics of the different actors in the system under a common perspective and to reveal the complexity of CLSC. In order to achieve this, a dynamic system model has been designed under a system dynamics approach under phased implementation of PBM methodology. In the next section, the drivers of CLSC are described as they have been found in the literature. Continuously, the theories about product return process that have been developed over time are presented and the new system concept for CLSC is revealed. Section 3 illustrates challenges we faced while designing a framework for strategic decision making and then presented PBM methodology to capture the complexities of these challenges at various levels. Section 4 and 5 describes the Enviro-technoeconmetric decision model and presents an operational CLSC system model with profit as performance parameter. In Section 6 implementation results are given and in section 7 the conclusions close this paper.

2. REVIEW OF RELATED LITERATURE

Although there has been a growing interest in extracting value from product returns both in business and academics, there has been little research and development on how to plan for investment and design for closed loop supply chain. However, extensive research has been conducted at the operation level. Fleischmann (2001), Guide (2000) and Guide and Wassenhove (2003) offer comprehensive reviews of the remanufacturing reverse logistics, and closed-loop supply chain research on returns processes. These literatures have focused on operating issues (e.g., inventory control, scheduling, and materials planning) and the logistics of product recovery. Few studies take a business perspective of how to make product returns operations profitable (Guide and Wassenhove 2001, and Guide *et al.*, 2003). From a marketing perspective, research shows how returns policies affect consumer purchase probability and return rates. Wood (2001) found that more lenient policies tend to increase product returns. Research has also focused on the problem of setting returns policy between a manufacturer and a reseller and the use of incentives to control the returns flow (Padmanabhan and Png 1997, 1995; Pasternack 1985; Davis *et al.*, 1995; Tsay 2001). Choi *et al.* (2004) studied the effect of an e-marketplace on returns policy in which internet auctions are used to recover value from the stream of product returns.

From the environmental perspective, Graedel and Allenby (1998) explains how the concept of industrial ecology deals with the interactions of society, industry and the environment. Anonymous, 2001, explains the discipline of industrial ecology is the idea of taking ecology as a blueprint for designing sustainable business strategies, or the so-called 'eco-mimicry'. Bourg (2003) describes this phenomenon as taking the lessons from natural metabolism in order to artificially form an Indus trial metabolism. These perspectives can be illustrated as shown by Figure 2.

Overall these researches for closed loop supply chain came from different perspectives, which focus on operational, economic or social sciences and create a complex net. This complexity often makes decision makers to take a decision, the outcome of which contradicts their original aim of product return exercise. The objectives of this paper are to communicate these wide perspectives in the closed loop supply chain system under a common platform and also to reveal the complexity of product return systems. The model has also kept its focus on improving overall system performance. A closed loop supply chain system has been codified, under a system dynamics approach, to create a decision and operational model.

Literature suggests SD methodology can be applied to various business policy and strategy problems. There are already few publications using SD in supply chain modeling, but most of them refer to forward logistics. Forrester (1961) includes a model of a supply chain as one of his early examples of the SD methodology. Towill (1996) 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. Minegishi and Thiel (2000) used SD to improve the understanding of the complex logistic behavior of an integrated food industry. They presented a generic model and then provided practical simulation results applied to the field of poultry production and processing. Sanghwa and Maday (1996) investigated effective information control of a production-distribution system by automatic feedback control techniques. Sterman (2000) presented two case studies where SD is used to model reverse logistics problems. In the first one, Zamudio-Ramirez (1996) analyzes part recovery and material recycling in the US auto industry to provide insights about the future of enhanced auto recycling. In the second one, Taylor (1999) concentrates on the market mechanisms of paper recycling, which usually lead to instability and inefficiency in flows, prices, etc. Georgiadis and Vlachos (2004) use SD methodology to estimate stocks and flows in a closed loop supply chain, while providing specific paradigms with a fixed remanufacturing capacity change per year. The literature review has highlighted the research motivation to study dynamic system modelling for supply chains and indicated various research gaps that can led to extension of studies in SD modelling to the integrated of CLSC. Accordingly, literature review indicated the need for more generic conceptual frameworks that could help practitioners to understand these concepts in a more intuitive manner.

3. IMPLEMENTATION PBM TO THE CLSC

The main objective of this paper is to propose an SD based decision model that integrates environmental, economic, technical, market and legislative factors while designing of CLSC that will yield a near optimal process. While developing the decision model for a CLSC, we realized a number of challenging issues that acted as motivation for the development of the proposed model, especially in developing countries. Some of the issues constituting the problem of designing CLSC include:

- *Unavailability of Sufficient Data:* There is a need for adequate data to test for availability of markets for the purchase of required parts and materials, as well as determining the size of demand for returned products. This is essential for planning purpose and to assure the stakeholders of the possibility of suitable return on their investment. The accuracy of some of the available data is also in doubt, particularly in many developing countries like India where adequate records are not kept. This also poses a problem in making plans for product recovery, particularly using CLSC.

- *Lack of Strategic Planning for CLSC:* Although industrialism intends to satisfy needs and improve efficiency, it has been overwhelmed by a culture of waste generation. This arose from a planned obsolescence based product design and manufacture. The ever-increasing shortness in time period between significant changes in product designs also makes strategic planning for designing of CLSC a complex task. As an essential part of creating a sustainable industrial culture, the design of a supply chain must be based on assessment of the environmental impacts in all phases of the product from supplier to end user. This will result in less frequent

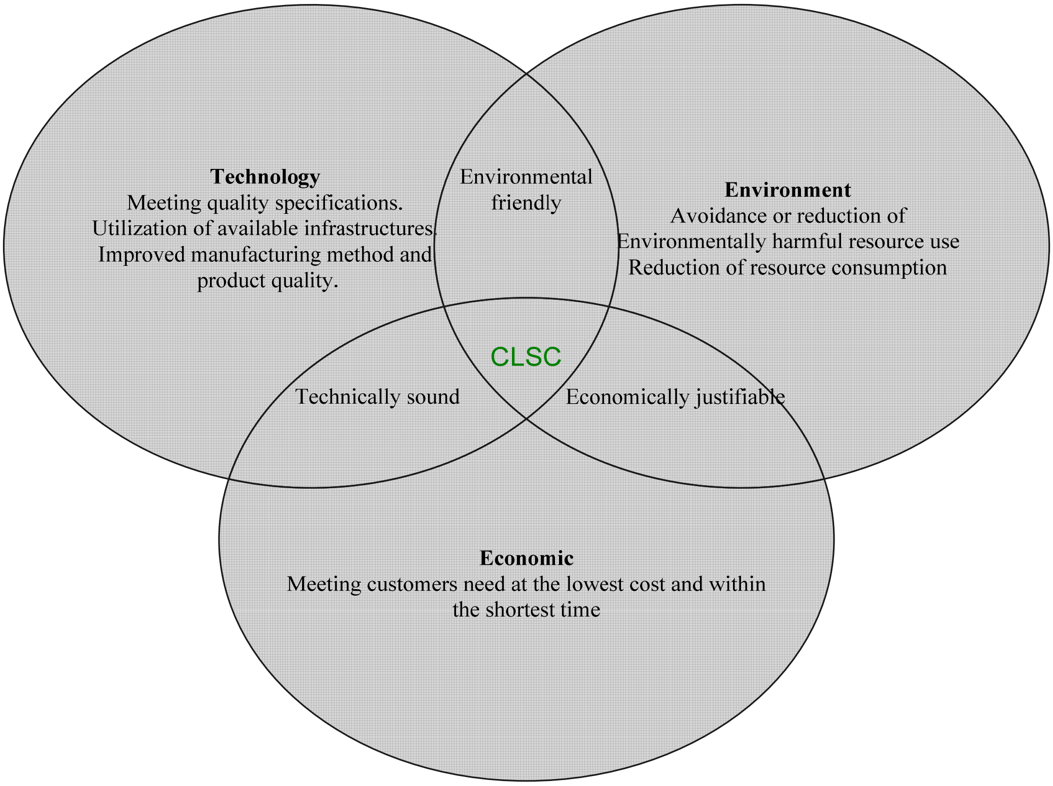

Figure 2. Proposed Goals of Designing a Closed Loop Supply Chain (CLSC)

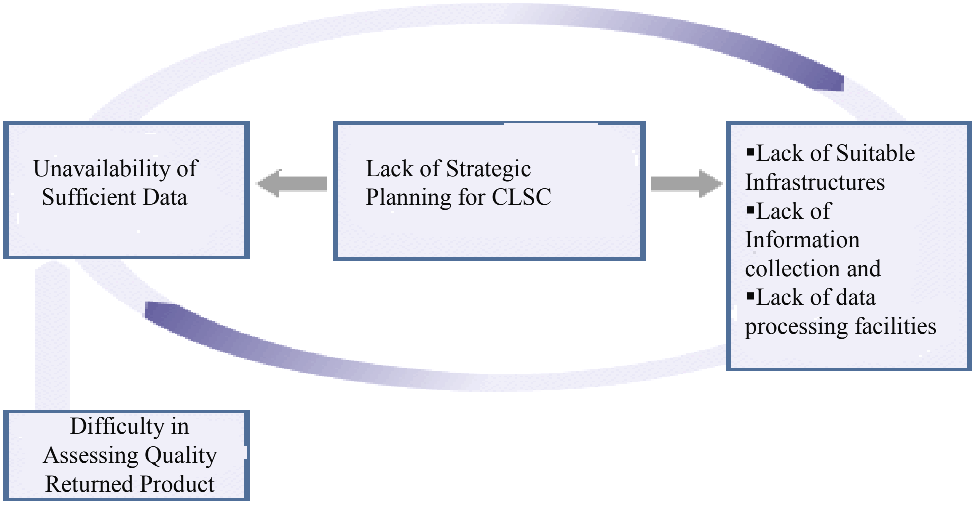

Figure 3. Challenging Issues for CLSC

product replacement which in turn means less waste and less use of energy and material resources (Shireman, 1999, Alting, 1999**)**.

- *Difficulty in Assessing Quality Returned Product:* The variation in the degree of use for product returned from forward chain depends upon product handling/use, differences in sourcing, and differences in corrosiveness of the environment where they were used. All these make it difficult to estimate the techno-economic life of a product to be sent to forward chain.

- *Lack of Suitable Infrastructures:* Information collection and data processing facilities are also essential for designing the appropriate "Enviro-Technoeconomic" CLSC system under a set of conditions. However, these are either not available or are inadequate in even developed countries. The interrelation among theses challenges can be illustrated by Figure 3.

Therefore, while designing a CLSC, these above issues can be undertaken with the use of an approach labeled "Participative Business Modeling" (PBM) by Akkermans (1995) to address not only the technical, but also the organizational, economical complexities inherent in the development of CLSC strategies. Participative Business Modeling combines intensive management participation with thorough analysis and extensive modeling aiming to facilitate learning about strategic issues of closed loop supply chain and therefore the gaining of insights decision-making in dynamic industrial management problems.

Starting with qualitative analysis, the method gradually leads to a more formal, quantitative operational modeling. PBM draws from several different methods, including System Dynamics Modeling, Operational Research, Social Sciences, process consultation etc., and aims to combine them for greater benefits. Here SD methodology for its flexibility and simulation advantages can be used as an implicit conceptual model which can be used as a technique that can specifically be used for long-term, chronic, dynamic management related problems and effective strategic decision-making in closed loop supply chain. Figure 4 illustrates the phased implementation PBM methodology for a CLSC system.

Participative Business Modeling comprises of four levels:

(1) The definition phase, using cognitive mapping of all the process involved in both forward and reverse direction the supply chain
(2) The model conceptualization phase where we employ brainstorming, causal loop diagramming, and stock and flow diagramming for the CLSC
(3) The model formalization phase, where System Dynamics Modeling as well as discrete event simulation can be applied (here we used SD methodology); and finally
(4) The knowledge dissemination phase, where 'what-if' models can be used for sensitivity and state analysis based on system performance that can continuously improve formalization phase factor rating.

This model can further be used to analyze various scenarios and identifying efficient policies for the whole system. Thus, it may prove useful to policy-makers/regulators and decision-makers in dealing with economic, technical, environmental, legislative etc issues in parallel.

4. CONCEPTUALIZATION FOR DYNAMIC SYSTEM MODELING FOR CLSC

Above discussed issues and proposed framework motivated us to design a system model for CLSC using SD methodology in conceptualization and formalization phase. The System Dynamics (SD) methodology, introduced by Forrester (1961), in the early 60's as a modeling and simulation methodology for the analysis and long-term decision-making of dynamic industrial management problems. Since then, SD has been applied to various business policy and strategy problems (Sterman, 2000). SD methodology provides a more flexible modeling and simulation framework for decision making in dynamic management problems. Beside this SD model can be built from elementary feedback structures with statistical data playing at most a mirror role; it doesn't depend too much on the past data as do the econometric models. It allows us to mix intuition, theory and method. Further, many cause-effect non-linear relationships can be easily captured by an SD model. In socio-technical settings, it draws from both the experimental and non-experimental modes of research as well as the participant's perception of purpose and validation (Starr, 1980). Further, it might be less sensitive to data error (Johnson, 1980). All this is required to capture the diverse dynamics of CLSC to some extent. Due to the lack of available data in CLSC and the arguments above, we consider it appropriate to use the SD model for estimating effects of variables on product returns. However, it is appropriate to say here that an SD model cannot fully signify the complex reality of CLSC. Further, the knowledge dissemination phase suggests the model needs to be continually viewed in its proper perspective and improved accordingly. It must be supplemented by the approximation, judgment, and experience of experts and decision maker's. We tried to incorporate important feedback from experts and focus on causes rather than consequences. In the process of proposing model, we resolved many contradictions and ambiguities. Here we used VENSIM for programming and running our product returns in CLSC.

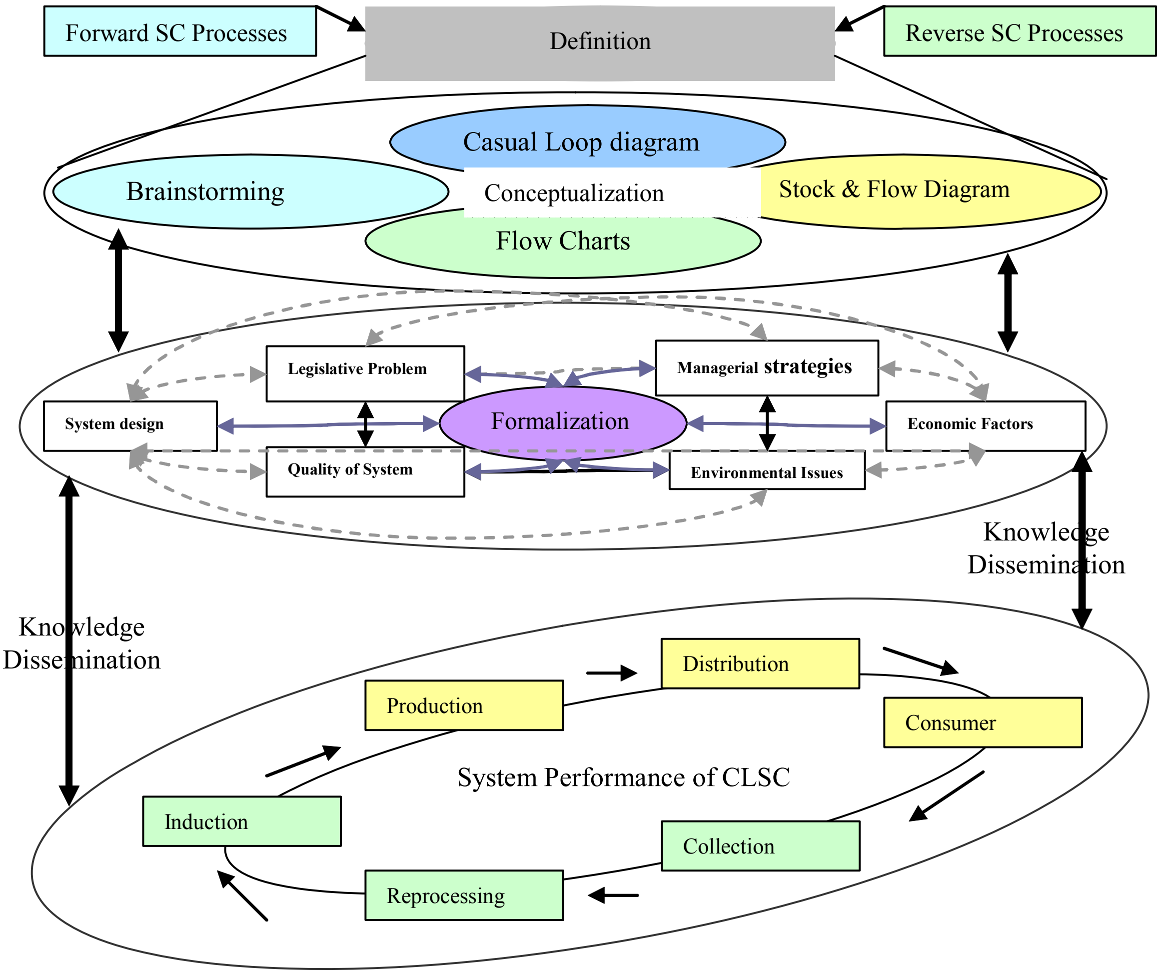

Figure 4. A PBM Model for Strategic Decision-Making in CLSC

The model applies various input parameters and generates output for different categories of products.

5. DYNAMIC SYSTEM DESIGN AND DEVELOPMENT FOR CLSC

The paper attempts to contribute by proposing a more generic conceptual framework that could help in understanding the dynamics involved in designing closed loop supply chains process. The objectives of the proposed conceptual framework are; (a) to capture and convey the idea of SD modelling in supply chain systems and extend the same to CLSC in a more generic manner (covering some service system features also); (b) to propose a conceptual framework for SD modelling in supply chains separately and with dynamic switching and decision sharing; (c) to identify various possible types of decisions at various stages and levels in CLSC; (d) to relate the proposed dynamic system model with the SD models commonly found in the literature; (e) to indicate some useful directions for further research. The conceptual framework for dynamic system modelling is based on the analysis of multiple entity flow, as discussed below.

We began our effort from the formalization phase by modeling a causal loop diagram for the CLSC system. These diagrams were constructed as per the expert's views of organizations that had knowledge of both forward and return process. They capture the important variables and their interrelationships as specified by the experts. At the point that a firm decides to invest in extending its forward supply chain to CLSC, it must commit financial, human knowledge and other resources (Figure 5). Research in CLSC together with other resources, such as market needs and public research, provides information for designing a return chain effectively. The direction of research shown here is influenced by the existing infrastructure for the forward chain and developing a CLSC needs investigation on the basis of the firm's internal factors, such as technological capabilities and corporate strategy.

A firm can introduce new and returned products into the primary or secondary market that have been developed and reprocessed by its own or it can license the return process from other firms. Their success however, depends on the satisfactory execution of the CLSC process; the specific project execution; the ability of the firm to produce and take back these products economically and send it to the end customer with a consistent quality. The consistency of production and launch of products depend on internal and external factors, such as adequate technological capabilities, the existence of legislative factors and environmental obligations of industries that will force the firm to take back the product and services from the market, the available infrastructure that may affect the economical and consistent dis-

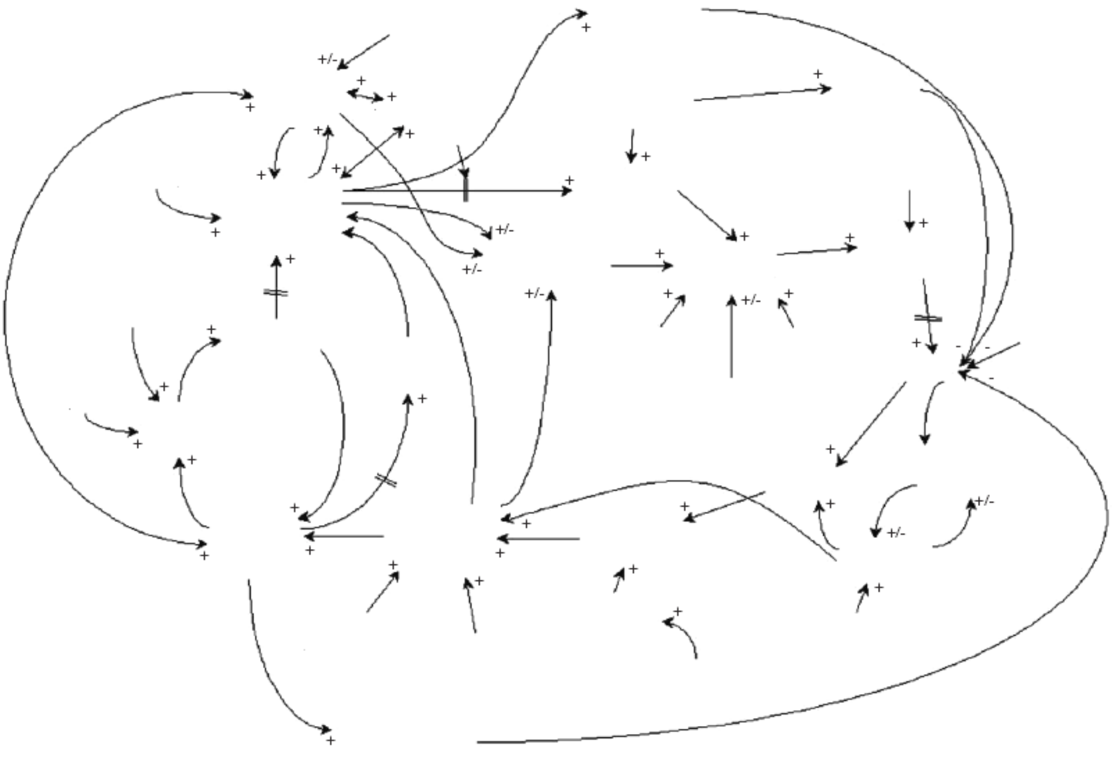

Figure 5. Enviro-Technoeconomic Model of CLSC

tribution of the product in the marketplace, and the existence of an adequate net market demand (new and returned products) (Burgelman *et al.*, 1996). The sales of new products together with the returned ones, after deducting the several costs, generate profit for the firm as formulated next section. Part of the profit is distributed to the firm's shareholders and another part is reinvested in the improvement of the CLSC process (Figure 5).

Furthermore we present the operational SD model shown in Figure 4 that measures performance of the CLSC in terms of time that allows a manager to quickly compute the value of the reducing delays. We discuss specific actions aimed at reducing delays in the network. The developed SD model allowed us to perform sensitivity analysis under complex scenarios, such as the presence of batching; (we comment on this later).

The facilities in the closed-loop supply chain include factory, distributor, retailer, customers; return centre facility for returns, collection and evaluation facility, reprocessing, and the secondary market, where remanufactured products are sold. We represent facilities by nodes, and the flow of products through the nodes is indicated in Figure 6. Here the strategic SD model for closed loop supply chain management deals with many diverse issues. It may include several types of possible criteria responsible for both forward and reverse movement of products. Reverse manufacturing brings the product back into an "as good as new" condition by carrying out the necessary disassembly, repair and replacement operations (Fleischmann M. *et al.*, 1997). Specifically, the finished products are first transferred to the distributors and then sold to satisfy the market requirement. The products sold, at the end of their life-cycle, turn into used products, which are either disposed or collected for reuse. The collected products after inspection/selection are either rejected and controllably disposed or accepted and transferred for various reverse manufacturing functions according to its condition. The loop "closes" with the reverse manufacturing operations into the forward chain in the following ways. First, through the flow of "as good as new" products to the serviceable inventory, as repaired product back to customer, as reusable product back to manufacturer and through the resale via "green image" in primary or secondary market, as shown in Figure 1. Raw materials input, net demand and legislation acts (take-back obligation) shape the external environment of the system. A major assumption of our model is the demand for remanufacturing with a relatively small variation.

6. IMPLEMENTATION

The structure for designing CLSC in SD methodology is captured by the proposed framework. This framework plays two important roles in SD approach. First, during model development, this framework serves as preliminary sketches of causal hypotheses and secondly, it can simplify the representation of a model. Hence, we try to capture the relationships among the system operations in an SD approach and to construct the appropriate framework for CLSC. Here in this framework we represent the major feedback mechanisms. To determine the flows of Figure 6, we use 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 (Van der Laan *et al.*, 1999). The size of the SD model is such that the analytical presentation of the interconnected networks and the control rules cannot be given within the limited paper's length. How-

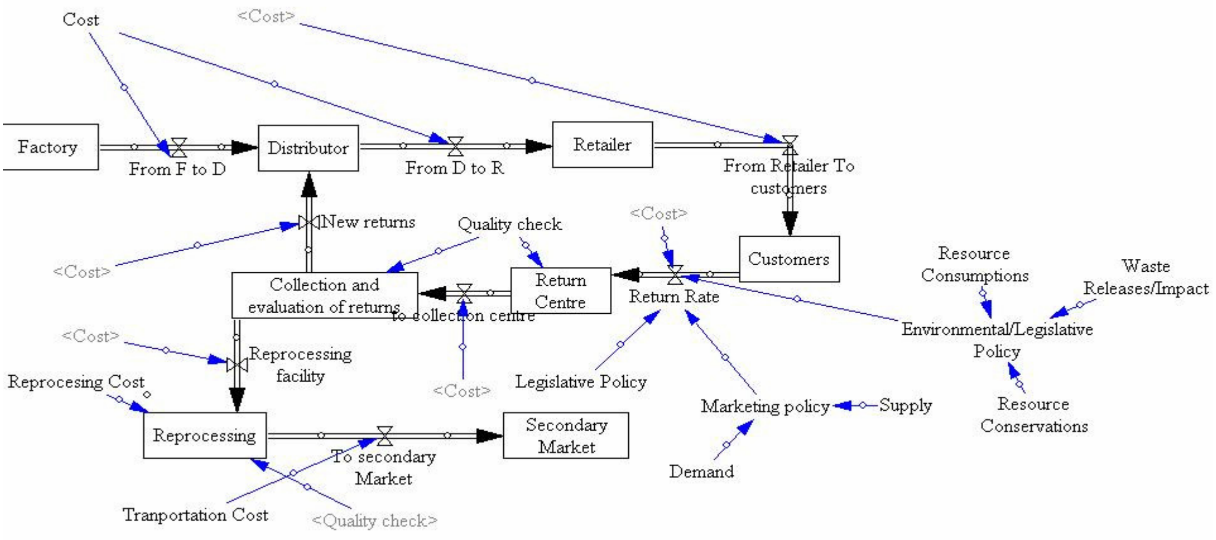

Figure 6. Performance Framework for CLSC

ever, the general form of the embedded control rules is indicatively presented in Figure 7 for the case of controlling the demand and return rate.

The CLSC framework begins with raw materials being provided by external suppliers, which consists of the sum of virgin raw material and recycled material from the return chain. Therefore, total order fulfillment consists of differences between these two inputs. Production depletes raw materials and it is the sum of two terms. The first is a forecasted value given by the difference of the orders from distributors minus the input from re-manufacturing rate (since the remanufacturing process supplements the production process). The second term is proportional to the difference between desired remanufactured inventory and actual remanufactured inventory, and it represents how quickly the firm tries to correct this difference. Naturally, the production rate is restricted by production capacity, which is assumed to be an external variable. The desired inventory level after remanufacturing depends on the distributor's

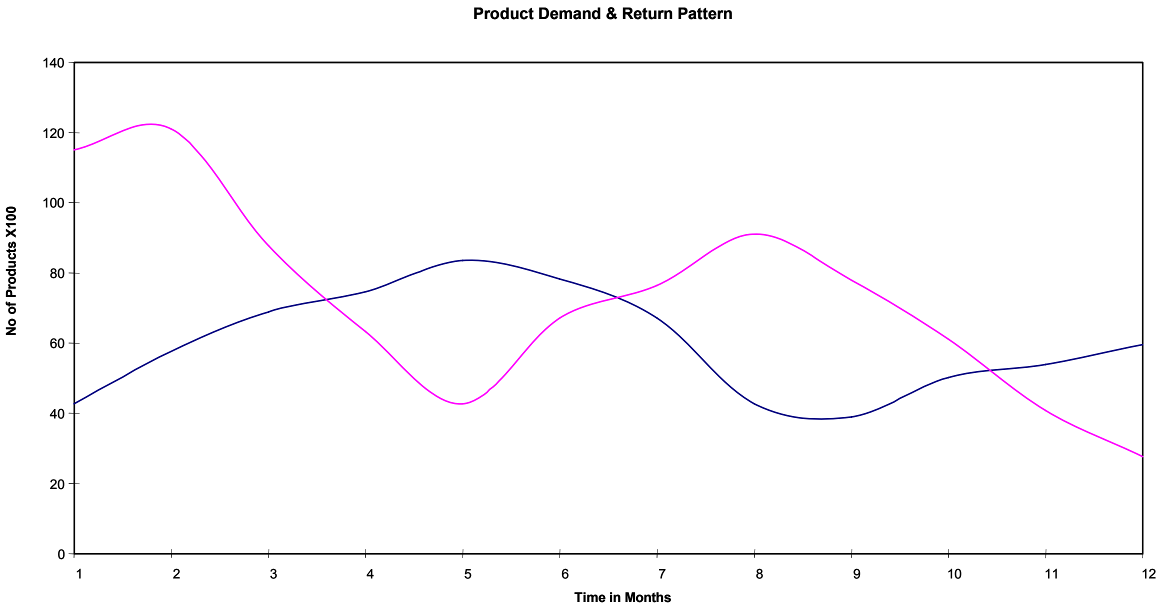

Figure7. Demand and Returns pattern with respect to time

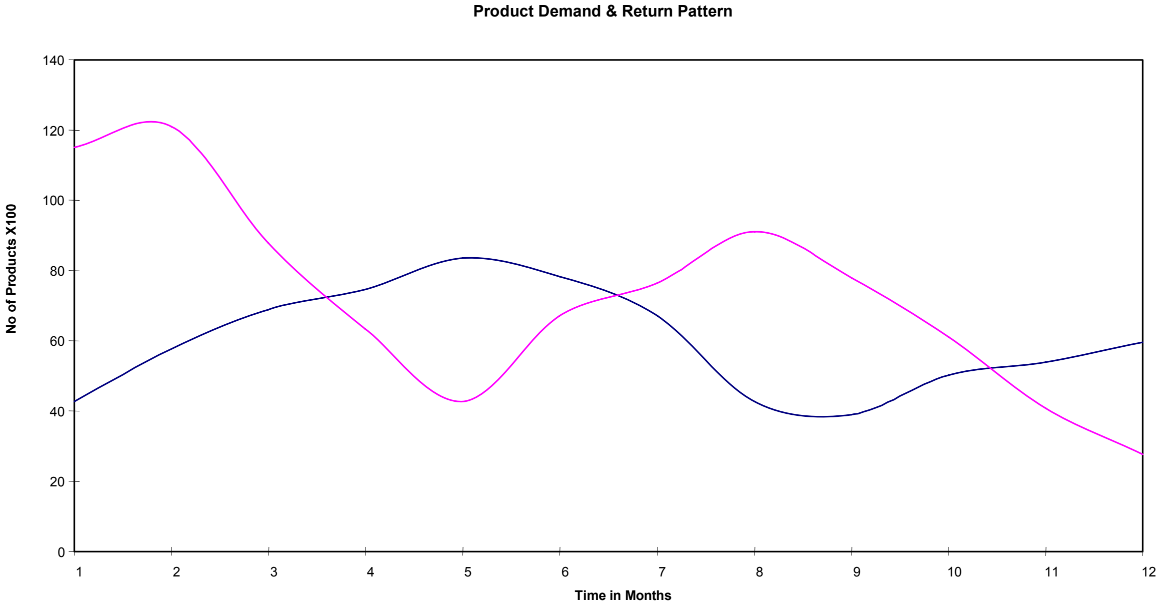
Figure7. Demand and Returns pattern with respect to time

orders and the required delay to cover these orders. Inventory at the production end will consist of production of new and remanufactured products and is depleted to satisfy as many as possible of the distributors demand through delay. The distributors demand depend on demand from retailers, which is satisfied through the difference of desired distributors inventory and actual distributor's inventory. Thus, distributor's inventory is depleted to satisfy retailers' demand which comes through sales to the customers. All these processes require delay time. Here, all unsatisfied demand is backlogged and may be satisfied in a forthcoming time period. Sales after their current usage turn into used products. The distribution of this usage time depends on the explicit product characteristics and it is easy to estimate by statistical study. Furthermore, used products are either disposed through uncontrollable disposal or collected for reuse. The reverse channels start with the collection and inspection procedures. Collected products after inspection are sent to respective reverse manufacturing functions depending on state of product with some time delay. Here collection rate can either be increased or decreased depending on capacity. The sales of new products together with the returned ones, after deducting the several costs, generate profit and total profit is calculated based on the dynamic-state behavior of the given CLSC. Different parameters considered can be represented as

Pr: Production rate; R_r: return rate of products; p: New returns; D_r: demand rate; Pr Processing rate at the node i;

To capture the gross effect of the varied system parameters we define the total profit function based on the CLSC network in Figure 8.

$$\text{Total profit} = N(P_r + R_r)P_k - \{(pR_rP_k + C_{raw}N(P_r + (1-p)R_r) + C_{dis}N(D_{dis}) + C_{insp}N(R_r) + C_{rep}N((1-p)R_p) + \sum_{1=1}^{n} C_{rep}N(R_{rep})p + C_{insp}(N(I)) + C_{ls}(N(LS)) + C_{pen}(N(I_{rej})) + C_T(N(P_r + (1-p)R_r))\}$$

Where:

P_k: Price /item

$C_{raw:}$: Raw material cost/item.

C_{dis} : Disassembly cost/item.

C_i : Inventory holding cost/item.

C_ls: Lost sales cost/item.

C_{insp} : Testing cost/item.

C_T : Transportation cost/item

C_{rep} reprocessing operations cost/item (i =1, 2, 3).

C_{pen} penalty cost of rejected returned products after inspection.

N (P_r +R_r): number of products produced

N (P_r+ (1-p)R_r): number of products produced

N P_r: number of returned products.

N (D_{dis}): number of disposed products.

N (R_r): number of inspected products.

N ((1-p)R_p): number of reprocessed products.

N (R_{rep}): number of remanufactured products by remanufacturing node i (i =1, 2, 3).

N (I): Number of on hand inventory.

N (L_s): number of lost sales.

N (I_{rej}): number of rejected items from the system.

In order to determine what the influence of (gradually) changing these parameters, from their respective base values, we performed a number of simulation runs. In the simulation runs, we gradually changed the value of one of these parameters. The results are illustrated in figure 7 and figure 8.

The model analysis allows for an easy visualization for the sources of revenues and costs in the network, as well as the monetary effects of various delays.

7. CONCLUSION

Limitation of this model arises from simplified representation of the real world CLSC. Thus, verification of models, in the sense of establishing truth, is difficult. Regardless of whether one agrees with this position, models seem to be most useful when they are used to challenge existing formulations, rather than to validate or verify them. Finally, operational level issues that affect the long-term development and operations of a firm, namely the determination of number, location and capacity of warehouses, manufacturing, reprocessing plants and the flow of material through the logistics network forward and backward directions, inventory management policies, distribution and collection strategies, integration, third party outsourcing strategies, decision support systems and information technology etc. can also be explored using this model.

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