System Dynamics Simulation for Strategic Green Supply Chain Management

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Abstract
The design of appropriate green supply chains in the manufacturing sector is a crucial task. The present paper seeks to (i) identify suitable performance measures for green supply chains and to (ii) develop a dynamic simulation model to assist supply chain decision-makers in developing appropriate policies and strategies in green supply chain management. Based on the principles of the system dynamics methodology, causal linkages between internal and external factors affecting the development of green strategies are investigated. Green concepts are used to develop crucial environmental and eco-efficiency performance measures in regards to strategic green supply management. Results from what-if analysis indicate that proper implementation of green strategies produces significant improvements for environmental, economic/financial and operational performance. Further numerical experiments demonstrate that the model can provide sound managerial insights.

Keywords
Green Supply Chain Management, System Dynamics, Environmental Performance

1 INTRODUCTION

The concept of greening the supply chain is a critical subject matter for competitive manufacturing. Environmental issues associated with resource depletion problems continue to rise. Manufacturers are often blamed for harming the environment through waste, resource depletion, and ecosystem disruption [1] [2]. Most of the stages of a product's life cycle influence the supply chain's environment burden, from resource extraction, to manufacturing, use and disposal. As such, environmental regulators continue to put in place strict controls. In addition, customers' environmental consciousness has evidently increased.

Green supply chain management (GSCM) is a systematic approach that incorporates green concerns into supply chain management. GSCM is an essential approach for improving supply chain profit and market share through reduction of environmental risk and impact. This has emerged as a strategy in most electronics companies such as Dell, HP, IBM, Sony, Motorola, Fujitsu, and Toshiba [3]. Firms have realised that environmental consciousness is a source of competitive advantage rather than a cost [4]. The most far-reaching approach of environmental management is to create value through greening the supply chain.

GSCM studies fall into two broad categories: (i) frameworks for GSCM implementation, and (ii) frameworks for performance measurement. GSCM frameworks seek to improve collaboration between manufacturers and suppliers, to investigate the gaps between the current state and the requirements of the framework, or to assist decision making [5] [6] [7]. On the other hand, performance measurement frameworks provide performance indicators that are for measuring system efficiency, to compare alternative systems, or to design proposed systems by determining the value of the decision variables that yield the most desirable performance levels [8] [9].

Questions arise as to which GSCM performance measures can be used to evaluate green activities. Which methodological tools can assist the decision makers in strategic green supply chain management? There is need to identify suitable performance metrics for evaluating alternative decisions. Obtaining an in-depth understanding of the factors that influence green supply chain behaviour is essential. Thus, factors related to environmental regulations, market green consciousness, and legislative penalties need to be investigated. The central objectives of this study are;

(1) to identify the essential indices for green supply chain performance;
(2) to develop a dynamic model to study the long-term behaviour of green supply chains;
(3) to carry out what-if analysis, deriving useful managerial insights into strategic green policies.

The remainder of this paper is structured as follows. An overview of GSCM is presented. Section 3 provides a brief background to system dynamics (SD) modelling. Section 4 presents the proposed SD model. Numerical investigations and illustrations are presented in section 5. Finally, section 6 concludes the paper.

2 GREEN SUPPLY CHAIN MANAGEMENT

Several academicians and practitioners have investigated the greening practices at operational and strategic levels. Specifically, green practices include product design [2], process design [10], purchasing [11] and green manufacturing practices [5]. From these greening concepts, GSCM can be defined as follows:

GSCM = Green Purchasing + Green Product Design + Green Manufacturing + Green Materials Management + Green Distribution + Green Logistics

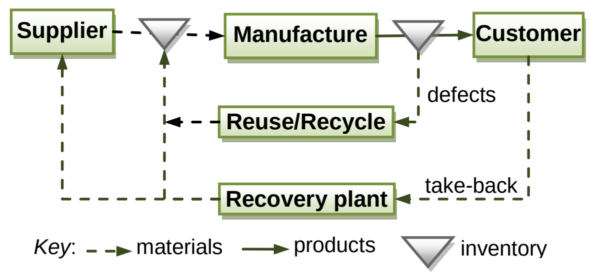

Figure 1 - Typical green supply chain structure

Figure 1 shows a typical green supply chain structure. Greening basically starts from the source, with supply restrictions, and goes its way through storage and packaging practices down to distribution and to customers. Product take-back follows the reverse flow channel, involving collection, disassembly, and re-use of parts. Used goods could be shredded and re-introduced into production as raw materials. Returned goods can be shipped to suppliers for remanufacture. Thus, “design for dis-assembly” is an important green concept to be incorporated in product design. Overall, GSCM is a holistic approach with far-reaching greening initiatives and competitive advantages [4] [6].

3 SYSTEM DYNAMICS

System dynamics (SD) is a simulation methodology first introduced by Forrester [12] in the early 60’s for long-term decision-making in dynamic business management problems. Since its inception, SD has been applied successfully to various policy and strategy problems [13]. One of Forrester’s [12] early examples of the SD methodology is an application on supply chain management. Towill [14] applied SD methodology for supply chain design, providing managerial insights into the underlying casual relationships. In the same vein, Minegishi and Thiel [15] used SD to improve the understanding of the complex logistics of a food industry chain. The authors presented a generic model, providing practical simulation results with application to poultry production. Little attention has been focused on reverse logistics. Georgiadis and Vlachos [16] used SD to model reverse supply chains, providing a specific scenario with a fixed remanufacturing capacity increase each year. Kumar and Yamaoka [17] presented a SD model of the Japanese car market providing an experimental simulation tool which can be used to forecast the relationship between reuse, recycle and disposal policies, and to investigate how various logistics elements will be impacted by government regulations. The application of a SD methodology can be extended to strategic GSCM.

4 SYSTEM DYNAMICS MODELLING

To illustrate the SD simulation approach for GSCM, a set of green performance indices, decision parameters, and the SD model are presented in this section.

4.1 GSCM performance measures

A set of indicators were designed to assess the performance of a typical green supply chain. We identify those indicators that directly relate to GSCM activities explained in Figure 1. Table 1 lists the indicators used.

Indicator	Description
1. Green image	Social or ecological responsibility over the environment
2. Raw material usage	New material consumed relative to the total materials used
3. Take-back penalty cost	Cost associated with disposal above maximum acceptable level
4. Investment cost	Investments in (re)manufacturing process technologies innovations
5. Operational cost	Costs associated with (re)manufacturing activities
6. Total profit per period	Realised revenue less total cost per period

Table 1 - Performance indicators used in this study

4.2 GSCM decision variables

In any green manufacturing supply chain, the choice of decision variables is important. Three typical structural decision parameters are identified and listed in Table 2.

Parameter	Description
1. Failure fraction, F	Average material inspection failure in the collection process
2. R_c	Collection capacity investment review period
3. R_r	Remanufacturing capacity investment review period

Table 2 - Major decision variables for the model

The *Failure fraction* signifies the extent of green innovation in product technology such as green design, in green packaging materials, and design for dis-assembly. R_c and R_r reflect green investments in process technology for collection and remanufacturing operations, respectively. Other decision parameters include non-negative constants

W_c and W_r, which reflect the willingness of the firm to invest in greening operations.

4.3 System dynamics model

Figure 2 presents the proposed SD model. The manufacturing plant utilizes raw materisl, *Raw_Materials*, at a rate, *manufacturing*, according to the expected demand, *Expected_Demand*, and produces serviceable inventory. Simultaneously, the remanufacturing plant produces serviceable inventory at a rate, *remanufacturing*, by utilizing *Recoverable_Inventory* from *Collected_Returns* collected from customers. On the other hand, some of the collected returns are sent for *Disposal* due to failure. Furthermore, some of the recoverable inventory is sent for disposal after a predetermined time period *RI Keeping Time*. For brevity of presentation, we only present key SD formulations.

Investment cost can be estimated [16] [18]. The cost *f*(*y*) for expanding manufacturing operations capacity by *y* is;

$$f(y) = ky^{a} \qquad (1)$$

where, *k* is a proportionality constant, and exponent *a* (usually *a* = 0.6) measures the ratio of the incremental to the average per unit plant capacity [18].

Therefore, the total investment cost, *InvestCost*, is determined as follows;

$$\begin{aligned} InvestCost = {} & CC\_BuildCost \cdot (CC\_AddRate)^{0.6} \\ & + RC\_BuildCost \cdot (RC\_AddRate)^{0.6} \end{aligned} \qquad (2)$$

Here, *CC_BuildCost* and *RC_BuildCost* are the collection and remanufacturing capacity building costs, respectively; *CC_AddRate* and *RC_AddRate* are the capacity addition rates, respectively. The reset of the cost formulations are outlined as follows;

$$\begin{aligned} PenaltyCost = {} & \mathrm{Max}[PenaltyLimit - collection, 0] \cdot \\ & UnitPenaltyCost \end{aligned} \qquad (3)$$

$$\begin{aligned} OperationsCost = {} & Collection \cdot CollectionCost \\ & + Remanufacturing \cdot RCost \\ & + Production \cdot MfgCost \\ & + RecoverableInventory \cdot HoldingCost \\ & + sales \cdot TransportationCost \\ & + SI\_Inventory \cdot HoldingCost \end{aligned} \qquad (4)$$

$$ProfitPerPeriod = Revenue - TotalCost \qquad (5)$$

$$\begin{aligned} TotalCost = {} & InvestCost + PenaltyCost \\ & + OperationsCost \end{aligned} \qquad (6)$$

$$Revenue = Sales \cdot Price \qquad (7)$$

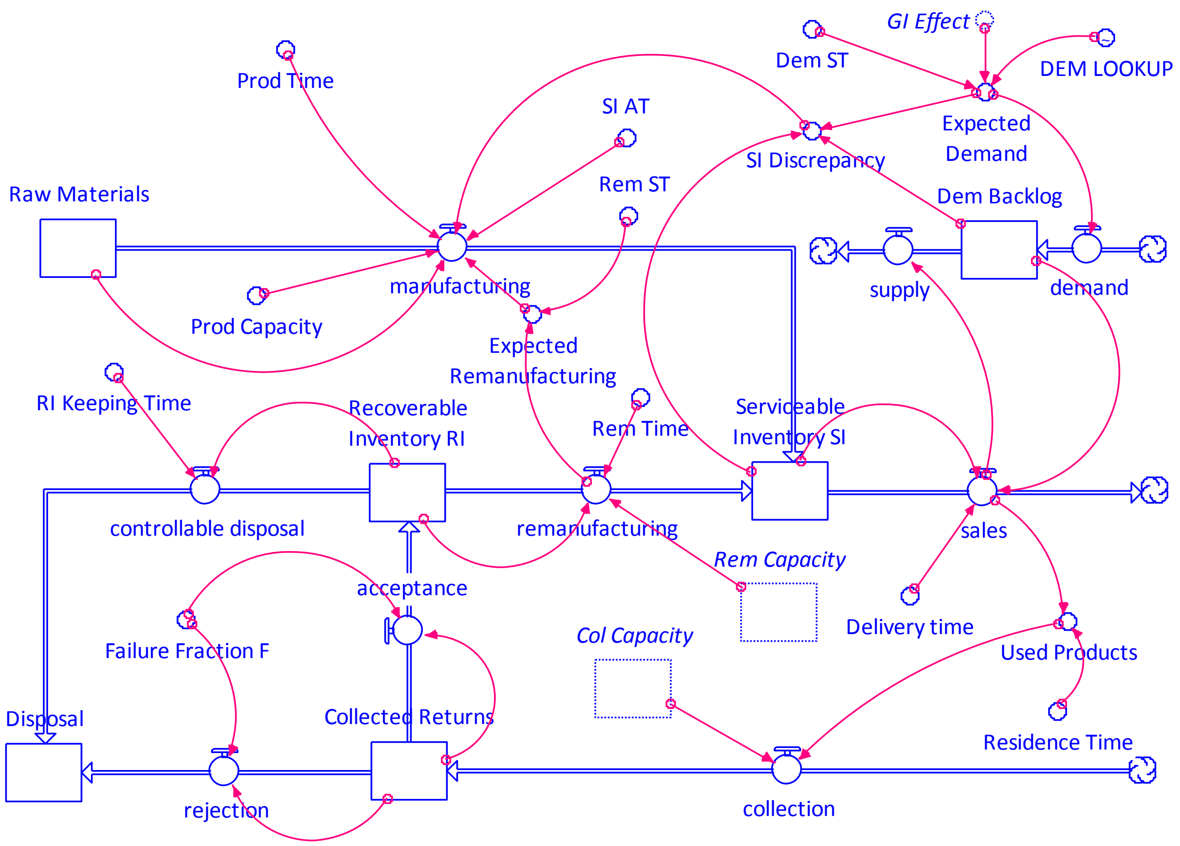

Figure 2 - System dynamic model for a typical green supply chain

Green Image (*GI*) depends on the market's perception of the manufacturer's ecological responsibility [11]. A suitable quantitative measure for *GI* is defined as a function of expected remanufacturing, and expected used products;

$$GI = b \cdot \left(\frac{Expected Remanufacturing}{Expected Used\ Products} \right) \quad (8)$$

Here, *b* is a constant of proportionality which depends on the market characteristics. The green image has a positive influence on customer demand; it gives the manufacture a competitive edge and increases the market share. This relationship is represented in Figure 3. The effective demand is amplified by green influence.

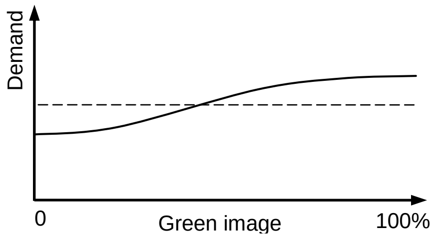

Figure 3 - Green effect on customer demand

Raw Material Usage (*RU*) pertains to the rate of consumption of new *Raw Materials* relative to that of the total materials (raw + recovered) used;

$$RU = mfg/(mfg + re\_mfg) \quad (9)$$

where, *mfg* and *re_mfg* are manufacturing and remanufacturing rates, respectively.

Figure 4 shows the collection operations capacity building model, where collection capacity *Col Capacity* is increased at a rate *CC Add* per period, depending on the magnitude of the desired collection capacity *Desired Col C*, which is a function of Used Products smoothed over time *CC ST*. Any discrepancy between the desired and the current capacities is adjusted according to the willingness (W_c) to invest in collection technologies.

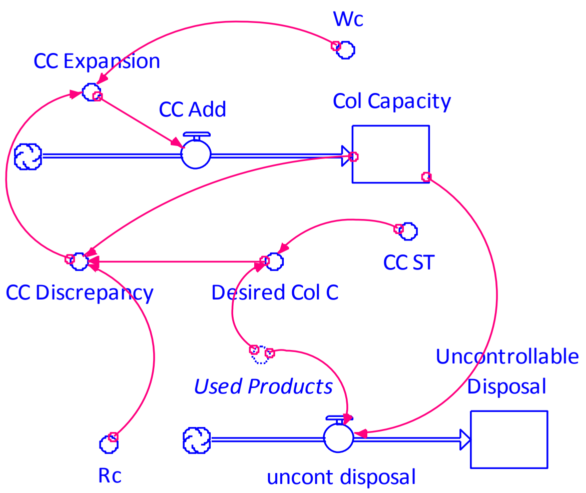

Figure 4 - Collection operations capacity building

Figure 5 shows the remanufacturing operations capacity building model. Here, the desired capacity *Desired RC* is influenced by the magnitude of the accepted used products *acceptance*. The rest of the model logic is analogous to the collection capacity model in Figure 4.

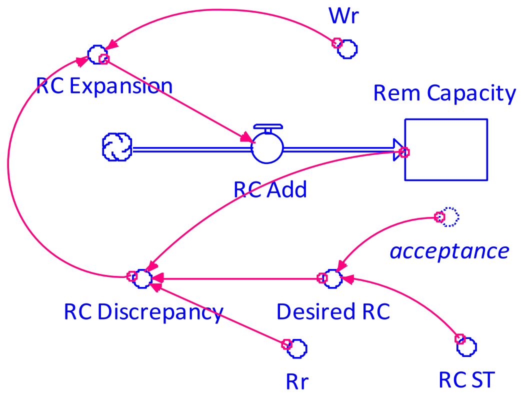

Figure 5 - Remanufacturing operations capacity building

5 NUMERICAL INVESTIGATIONS

The main decision variables are *F*, R_c, and R_r. Other variables used in further experimentations were *Wc* and W_r. The simulation would ideally include a study of the impact of all possible combinations of various levels of the variables. The planning horizon is 250 weeks, therefore experiments were run over a simulation period of 250 weeks. A growing demand input was assumed, as shown in Figure 6. It is assumed that the initial market share for the manufacturing supply chain is 40%.

The base set up is as follows: *Failure Fraction* is set to 25%. The cost parameters for the base scenario are: Manufacturing cost *MfgCost* is set to $40. Transportation and holding costs are $1/item and $0.50/item/week respectively. The rest of the costs are as follows: *CollectionCost* = $5/item, *RCost* = $30/item, *CC_BuildCost* = $500/item increase in collection capacity, *RC_BuildCost* = $1500/item increase in remanufacturing process capacity, *UnitPenaltyCost* = $0.5. The sales price is $120/item.

The next section provides simulation experiments, results and discussion.

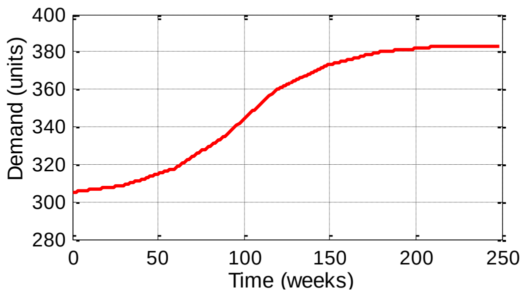

Figure 6 - Overall market demand input

5.1 Base simulation results

Base experiments evaluate the effect of decision variables on system performance. To that effect, a series of experiments were conducted by varying each decision variable while holding other variables constant.

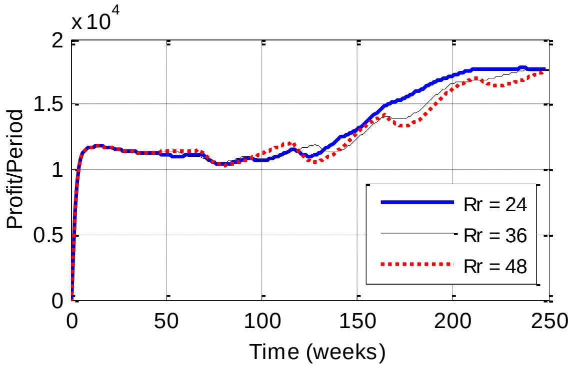

Figure 7 - Impact of R_r on Profit

Figure 7 illustrates the impact of the remanufacturing capacity review period (R_r) on profit per period. As R_r increases from 24 to 48, the profit/period decreases in the medium to long term. This shows that management commitment to investment in greening the manufacturing process is crucial if the supply chain is to gain or at least maintain its competitive advantage. The same analysis was obtained for the impact of W_c on Profit/Period, Green Image (GI), and Raw Material Usage (RU).

5.2 Sensitivity analysis

Sensitivity analysis evaluates the behaviour of the supply chain system so as to answer what-if questions in regards to variations of specific decisions. To this end, F, W_r, and W_c were varied one variable at time, keeping other variables constant. For brevity of presentation, only simulation results based on F and W_r will be presented.

Results in Figure 8 indicate the impact of F on supply chain performance in terms of GI, RU and Profit/period. Part (a) indicates that GI varies inversely with F. In (b), the raw material consumption increases with F. As expected, profit/period tends to increase as F decreases. We infer from these results that as the supply chain invests more in green product technology the failure fraction will be reduced considerable, e.g., green design will enable used products to be recycled or reused effectively, with considerable supply chain profit. Furthermore, it is important to consider long-term investments in green product technology, especially for a product with growing demand. This provides the manufacturing firm with a competitive advantage in the medium to long term.

As shown in Figure 9, a similar evaluation can be made: The willingness or management commitment in capacity building and process technology innovation is crucial for long-term competitive advantages in terms of green image, raw material usage and the overall profit of the chain. Sensitivity analysis based on W_c yielded a similar evaluation.

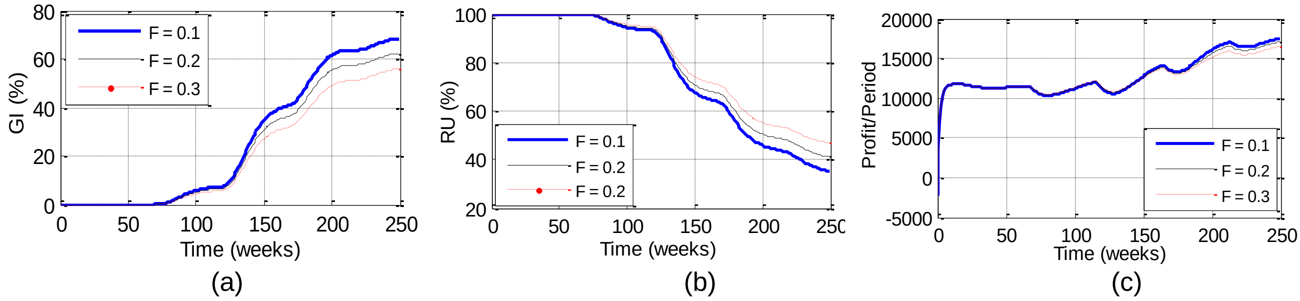

Figure 8 - Impact of F on GI, RU and Profit

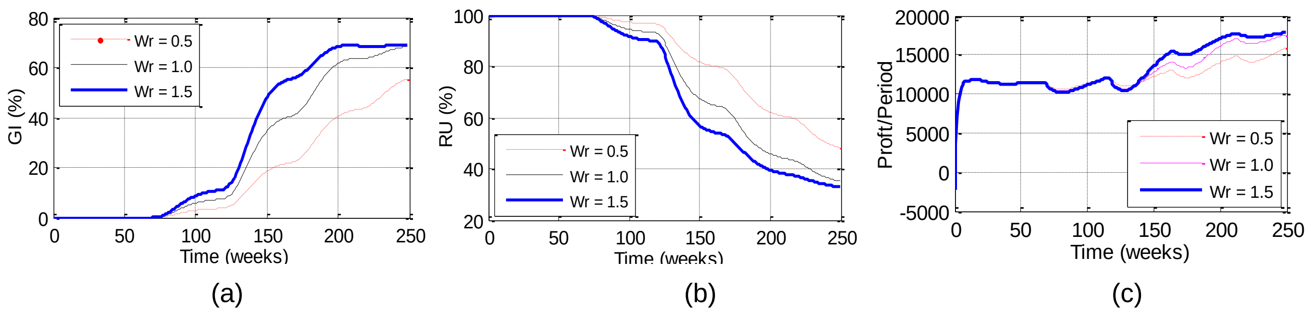

Figure 9 - Impact of W_r on GI, RU and Profit

6 SUMMARY AND CONCLUSTIONS

Apart from regulatory compliance, green manufacturing practices offer invaluable competitive advantages. A system dynamics model is developed to investigate the behaviour of a typical green supply chain. To assess the performance of the green supply chain, a set of suitable green performance measures are identified: green image, raw material usage, product take-back cost, investment cost, operational cost, and total green supply chain profit. In addition, the system dynamics model can assist supply chain decision-makers in developing appropriate policies and strategies when greening the supply chain. In order to gain competitive edge, the model can be used to cautiously assess investment decisions in product and process technology innovations so as to avoid waste and achieve optimal material usage. Based on numerical investigations and what-if simulations, useful managerial insights can be drawn to enable fast informed decision generation from a systems view point.

“Greening” investments enhance resource utilization, waste reduction and productivity improvement. Consequently, green initiatives minimize not only the environmental impact of a manufacturing supply chain but also raise efficiency and create major competitive advantages in operations and innovations. Thus, greening is a source of manufacturing competitiveness based on green image, leveraging innovation, and minimal resource usage.

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