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A System Dynamics Approach for Capacity Planning and Price Adjustment in a Closed-Loop Supply Chain

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Abstract— **In the recent years, there is a significant attention to closed-loop supply chain planning because of important business and environmental factors. Relevant literature shows that most of the researchers used mixed integer programming models (MIP) for closed-loop supply chain planning. Although MIP models are powerful tools for modeling and optimizing the design and planning of supply chains, but these models are unable to model the dynamics of such supply chains in planning problems. In this paper, a system dynamics model is developed to cope with the dynamics of closed-loop supply chains in capacity planning and price adjustment problems. To assess the performance and usefulness of the proposed model, the behavior of the model is analyzed through simulation. Normal parameter adjustment always can lead to proper and desired dynamic and static behaviors.**

Keywords— system dynamics; closed-loop supply chain; supply cahin planning

I. Introduction

The concern about environmental protection and also the economic benefits of using returned products has spurred an interest in designing and implementing reverse supply chain networks [1]. In recent decades, many companies focused on reverse logistics activities and they have achieved significant successes in this area [2, 3].

In most of cases the design of reverse supply chain networks leads to complex closed-loop structures. The coordination across supply chain is more difficult in this situation in compare with the traditional forward supply chains. Determining the capacity of recovery and recycling facilities is an important decision in reverse supply chain network design. Beside capacity planning determining the buy-back price of used products is also an important decision that has a strong influence on capacity planning. In the other words, these two decisions are interrelated and they should be optimized as a whole.

As the body of literature about reverse supply chain network design shows, mixed integer programming (MIP) models are the common models used in this area. These MIP models range from simple incapacitated models (e.g. [4]) to more complex capacitated (e.g. [5, 6]) or stochastic models (e.g. [7, 8]). Also, since most of these MIP models belong to the class of NP-hard problems, many heuristic algorithms (e.g. [9]) and meta-heuristics such as genetic algorithm (e.g. [10]), simulated annealing (e.g. [11]) and tabu search (e.g. [12]) are developed to solve these models.

In the recent years some researches (e.g. [13]) develop MIP models to integrate design of reverse network with buy-back price adjustment decisions. Buy-back price plays an important role in the profitability of the reverse supply chain and it can affect the quantity of returned products from customers. Although MIP models are powerful tools for modeling and optimizing the design and planning of reverse supply chains, but there are two major drawbacks in using MIP models in supply chain planning especially in strategic level: 1) in most of the cases MIP models cannot model the dynamic of closed-loop supply chains. 2) MIP models have weak ability for sensitivity analysis.

On the other side, System Dynamics (SD) is used widely for closed-loop system analyses in business, marketing, economics, etc [14]. Demand forecasts and supply chain studies are two especial fields that SD has contributed to investigate dynamic behavior of such complex systems (e.g. [16], [16]).

Therefore, as an alternative for MIP models, SD approach provides a flexible framework to overcome the abovementioned problems. In this paper we develop a system dynamic model for capacity planning and buy-back price adjustment in a closed-loop supply chain and we have verify and validate the proposed model by doing simulation and computational experiments.

II. Modeling Approach

The approach in this case is to develop a system dynamics model as a methodology in order to analyze the profitability of the reverse supply chain. The steps involved are adapted from Sterman's [14] modeling process:

(1) Define the dynamic problem to be solved and its scope;
(2) identify the variables involved and their relationship;
(3) draw the causal loop diagram;
(4) select suitable software to model the system;
(5) construct the stock and flow diagram;
(6) Simulate the model;
(7) Verify the model; and
(8) Validate the model.

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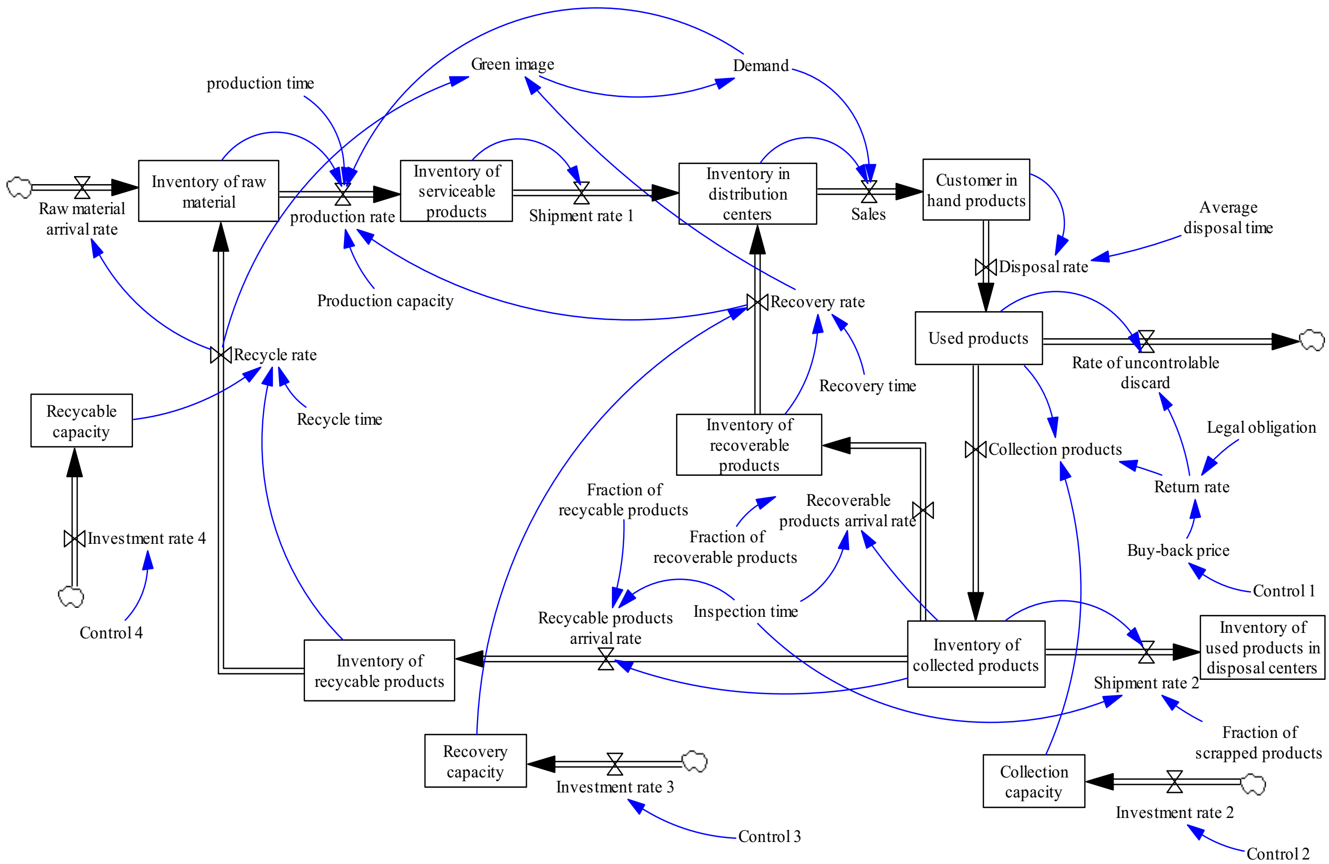


Fig. 1: Stock-flow diagram of the considered closed-loop supply chain network

Fig. 1 illustrates the discussed closed-loop supply chain network. In the forward flow, new products are shipped from production centers to customer zones through distribution centers and in the reverse flow, returned products are collected in collection centers and, after testing, the recoverable products are shipped to recovery facilities, and scrapped products are shipped to recycle centers. The recovered product and recycled products are reinserted into the forward chain at distribution and production centers.

This model has four control variables; three of which control the investment rate for adjusting the capacity of collection, recovery and recycling and the other one adjusts the buy-back price of used products. For example the mechanism of capacity adjustment for recovery center is formulated below.

Recovery capacity $(t) = \int(\text{Investment rate 3})dt$,
Recovery capacity (0) = 1500
Investment rate 3 = 40*DELAY3(Control 3 , 3)
Control 3 = PULSE(10, 10)

A similar mechanism and formulation with a little difference is used for other control variables. Another important point about the proposed model is the consideration of the impact of recovery and recycling activities on the green image of the company. The green image also influences the demand of customers. Therefore, the green image of company enhanced when the recovery and recycling rate increased, and this leads to increscent in the demand of customers (reinforcing loop).

III. Numerical Investigation

It can be shown by simulation based on many various parameter adjustments on the model that the system is a well-behaving one. There is a simple “Goal Seeking” behavior. The production capacity always limits the system from instability; however, increase in the demand due to the “Green Image” of the product which is subject to the recovery and recycling, causes more sales and more benefit for the company. To evaluate the performance of the proposed model, the model is implemented in Vensim 5.7 and some numerical investigation is done.

As the first run, the numerical experiments are done without using the control variables. As illustrated in Fig. 2, "Sales" are stabilized on 1700 at period 20 (months). The limitation of recovery and recycling capacity (see recovery and recycling rates in Fig. 2) forces the sales to stop at 1700. Now, we assume that the company decides to increase the sales up to 2000.

By using the control variables we can increase the buy-back price (Control 1) and the capacity of recovery and recycling centers. As illustrated in Fig. 3, the recovery and recycling rates increase and as a result the demand is also increased because of "Green image" enhancement. This reinforcing loop leads to increment of the sales' steady state to 2000.

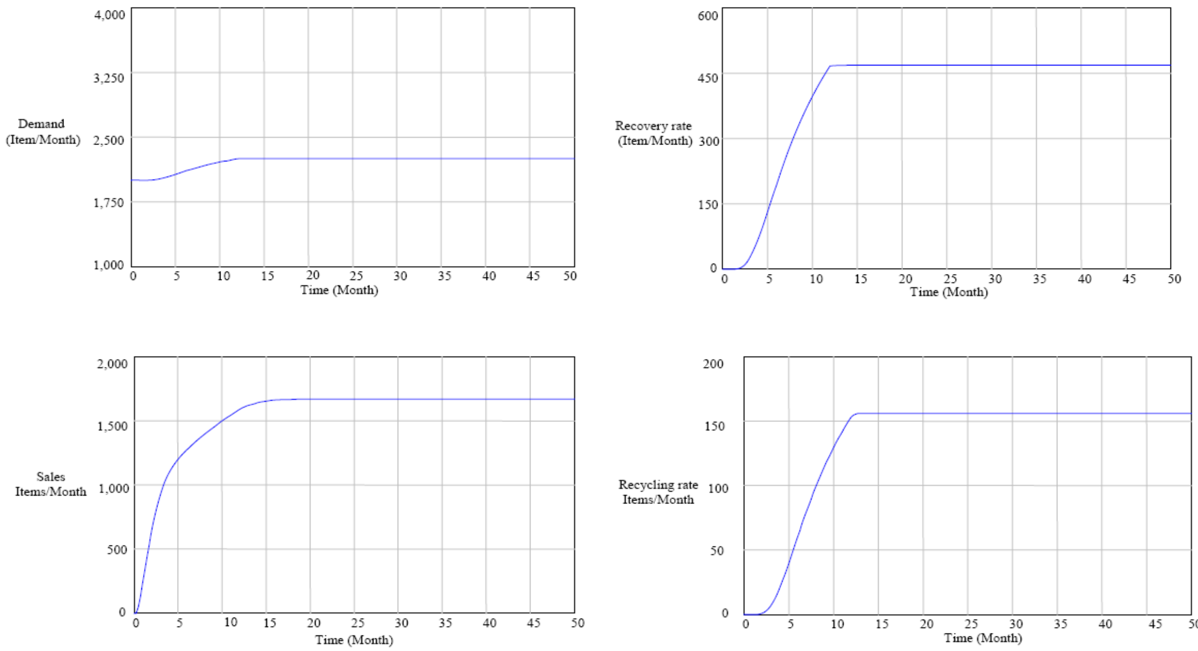


Fig 2: Experiment results without using control variables

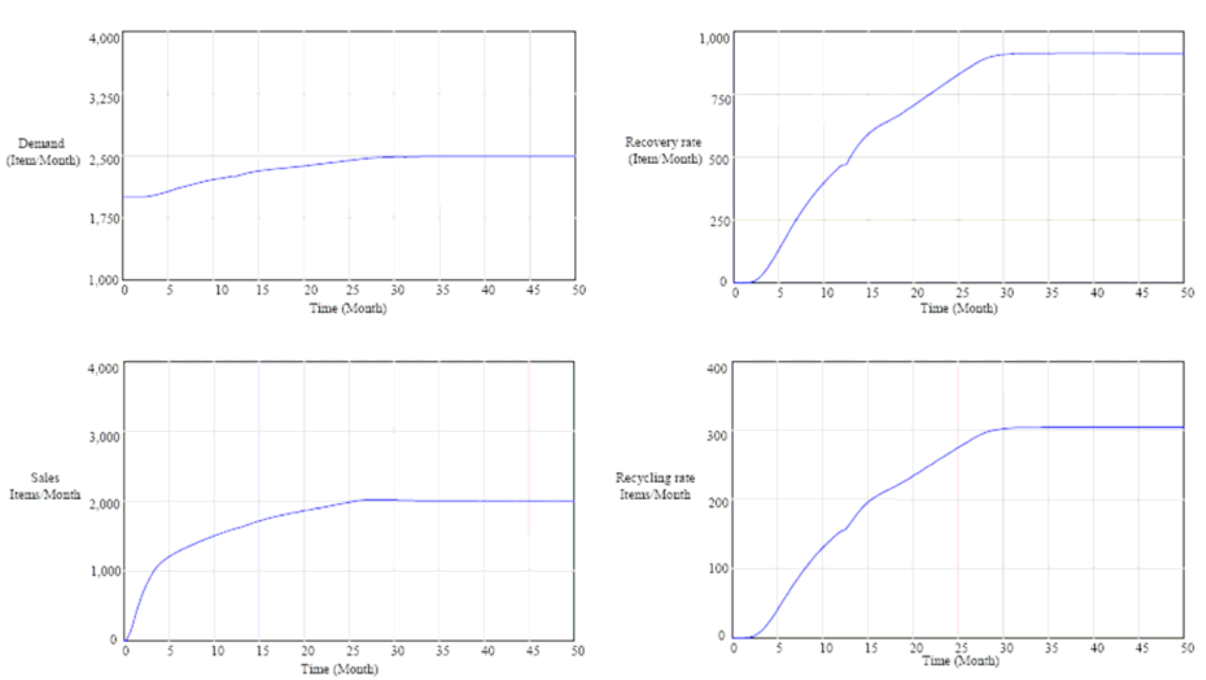
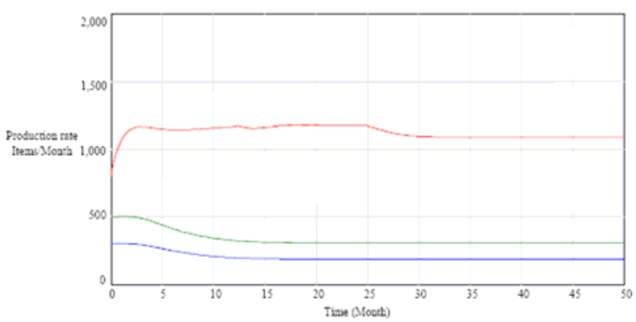
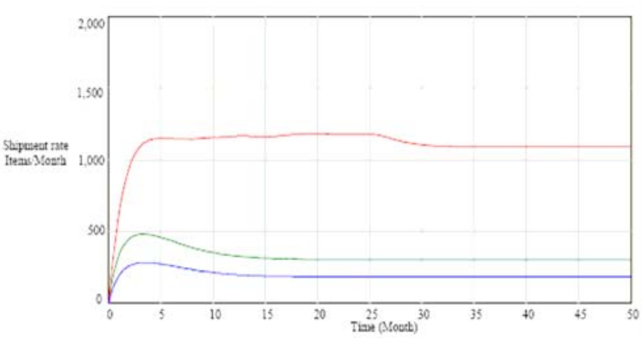


Fig. 3: The impact of control variables on experiment results

Another point that should be noted here is the impact of the recovery and recycling activities on the behavior of production and shipment rates between production centers and distribution centers. As Fig. 4 shows, the shipment and production rates show overshoots and then decrease. At the initial periods after the pulse input, the shipment rate increases according to the arrival of new products and this increscent will continue up to the production capacity. After that, when the used products enter the recovery and recycling centers, the recovery and recycling rates increase gently. Therefore, the recovery loop is activated and then some portion of demand will be satisfied by the recovered products. Finally, as a result of abovementioned events, the shipment rate will decrease and reach a new steady state (see Fig. 4). The production rate also decreases smoothly in most of the cases. In Fig. 4 the behavior of these two rates is investigated applying different production capacities.



(a) Production rate



(a) Shipment rate

Fig. 4: The behavior of production and shipment rates
Each color is related to a different production capacity

The results of the simulation show that: when the recovery and recycling loops are activated the demand increases and the rate of production and shipment in the forward supply chain decreases. As a managerial view, this is a desirable event, since the sales grew and the production and procurement costs decreased.

IV. CONCLUSIONS

Although MIP models are powerful tools for modeling and optimizing the design and planning of reverse supply chains, but they have lack of capability and flexibility to model the dynamics of closed-loop supply chains and also providing desirable sensitivity analysis on the model parameters. To overcome the drawbacks of using MIP models in closed-loop supply chain planning, in this paper a system dynamics approach is used for capacity planning and price adjustment in a closed-loop supply chain. The proposed model is able to consider the impact of recovery and recycling activities on the green image of the company and the impact of the green image on stimulation of the customers' demand. Numerical experiments are used to evaluate the performance of the proposed model. It is shown that the overall behavior of such a system is desirable.

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