A SYSTEM DYNAMICS MODELING APPROACH FOR RECYCLING NETWORKS

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Abstract: Recycling networks have been an area of increasing attention during the last decade as their economic impact have been increasingly important and as environmental legislation has been becoming stricter. Moreover, the need for holistic modeling efforts that capture the recycling network operations at a strategic level has been clearly recognized first by industry and recently by academia. In this work we propose such a holistic model of recycling networks based on the principles of System Dynamics methodology and we provide guidelines for the development of integrated dynamic simulation tools for policy design and evaluation in real world cases. We first present the material and information flow structures of recycling networks and then we discuss how these two structures interacts via a set of decision rules to govern the material flows. Finally we discuss how the System Dynamics modeling approach can be used to conduct various "what-if" analyses and further to answer managerial questions about the long-term operation of recycling networks.

Keywords: Recycling Networks, System Dynamics, Reverse Logistics, Closed-loop Supply Chains.

1 Introduction

Over the past few years, public awareness of environmental aspects of production-distribution systems has dramatically increases. Waste reduction has become a prime concern in industrialized countries. Products are obviously still streaming in the direction of the end customer but an increasing flow of products is coming back for recycling. For example European glass recycling grew by almost 10% (in tones collected) in 1994 to more than 7 million tones, being a recycling rate (in percentage of total glass consumption) of 60% (EUROSTAT, 1997). Paper recycling in Europe in 1994 recorded an annual growth rate of about 7% (Fleischmann, 1997), while the EU directive prescribes recovery goals of 65% for packaging (a large part of the paper volumes in Europe is used for packaging). Moreover, the EU Environmental Ministers in June 2001 agreed in principle to enter special directives into force for various industries in which the recovery of waste is an essential element (for example the directive on waste of electrical and electronics equipment). Promote design for recycling and mandated recovery are now a few of the targets of environmental policies for EU member states. From a business perspective, for many used products the recycling is economically more attractive than disposal providing, thus, a strong economical motivation to develop recycling networks.

Numerous recycling networks have been addressed in literature aiming at structuring the field by delineating distinct types of networks taking into account aspects such as topology, economics, parties involved, and decision and control issues. Carpet recycling logistics networks (Realff and Newton, 1999; Louwers et al., 1990), sand recycling (Barros et al., 1998), recycling of industrial by-products in German steel industry (Spengler et al., 1997) and paper recycling networks (Bloemhof-Ruwaard et al., 2004) are a few reported networks. In these approaches linear and mixed integer linear programming models are used not only to find optimal solutions but also to analyze and understand the system's behavior. We refer to Fleischmann (2000) and Fleischmann et al. (2000; 1997) for a detailed discussion of this field. In these modeling approaches shipment times, processing times and product usage periods are assumed deterministic. Moreover, a critical shortcoming of most of the existing models is their inability to take into account the uncertain business environment in reverse supply channel characterized by highly variable volumes, timing and quality of returns. Decision-making in such recycling networks with high degree of dynamics, calls for a methodological approach which has the ability to take into consideration the dynamics of existing stocks and flows (Bloemhof –Ruwaard et al., 2004).

The System Dynamics (SD) methodology, introduced by Forrester (1961), provides a more flexible modeling and simulation framework for decision-making in dynamic management problems. The purpose of this paper is to introduce how the methodological tool of SD can be employed to assist the modeling of recycling networks and to develop integrated dynamic simulation tools for policy design and evaluation in real world cases. In the next section we present the recycling system under study. The SD modeling approach including the stocks and flows diagram, the control rules and the mathematical equations are presented in Section 3. The final section contains a discussion of SD capabilities in developing dynamic strategic tools for recycling networks.

2 System description

We focus on a single producer closed-loop recycling network which includes the following distinct operations: Supply, Production, Distribution, Use, Collection, Inspection, Recycling and Disposal. We consider that the manufacturing process uses recycled waste products as basic raw material. Figure 1 presents the system under study. The forward channel includes the producer, the distributors and the customers. In the reverse channel, we assume that the only product reuse activity is recycling. The reverse channel includes the waste merchants, the producer's collection centers and recycled raw material merchants.

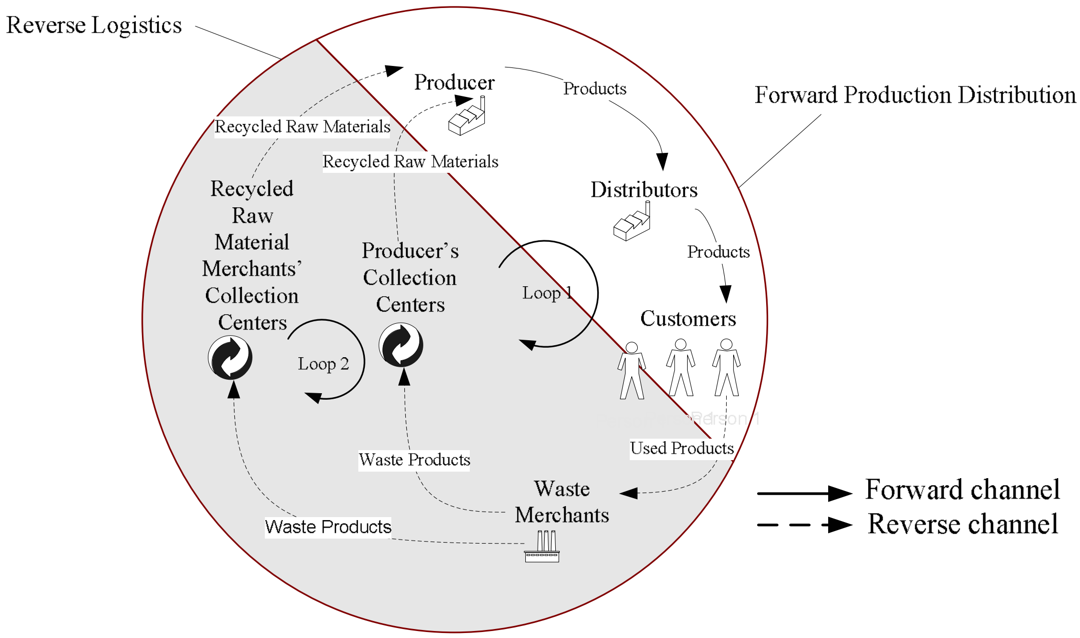

Figure 1: Recycling loops

The forward supply chain includes two echelons (producer and distributors). Specifically, the end products are first transferred to the distributors and then sold to satisfy demand. The product sales at the end of their life-cycle turn into used products. Used products at the end of their current use are either directly disposed (uncontrollably disposal) or collected for reuse. The reverse channel starts with the collection procedures. The waste merchants transport and sell the collected used products as waste either to the producer's collection centers or to recycled raw material merchants' collection centers. Waste products in the producer's collection centers are transformed to recycled raw material after a number of operations (for example inspection, sorting in different qualities and compression operations in waste paper recycling networks) and then are transported to the producer's manufacturing facilities (for example compressed waste paper shipments from collection centers to the paper-mill in paper recycling networks). Similar activities take place, at the recycled raw material merchants. Paper, glass, iron scrap, aluminum and plastic recycling networks are a few representative examples of the described system. Two main recycling loops, Loop #1 and Loop #2, are exhibited in Figure 1. From the single producer's point of view Loop#1 represents the internal environment of the recycling network while Loop #2 represents the external environment.

The basic system assumption is that the cost to produce recycled raw material in producer's collection centers is lower than the price of recycled raw material offered by merchants.

3 Modeling approach

Stocks and flows, along with feedback loops, are the two central concepts of SD theory. Stocks are the accumulations (e.g. inventories) of the inflows (e.g. production rate) and the outflows (e.g. shipments) of a system (Sterman, 2000).

A SD recycling model can be viewed as consisting of two interconnected networks. The first network is the material network which includes the stocks and flows of products, used products, waste products and recycled raw material exhibited in a stock and flow diagram. The second network is the information network which includes the flow of information (for example serviceable inventory level in end products, expected product demand from distributors, inventory level in producer's collection centers) through the actors involved in the recycling loop (producer, distributors, customers, waste merchants and recycled raw material merchants). The two networks interact via a set of decision rules which control the material flows.

3.1 Stock and flow diagram

SD uses a particular diagramming notation for mapping the stock and flow diagram. Stocks are represented by rectangles, inflows are represented by pipes pointing into (adding to) the stock and outflows are represented by pipes pointing out (subtracting from) the stock. Figure 2 illustrates the stock and flow diagram of the system under study. It is a representation of the material stock and flow of Loop #1 shown in Figure 1. Delays introduce time delay in product flow through the forward and reverse supply channels. Although delays exist in all product flows, only the significant ones (compared with the simulation time step) are included in the diagram (Forrester, 1961). Demand is treated as exogenous variable.

3.2 Flow of information

The material flows exhibited in Figure 2 represent the actions within the chain. In these points flows are governed by decision rules (policies). Every decision rule can be considered as an information processing procedure. The inputs to the decision process are various types of information. Information feedback mechanisms couple the stocks to the flows and close the loops in the system. These loops are either negative feedback (balancing) or positive feedback (reinforcing) loops. A negative feedback loop exhibits goal-seeking behavior: after a disturbance, the system seeks to return to an equilibrium situation. In a positive feedback loop an initial disturbance leads to further change, suggesting the presence of an unstable equilibrium. To determine the flows of Figure 2, 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. For more details about "push" and "pull" policies in forward and reverse channel see Van der Laan et al. (1999).

The size of the SD model is such that the analytical presentation of the two interconnected networks and of control rules cannot be given within the limited paper's length. However, the general form of the embedded control rules is indicatively presented in Figure 3 for the case of governing the *Production Rate*. The arrows (influence lines) in Figure 3 represent the relations among variables. The direction of the influence lines displays the direction of the effect. Signs "+" or "-" at the upper end of the influence lines exhibit the sign of the effect. When the sign is "+", the variables change in the same direction; otherwise they change in the opposite one. Specifically, the *Production Rate (PR)* is defined by the *Indicated Production Rate (IPR)* which is governed by a decision rule based on the well-established stock management structure suggested by Sterman (1989). The rule proposes the combining of *Expected Distributors' Order Rate (EDOR)* with an adjustment (*Serviceable Inventory Adjustment SIA)* that brings the *Serviceable Inventory (SI)* in line with its desired value (*Desired*

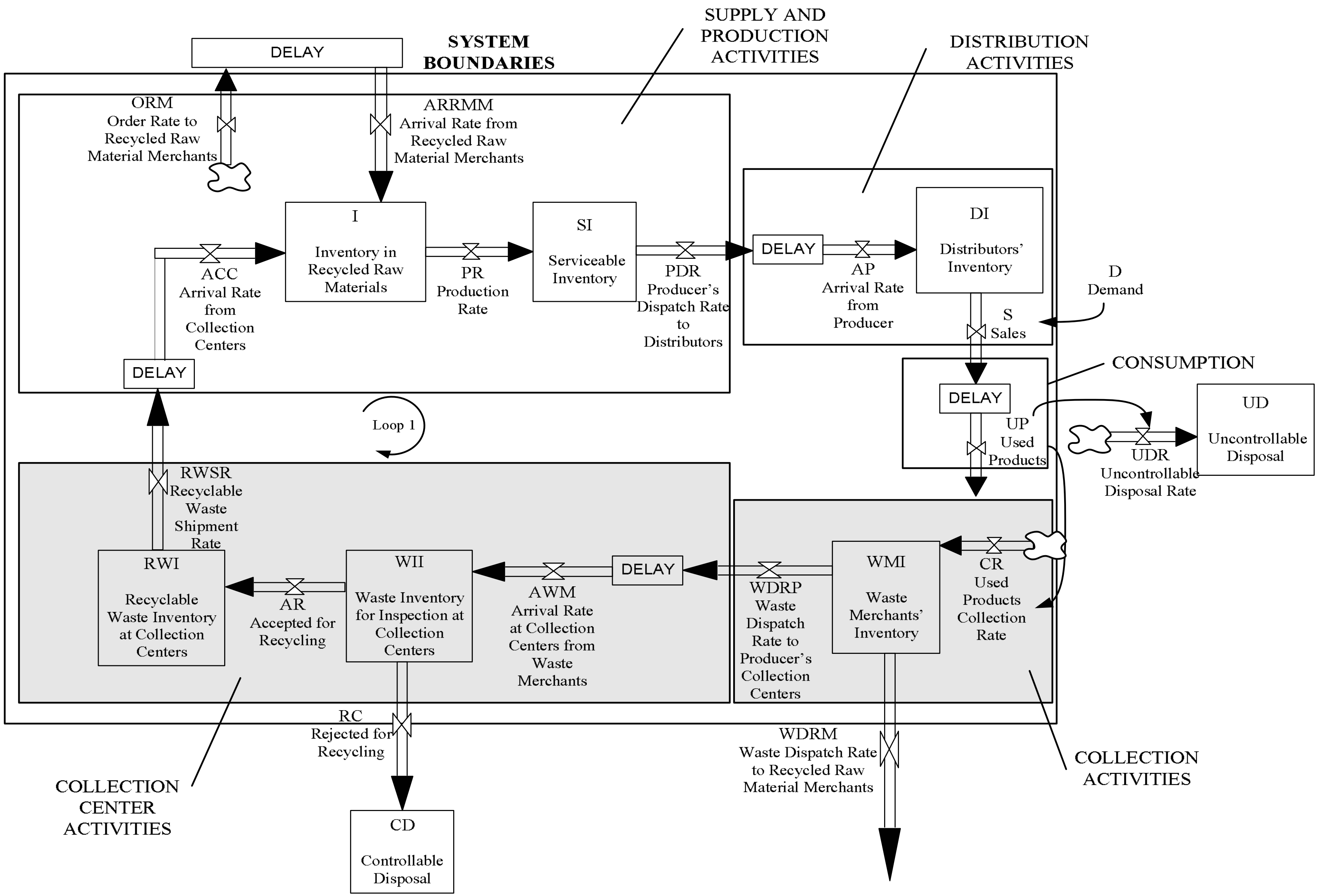

Figure 2: Stock and flow diagram

Serviceable Inventory, DSI). The *Expected Distributors' Order (EDOR)* is a forecasted value for distributors' orders calculated from a first order exponential smoothing of *Distributors' Order Rate (DOR)* with parameter a_D, implying a smoothing coefficient of $1/a_D$. The *Serviceable Inventory Adjustment (SIA)* is an adjustment, which is proportional to the discrepancy between *Desired Serviceable Inventory (DSI)* and actual *Serviceable Inventory (SI)* using *Serviceable Inventory Adjustment Time (SIAT)* as a control variable which represents how quickly the producer tries to close the gap between the desired and actual inventory level. The *Desired Serviceable Inventory (DSI)* is given by the product of *Expected Distributors' Order Rate (EDOR)* and *Serviceable Inventory Cover Time (SICT)* which is the base stock expressed in time units. Naturally, *Indicated Production Rate* (*IPR*) is limited by the *Production Capacity (PC)*. Finally, *Production R*ate (*PR*) is equal to *Indicated Production Rate (IPR)* and is limited by the availability of *Inventory in Recycled Raw Material (I)*. It appears that the control variables to regulate the *Production Rate (PR)* are *SI Adjustment Time (SIAT)*, a_D and *Serviceable Inventory Cover Time (SICT).*

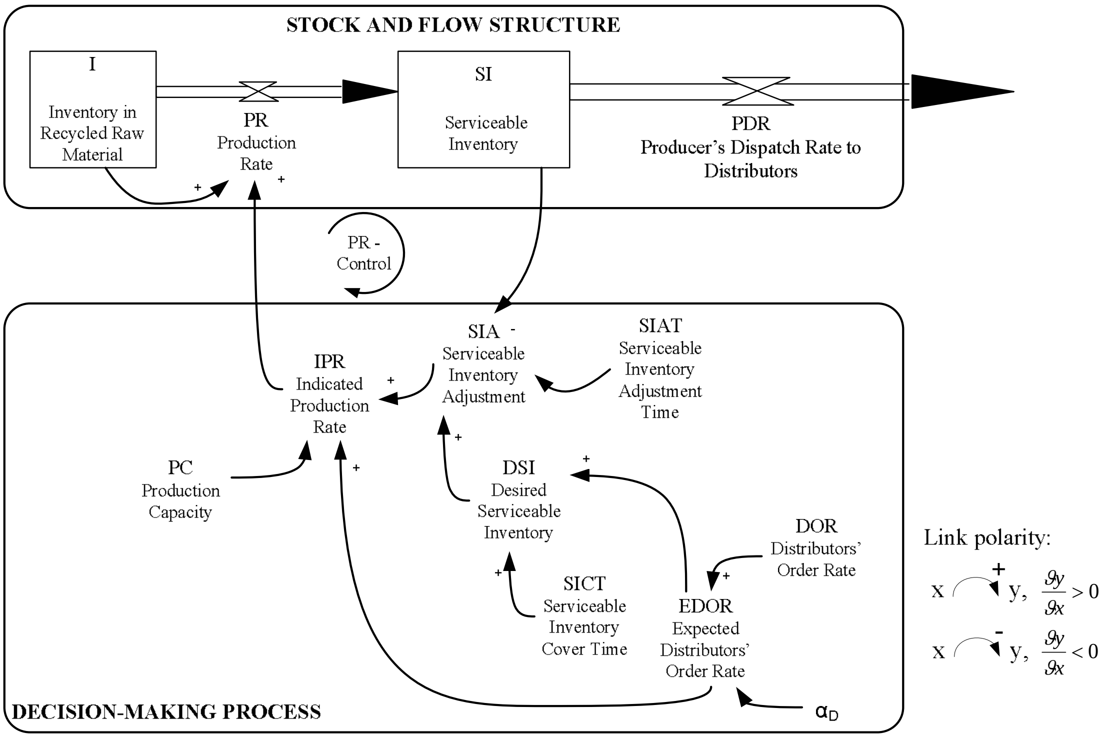

Figure 3: Production Rate control mechanism

3.3 Mathematical formulation

The next step of the SD methodology is to translate the stock and flow diagram to a system of differential equations. The embedded mathematical equations are divided into two main categories: the stock equations and the rate equations. The stock equations define the system's stocks as the time integrals of the net flows, and the rate equations define the flows among the stocks as functions of time.

In what follows, we first introduce the notation for indices, next the stock equations which may also be deduced from Figure 2 and finally the equations that govern the *Production Rate (PR)* which may also be deduced from Figure 3.

Indices:

p: types of products (p = 1, 2 .. P).

q: quality categories in recycled raw material (q = l, 2 .. Q). The p types of products at the end of usage period are collected in q quality categories.

m: locations for producer's collection centers (m = 1,2 .. M).

Stock equations

$$I_q(t) = I_q(t=0) + \int_0^t (\sum_{m=1}^{M} ACC_{mq}(t) - c_{qp} PR_p(t)) dt \quad (1)$$

where c_{qp} is the amount of material input of quality q for producing 1 item of product type p.

$$SI_p(t) = SI_p(t=0) + \int_0^t (PR_p(t) - PDR_p(t)) dt \quad (2)$$

$$DI_p(t) = DI_p(t=0) + \int_0^t (AP_p(t) - S_p(t)) dt \quad (3)$$

$$WMI_{mq}(t) = WMI_{mq}(t=0) + \int_0^t (CR_{mq}(t) - WDRP_{mq}(t)) dt \quad (4)$$

$$WII_{mq}(t) = WII_{mq}(t=0) + \int_0^t (AWM_{mq}(t) - AR_{mq}(t) - RC_{mq}(t)) dt \quad (5)$$

$$RWI_{mq}(t) = RWI_{mq}(t=0) + \int_0^t (AR_{mq}(t) - RWSR_{mq}(t)) dt \quad (6)$$

Production Rate control equations

$$PR_p(t) = Min\ (IPR_p(t), \frac{I_q(t)}{c_{qp}}) \quad (7)$$

$$IPR_p(t) = Min\ (EDOR_p(t) + SIA_p(t), PC(t)) \quad (8)$$

$$EDOR_p(t) = EDOR_p(t-dt) + \frac{1}{a_D}(DOR_p(t) - EDOR_p(t-dt))\ dt \quad (9)$$

$$SIA_p(t) = \frac{DSI_p(t) - SI_p(t)}{SIAT_p} \quad (10)$$

$$DSI_p(t) = EDOR_p(t) * SICT_p \quad (11)$$

The solution of the system of differential equations is supported by high-level graphical continuous simulation programs such as *i-think*®, *Powersim*®, *Vensim*® and *Stella*®.

4 Concluding discussion

The SD modeling approach presented in the previous sections may be employed by modelers to develop dynamic models in a wide range of recycling systems. Accurately mapping of the stock and flow structure of a recycling system is relatively straightforward. In contrast, adding information feedbacks and effective decision rules to the stock and flow structure is subtle and challenging. Robust, realistic and effective decision rules must be specified for every flow. In Figure 3 and in Equations 7 - 11 we presented the negative feedback mechanism of such a decision rule in the context of a single producer recycling networks.

Decision rules having the same generic form as the one described above could be used in governing several flows of the presented recycling system, e.g. *PDR, WDR and ORM.* There are clearly a number of ways in which this decision rule could be redesigned. One such way would be to modify the forecast term *EDOR* (for example the first order exponential smoothing might be replaced by a higher order exponential smoothing). Another way would be to modify the stock correction term *SIA* (for example the simple proportional control term might be replaced by a term which could be designed using the full range of classical control engineering techniques). A third way would be to modify both the forecast term and the stock correction term. In every circumstance using SD methodology the optimal values of the control variables can be identified via simulation combined with appropriate search procedure using for example maximization of production capacity utilization or maximization of total supply chain profit as optimization criteria.

Another challenging extension of the presented modeling approach is to develop powerful dynamic models which can be used as a long-term decision tool, through the evaluation of alternative strategic policies and structures in recycling networks. Towards to this direction, the interconnected material and information networks are extended incorporating new stocks, flows, information feedbacks and control rules. For example in production rate control equations, production rate is limited by the *Production Capacity (PC)* (see Equations 7 and 8). Embedding a capacity planning mechanism in the model, *PC* turns to a stock variable and the proposed modeling approach could be used for making decisions to acquire/reduce capacity (inflows/outflows) or not considering the tradeoff between maximization of market share and maximization of capacity utilization. The investigation for capacity adjustment policies in producer's collection centers is another similar example of capacity related decision making.

Finally it appears that the model can be used to analyze various scenarios (i.e. to conduct various "what-if" analyses) thus identifying efficient policies and further to answer questions about the long-term operation of recycling networks. Capacity planning, inventory management, production planning and cooperation between involved actors in the recycling loop (different forms of organization in terms of ownership) are the main management areas in which SD models facilitate decision making. Thus, it may prove useful to policy-makers/regulators and decision-makers dealing with long-term strategic management issues in recycling networks along with researchers in environmental management.

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