A Demonstration of Reverse supply chain for reusable products (Cradle-to-Cradle approach) using system dynamic modelling.

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Abstract

Keeping the fast-growing demand for using resources in a **sustainable** manner, the paper develops a system dynamics model to analyze **reverse supply chains** for reusable products from a **Cradle-to-Cradle** perspective. The basis for the modelling framework is the Cradle-to-Cradle approach. The entire life cycle of sustainability finds its foundation with the Cradle-to-Cradle approach for designing closed-loop supply chains that focus on reusability, **remanufacturing**, and minimal waste. It focuses on critical activities in reverse supply chain-scavenging, sorting, and reprocessing products to be returned to the market. It brings all relevant parameters like **return rates, reprocessing capacity, material recovery, and refurbished product's market demand** for sustainable viability in the reverse logistics. In this regard, system dynamics modelling allows for assessing the holistic effects of dynamic interdependencies and feedback effects impacting product flows, resource allocations, and environmental gains. Analysis indicates important leverage points and defines strategies for increasing the efficiency of reverse supply chains through sustainability-friendly practices while catering to a closed-loop system. Results will thus indicate how the application of system dynamics can be used in making informed choices toward the implementation of Cradle-to-Cradle principles, thus giving pragmatic orientations to businesses and policymakers in developing circular economy goals.

Keywords

Reverse supply chains, Reusability, System dynamics, Cradle to Cradle approach, Circular economy, Product lifecycle, Sustainable supply chain

1. Introduction

Global environmental issues have made sustainable practices within a supply chain indispensable with regard to the significant minimization of resource depletion and reduction of waste. Traditional linear supply chains, which involve a **"take, make, dispose"** approach, have failed to sustain themselves in the wake of increased demand for their consumables and growth in generated waste. For this reason, reverse supply chains have become increasingly relevant as an ever more obvious strategy with which to deal with product end-of-life management, especially as used in the context of a circular economy. This research employs the C2C approach, which transcends any system of old 'end-of-life' recyclable solutions, and which focuses on a system which 'sees materials continually circulated around a closed loop without loss of quality or purpose'.

This synthesis allows, with the Cradle-to-Cradle philosophy, consideration of the whole cycle of products-creation, recovery, and reuse-to enhance anticipation and prevention of shortcomings in the reverse supply chain. And since system dynamics emphasizes feedback loops and interdependencies, it could elaborate more intricately the interactions between collection, reprocessing, and redistribution. In that sense, this study will provide a framework by which decision-makers will evaluate and optimize the reverse logistics processes under the constraint of circular economy principles to ensure the continuous cycling of resources within $2+2$the supply chain, thus reducing the environmental impact and promoting sustainability.

Stage	Description	Key Metrics	Challenges
Collection	Collection of end-of-life or used products	Return rate	Variability in return quantities
Sorting	Categorizing items for reuse or reprocessing	Efficiency of sorting	Product condition and handling costs
Reprocessing	Refurbishing, remanufacturing, or recycling items	Reprocessing rate, cost	Technological requirements, quality control
Redistribution	Redistribution of processed goods to the market	Market demand, price sensitivity	Consumer perception, competition with new
Feedback & Monitoring	Continuous feedback to improve process	Sustainability index, cycle time	Data accuracy, system adaptability

Combining Cradle to Cradle principles with system dynamics modelling $2+2$ can lend an innovative lens through which the reverse supply chain can be analyzed. This model could show the potential of reusability strategies toward improving sustainability in the supply chain while paving the way for effective practices to be adopted by business leaders and policymakers as a mechanism for stimulating a circular economy. This study's implications give important insights into designing sustainable supply chains that minimize waste and, consequently, maximize utility in the use of resources by contributing to broader environmental and economic goals..

2. Problem definition

A **traditional supply chain** enables a straight and relatively linear flow from material acquisition to end-use in consumer markets, with very little support for recovery or reuse postconsumption. In response to increasing environmental pressure and regulatory requirements, there is an increasing need for sustainability within supply chain practices. One of the viable solutions, emerging in this area is a **reverse supply chain**-the process of returning used products through the supply chains for possible reuse, remanufacturing, or controlled disposal. Unlike a forward supply chain, the reverse supply chain is complicated as it involves intricate planning for the return of products, inspection, and reprocessing and reintroduction into the cycle of supply. The process becomes even more complex when implementing the Cradle-to-Cradle method - a process that advocates for constantly repeated cycles of material without losing its quality.

While this is complicated enough, the reverse supply chain design with a Cradle-to-Cradle framework is further complicated by return volume uncertainty, variable conditions of returned products, and a demand for **"as good as new"** products. Its efficient running will require a dynamic capacity planning model responsive to steady and variable demand cycles, external regulations as the force behind such take-back obligations, and how green consumer expectations are changing markets. Another important consideration is the proper balance of resource allocation, remanufacturing capacity, and market response to reconditioned goods that would ensure maximum sustainability along with economic viability.

This paper addresses such challenges by using system dynamics (SD) modelling to simulate a closed-loop reverse supply chain for reusable products under a Cradle-to-Cradle approach. These capacity planning strategies will be captured in the SD model by performing transient effects, policy implications, and the impact of capacity planning strategies on the performance of the reverse supply chain. Therefore, the study will aim at providing a framework that informs the decision-maker about the best ways to optimize the reverse logistics processes in achieving adequate capacity utilization to meet the market demands and attains sustainability goals.

3. Literature Review And Research Gap

In addition, with greater pressure on industries to become increasingly sustainable and minimize their environmental footprint, the importance of reverse supply chains has grown. Whereas the straightforward forward flow at traditional supply chains emphasizes raw material acquisition and final product delivery, the corresponding return flow of products toward a set of potential re-use, re-manufacturing, recycling, or disposal channels forms critical support to a circular economy. This literature review surveys past research on reverse supply chains, approaches toward Cradle-to-Cradle, and models that take advantage of system dynamics in sustainable supply chains, with crucial research gaps identified.

3.1. Reverse Supply Chains and Closed-Loop Supply Chains

These are the works of Fleischmann et al. 2000; this forms the basis of research on which closed-loop supply chains operate. Collection forms the first key operation then followed by inspection, reprocessing, and redistribution. Some later works, like those from Guide and Van Wassenhove 2001, reverse this train of thought in order to centre the interest on reverse logistics and product returns. Industry-specific studies - electronics for instance, show that reverse logistics is an important point but hardly ever proceed further towards full closed-loop systems where Cradle-to-Cradle becomes essential.

3.2. Cradle-to-Cradle Approach in Supply Chain Management

McDonough and Braungart (2002) introduced the Cradle-to-Cradle model in relation to continuous product reuse through biological and technical nutrients. While this approach does have environmental and economic implications, most studies on this topic tend to focus on product design at the expense of C2C application in reverse supply chains. Indeed, the challenges in the adoption of C2C into the supply chain were also highlighted by Lacy and Rutqvist, making models that integrate C2C principles into reverse supply chain practice crucial.

3.3. Modelling of Reverse Supply Chain Dynamics

System dynamics (SD) is applied for modelling reverse supply chains, and various research works concerning managing inventory and describing the behaviour of the system have been developed by Georgiadis and Athanasiou (2010), Beamon (1999), and others. It has also been applied in the area of remanufacturing processes, as Georgiadis et al. (2006) demonstrate an approach with consumer behaviour and capacity planning. Most related works are, however, biased towards partial parts of the Cradle-to-Cradle cycle rather than the whole cycle and only a handful of studies have approached the dynamic effect of regulation and customer behaviour on the reverse supply chain.

3.4. Research Gap

Whereas research into reverse supply chain has focused on standalone aspects such as remanufacturing or collection, end-to-end models, that integrate the Cradle-to-Cradle framework and system dynamics, are lacking. Very little effort exists that suits the **complete scope of reverse logistics** with feedback loops created by regulations, sustainable product market demand and dynamic capacity planning strategies.

4. Methodological approach

Adopting the System Dynamics (SD) modelling approach, this research analysed the reverse supply chain of reusable products in a Cradle-to-Cradle framework. The use of SD takes into account the dynamic character of the system and models its key structural components, such as production, distribution, remanufacturing, and flows of product returns. The model looks into the feedback loops and simulates different capacity planning policies, such as leads, lags, and matching strategies, to measure their influence on system performance, sustainability, and profitability. In this regard, the study through simulations will determine optimal policies that best balance resource use and environmental impact while fulfilling demand for sustainable products.

4.1. System Dynamics (SD)

System dynamics (SD) modeling is a computational approach used for understanding complex relations within a system over time. It was formulated in the 1950s by Jay W. Forrester at the

Massachusetts Institute of Technology (MIT) and was first applied to corporate management for the analysis of industrial systems with the motivation of making better decisions. In the years spanning decades, this theory has been applied to different fields, including environmental science, public policy, healthcare, and supply chain management. SD modeling is therefore powerful in the understanding of the interactions of different elements within a system over time and hence allows for the forecasting of outcomes and testing different scenarios.

In the reverse supply chain for reusable products, modelling through system dynamics is an appropriate tool in demonstrating how products move through lifecycle stages from collection and remanufacturing up to redistribution. Using SD, one can search for various key variables such as collection rates, remanufacturing capacity, distributor inventory, and its impact on the performance of the whole system. Since this approach simulates different scenarios, it can pinpoint bottlenecks and forecast levels of inventory, and it could determine how a change in one process- say, collection capacity-might affect the availability of serviceable products. This will enable a holistic cradle-to-cradle analysis, contributing to sustainable product lifecycle management and insights for improving efficiency and sustainability in reverse supply chains.

3.2. Casual Loop Diagram (CLD)

Causal loop diagrams (CLDs) were born out of the advancement of system dynamics modeling by Jay W. Forrester at MIT in the 1950s. His initial purpose was to further represent and understand feedback loops and causal relationships in complex systems, which he first applied to industrial and social systems. Building on cybernetics and control theory, CLDs offered a framework that researchers could map out how different factors interplayed with one another through reinforcing (positive) and balancing (negative) loops. From then onwards, CLDs were applied to everything from areas of business and environmental science to public policy, in establishing a graphically clear method of demonstrating interrelated systems and discovering points of leverage for intervention.

A causal loop diagram is a graphical tool in system dynamics modeling that illustrates the interrelations and feedbacks between the variables in a system. The diagram shows how variables interlock positively or negatively to ultimately determine the interdependencies driving system behavior. In the CLD, lines connecting variables customarily make use of arrows and " + " or " - " symbols to show whether it is reinforcing or balancing. While reinforcing loops force change in the system with the change being either growth or decline, the action of balancing loops produces stability with the hope that the system reaches a better equilibrium. The identification of these loops allows a CLD to be used by researchers in getting hold of complex systems as well as in identifying leverage points where interventions can be placed.

The research will use a Causal Loop Diagram (CLD) as a key tool in portraying and conceptualizing the dynamic interrelations within the reuse supply chain of the Cradle-to-Cradle reverse supply chain of reusable products. The CLD will focus on how the key elements, such as production, distribution, collection, remanufacturing, and disposal, interact over time and influence one another.

The CLD will highlight the types of reinforcing and balancing feedback loops that cause system behavior, for example:

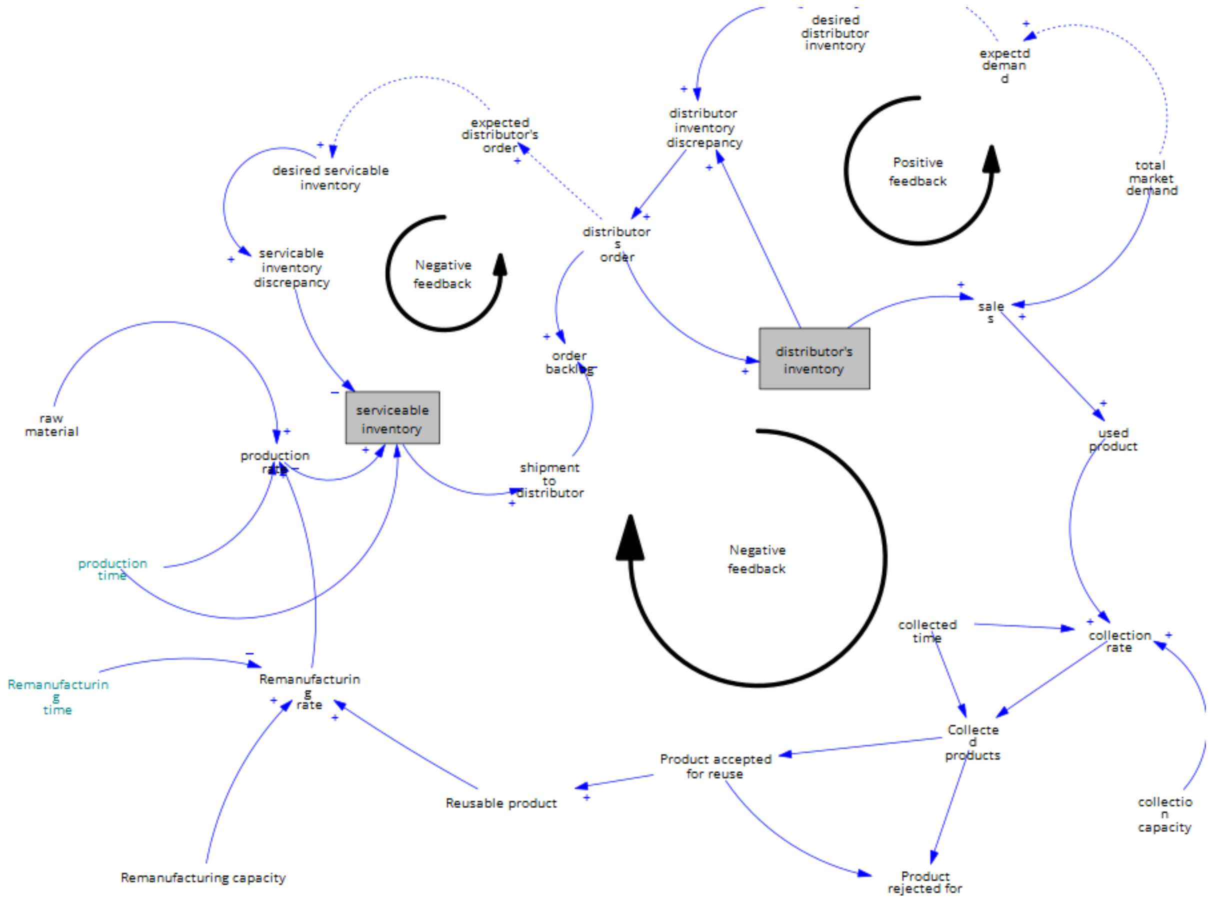
1. **Reinforcing loops** can illustrate how the higher the rates of product collection, the higher the accumulation of the remanufactured output. In this way, they could present a **positive loop** cycling of reuse and sustainability.
2. **Balancing loops** can represent some limitations that include: REMANUFACTURING capacity, and demand fluctuations from the consumers in curbing the flow of reusable products through the reverse supply chain.

The CLD will be important for

1. **Identification of Leverage Points:** It allows, through interdependency mapping, the identification of elements of a system where minimum interventions, such as collection rate or process improvements in remanufacturing, would trigger large positive effects on sustainability and profitability.
2.**Testing and Analysis Based on Policies:** The CLD shows the possible effects resulting from different policies like better manufacturing capacity or increased take-back obligations. Hence, this help us to illustrate how the dynamics could be impacted through policy changes.
3. **System Behaviour Analysis:** by investigating loops and interactions, the CLD helps understand how variables-such as consumer demand, regulatory requirements, or product returns-mutually interact to create patterns of behaviours like growth stabilization or oscillation.

Thus, the CLD will be used as a basis for a more complex System Dynamics model in order to allow in-depth analysis and to contribute to the development of efficient strategies for controlling the reverse supply chain within the framework of the Cradle-to-Cradle principles.

As shown, the model includes numerous variables and their interconnections. The arrows depict the causal flow, while the signs at the arrowheads (+ or -) indicate whether the impact of one variable on another is positive or negative, depending on their relationship.



3.2. System variable

As indicated in the figure, it depicts variables applied to the model that describe different stages and factors of any collection, remanufacturing, and distribution process. Each of these variables attempts to capture some form of dynamics in the life cycle for the purpose of an overall assessment of the behaviour of the system. As shown below is a description of every variable followed by a summary of roles pertaining to the application in the model.

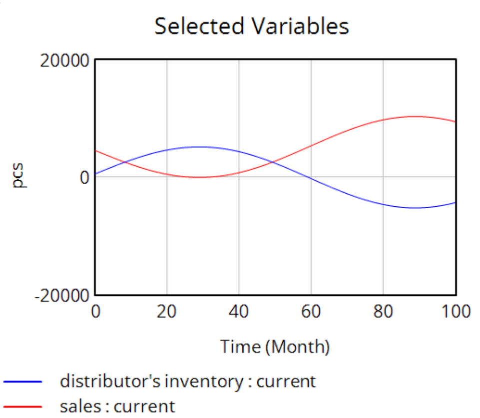
Table 1. Dependent variables and definition

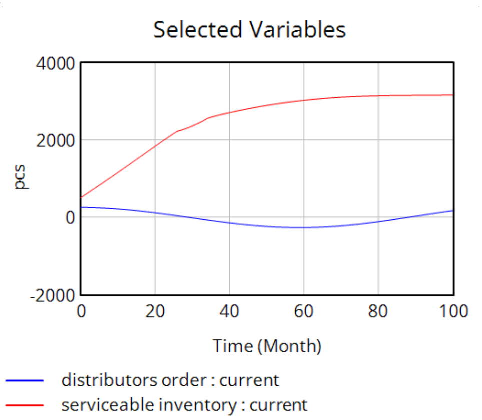
Variable	Definition	Formula
Collected products	Number of products gathered from various sources for reuse or recycling.	collected time*collection rate
Collection capacity	Maximum number of products that can be collected within a certain period.	1000
Collection time	Duration needed to collect products from different sources.	7
Collection rate	Speed at which products are collected.	(used product+collection capacity)/collected time
Total market demand	Overall demand from consumers in the market for the product.	5000

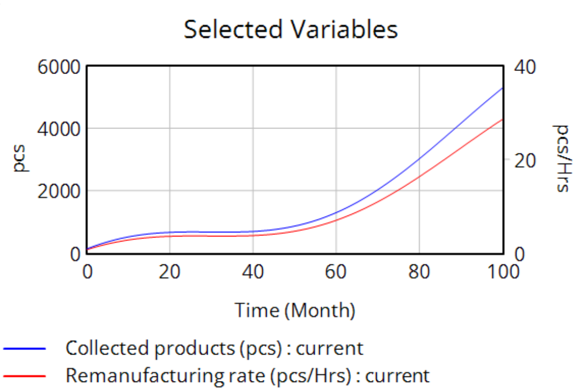
Desired Distributor inventory	Target level of inventory a distributor aims to maintain.	0.1*expectd demand
Desired serviceable inventory	Ideal quantity of inventory ready for sale or use.	1*expected distributor's order
Distributor inventory discrepancy	Difference between desired and actual distributor inventory levels.	0.011*(desired distributor inventory-distributor's inventory)
Distributors inventory	Current inventory held by distributors.	distributors order
Distributors order	Orders placed by distributors to meet demand.	0.25*distributor inventory discrepancy
Expected demand	Forecasted demand for products from customers.	total market demand/4
Expected distributors order	Anticipated order quantity from distributors.	distributors order
Order backlog	Accumulated orders waiting to be fulfilled.	distributors order-shipment to distributor
Product accepted for reuse	Quantity of collected products deemed suitable for reuse.	Collected products
Product rejected for reuse	Quantity of collected products deemed unsuitable for reuse.	Collected products-Product accepted for reuse
Production time	Time required to produce a new product.	5
Production rate	Speed of producing new products.	raw material/production time-Remanufacturing rate
Raw material	Basic materials needed for production.	10000
Remanufacturing capacity	Maximum capacity for remanufacturing products.	500
Remanufacturing rate	Rate at which products are remanufactured.	Reusable product*Remanufacturing time/Remanufacturing capacity
Remanufacturing time	Duration required to remanufacture products.	3
Reusable product	Product that can be used again after remanufacturing or refurbishing.	0.9*Product accepted for reuse
Sales	Quantity of products sold to end users.	total market demand-distributor's inventory
Serviceable inventory	Inventory ready for sale or immediate use.	0.0058*((production rate*production time)+servicable inventory discrepancy)
Shipment to distributors	Quantity of products shipped to distributors.	serviceable inventory
Serviceable inventory discrepancy	Difference between desired and actual serviceable inventory levels.	0.3*desired servicable inventory
Uncontrollable disposal	Quantity of products discarded without reuse or recycling.	
Used product	Product returned after use, potentially for remanufacturing or recycling.	0.056*sales

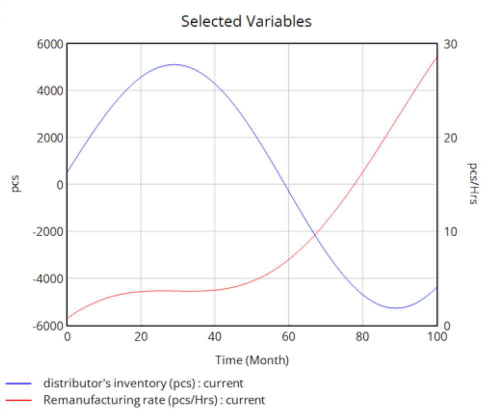
4.Model Validation

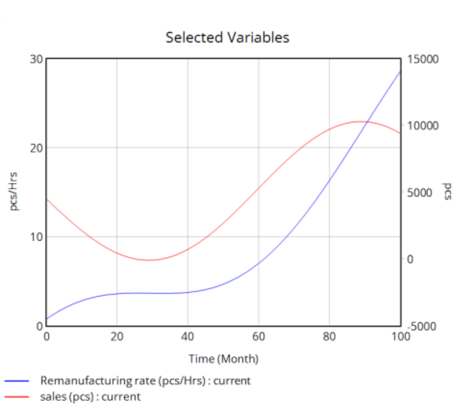
In structure validity, the research for the SD model bases the validity of the research on accuracy relationships and equations within the model to real processes in the world concerning a reverse supply chain of Cradle-to-Cradle. Structure validity in SD is essential because this type of validation is more relevant than behaviour replication since an approximate reproduction of the system behaviour is enough in this modelling, but an exact one as required in the case of forecasting models. Validation involved direct and indirect structure tests; indeed, direct structure tests compared model equations with real relations, but a validation approach always includes some degree of subjectivity. For these reasons, indirect tests, among which extreme-condition and behaviour sensitivity tests come into prominence, turned out to be crucial. Extreme-condition tests assigned extreme parameter values, such as Collection Capacity, to see if the model behaved as it ought to under those conditions. Behaviour sensitivity tests tested the reaction of the model to small changes in key parameters, such as Raw Materials, Production Capacity, and Remanufacturing Capacity. These tests confirmed that the behaviour of the model is consistent with theoretical expectations as well as expectations from empirical evidence; the model reacts meaningfully even in extreme conditions. Sensitivity tests have also shown that variation levels up to 10% of parameters do not affect the qualitative behaviour of the model, and hence, it has confirmed the robustness of the model for its exact prescription for reverse supply chain dynamics.

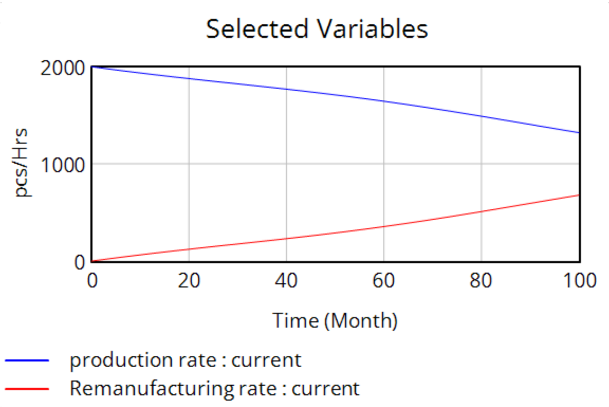












5. Conclusion and discussion

We presented the development of a dynamic SD-based model for strategic remanufacturing and collection capacity planning of a single product reverse supply chain for product recovery. For reverse chains ever increasing environmental concerns impose constant pressure on regulators for stricter policies and/or legislation. The developed model allows for the complete description and analysis of system operations (product flows and stocks) with account taken for capacity considerations, alternative environmental protection policies involving take-back obligation and "green image" effect on product demand. We first validated the SD simulator using indirect structural tests and then proceeded with numerical investigation. The latter yields insights that can be leveraged in developing dynamic policies for efficient capacity planning.

The model is now available for use in analysing scenarios (ie, conducting various "what-if" analyses) in determining efficient policies and further for answering questions about the long-term operation of reverse supply chains using total supply chain profit as a measure of performance. Further, the model could be adapted and applied not only for product recovery but also for material recycling systems. Therefore, it may be helpful to policy-makers/regulators and decision-makers dealing with long-term strategic reverse supply chain management issues as well as researchers in environmental management.

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