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An integrated logistics operational model for green-supply chain management

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Abstract

This paper presents an optimization-based model to deal with integrated logistics operational problems of green-supply chain management (G-SCM). In the proposed methodology, a linear multi-objective programming model is formulated that systematically optimizes the operations of both integrated logistics and corresponding used-product reverse logistics in a given green-supply chain. Factors such as the used-product return ratio and corresponding subsidies from governmental organizations for reverse logistics are considered in the model formulation. Results of numerical studies indicate that using the proposed model, the chain-based aggregate net profits can be improved by 21.1%, compared to the existing operational performance in the particular case studied.

Keywords: Green-supply chain management; Integrated logistics systems; Systematic optimization; Reverse logistics

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1. Introduction

With the increased environmental concerns over the past decade, there is growing recognition that issues of environmental pollution accompanying industrial development should be addressed

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simultaneously in the operational process of supply chain management, thus contributing to the initiative of green-supply chain management (G-SCM). Correspondingly, all the solutions, including logistics management, for managing the overall lifecycle of products should be integrated in a more comprehensive supply chain procedure. One striking example is that several industrial countries in Europe have enforced environmental legislation charging manufactures with the responsibility for reverse logistics flows, including used products and manufacturing-induced wastes (Robeson et al., 1992; Fleischmann et al., 2000). In addition, globalized enterprises, e.g., IBM, Hewlett–Packard, Xerox, have increasingly undertaken measures, including the integration of corresponding suppliers, distributors, and reclamation facilities in order to green their supply chains (Ashley, 1993; Bergstrom, 1993; Maxie, 1994). The above cases consider designing products which can be reused, together with the different possibilities of used product recovery. Environmental issues, e.g., used product recycling, waste disposal, and industry-induced pollution protection, therefore, can be addressed in an integrated fashion within the achievement of business operational goals.

Despite the importance of G-SCM in industrial ecology, the integration of logistics flows in a green-supply chain still remains as a critical issue in G-SCM for the following reasons. First, from an organizational strategic point of view, it is difficult to coordinate the activities of all the chain members, including the product-oriented logistics distribution channels and corresponding reverse-logistics channels. To a certain extent, this difficulty is rooted in the conflicts of operational goals among these chain members. For instance, maximizing the profits of one member in a reverse-logistics chain does not necessarily maximize the profits of a manufacturer in a given green supply chain due to the induced reverse logistics costs. Second, there is a lack of appropriate models for use as tools to manage the corresponding logistics flows associated with each chain member under the condition of system optimization in the process of G-SCM. Furthermore, the corresponding end-customer behavior, e.g., the willingness to return used products, and other external factors such as governmental policies and regulations, also influence the performance of a green-supply chain, particularly in the reverse logistics distribution channels.

Accordingly, formulation of a comprehensive framework with appropriate analytical models for systematically managing logistics flows among chain members in a green-supply chain is urgently needed. In addition, factors such as end-customer behavior and corresponding governmental policies and regulations in environmental protection must be considered in model formulation.

2. Literature review

Although the integration of logistics flows is vital for green-supply chain management (G-SCM), previous methods seem limited to specific applications for a single firm or within a limited number of chain members, rather than searching for systematic optimization across the entire green-supply chain. Correspondingly, comprehensive models involving reverse logistics strategies across green-supply chains are rare. Supportive arguments can also be found in Stock (1998). These published models can be classified into deterministic models (Schrady, 1967; Mabini and Gelders, 1991; Richter, 1996a,b) and stochastic models (Simpson, 1978; Cohen et al., 1980; Kelly and Silver, 1989; Cho and Parlar, 1991; Inderfurth, 1996, 1997; Heyman, 1997), differing mainly with respect to their assumptions on the demand and recovery processes of logistical flows. Some typical models are illustrated below.

Assuming constant product demand and return rates associated with each chain member, Schrady (1967) proposed a deterministic model to manage inventories of repairable items under the condition of fixed lead-times for external orders and recovery. More recently some extensions from Schrady's model have been made in Mabini and Gelders (1991), where a multi-item repairing system was proposed to optimize item repair problems with constraints in terms of in-stock service levels. Similar to Schrady's method, Richter (1996a,b) proposed a model with a different inventory control policy, where the optimal control parameter values are searched, also discussing their dependence on return rates. Nevertheless, as pointed out in Fleischmann et al. (2002), deterministic models may be limited to searching for the optimal solution giving preset supply and demand parameters in a given operational environment. Thus, this may lead to impracticality of those deterministic models when corresponding supply and demand environments are uncertain and complex.

In contrast to the aforementioned deterministic models, corresponding stochastic models have focused mainly on deriving optimal control policies under various assumptions, and minimizing expected costs over a finite planning horizon. Muckstadt and Issac (1981) considered formulating the single-item inventory control problem under the condition of non-zero lead times with a continuous model. In their research, the demand and return occurrences were assumed to be of unit quantity following respective Poisson distributions. Similarly, aiming at single-item inventory systems, Heyman (1997) considered the trade-off relationship between additional inventory holding costs and production cost savings, where product demands and return inter-occurrence time are assumed to follow respective stochastic processes. Cohen et al. (1980) investigated a dynamic inventory system where both recoverable and serviceable inventories are considered. Later, their system was modified by Kelly and Silver (1989) to be a system with random returns. To optimize both maintenance and replacement activities, Cho and Parlar (1991) proposed a multi-unit inventory control system in which recoverable inventory is allowed to coincide with serviceable inventory, considering that returned products are reused directly. In reality, their model can be regarded as a simple stochastic inventory model with a simplifying assumption that the product issued in a given period is returned with a constant returned rate after a fixed lead-time. In contrast to Cho's approach, an extended system with random returns was proposed by Kelly and Silver (1989) to deal with new container purchasing problems.

Furthermore, Simpson (1978) proved that the optimum solution structure for an n-period repairable inventory problem is completely defined by three period-dependent values, and thus proposed a solution methodology. Recently, the work of Simpson has been improved in Inderfurth (1996, 1997), where the effects of non-zero leadtimes for orders and recovery are considered. In Inderfurth's method, the difference between the two lead times is regarded as a critical factor which complicates inventory systems, and similar arguments can also be found in Kiesmuller (2003). It should be noted that assuming identical lead times may lead the results of Inderfurth's model to be the same as Simpson's.

In addition, some stochastic models are formulated with continuous forms; correspondingly, the time axis is modeled continuously and the objective is to find optimal control policies minimizing the average costs for a long-term time horizon (van der Laan et al., 1996a,b). More recently, various manufacturing/remanufacturing systems with PUSH and PULL disposal strategies were investigated in van der Laan and Salomon (1997, 1999). Nevertheless, product demands and returns are assumed to be independent stochastic processes in the previous literature. However, such a postulation may not hold true in most practical reverse logistics cases.

Considering the limitations of applying the existing models for integrated logistics management in a green-supply chain, this study proposes a multi-objective optimization-based methodology. Here, an integrated logistics control model is formulated to systematically maximize the aggregate net profit of logistics flows across a given green-supply chain which combines both the product manufacturing supply chain and used-product reverse logistics chain. Correspondingly, given that a set of distribution channel members associated with these two chains are coordinated as partners, the optimal solutions for corresponding logistical flows across chain members are searched according to the proposed model following the aforementioned goal. Herein the trade-off relationships between the business logistics flows and corresponding used-product reverse logistics flows across the given green-supply chain are considered for G-SCM. It is also noteworthy that the model proposed in this paper is formulated in a generalized form, which may be more applicable for more general cases of G-SCM than previous specific models.

3. System specification

In order to formulate the aforementioned integrated logistics management (ILM) problem, a comprehensive conceptual framework is proposed, as shown in Fig. 1, which involves 11 potential chain members in charge of respective functions of ILM.

As can be seen in Fig. 1, these chain members are classified into two groups: (1) manufacturing supply chain (*mc* for short) members, and (2) used-product reverse logistics chain (*rc* for short) members. Here a typical 5-layer manufacturing supply chain is proposed to characterize 5 respective ILM functions in corresponding layers, including raw material supply, manufacturing, wholesaling, retailing, and end-customers, which are coded as *mc*-layers 1–5, respectively. Similarly, a 5-layer used-product reverse logistics chain is specified, which includes collecting points, recycling plants, [1] disassembly plants, secondary material markets, and final disposal locations of wastes, coded as *rc*-layers 1–5, respectively. Furthermore, considering the potential effects oriented from corresponding governmental regulations, the environmental protection administration (EPA) of the government is included as an actor. Accordingly, these members are linked with solid and dashed lines, representing corresponding directional relationships in terms of logistics flows and induced monetary flows, respectively, in the ILM process.

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[1] Here the major function performed by recycling plants is minor transitional treatment, excluding the activity of used-product disassembly. Generally, such a minor transitional treatment mechanism does not need sophisticated disassembly techniques and facilities, as needed by disassembly plants. However, in real-world operations, both recycling and disassembly plants may be needed in a green-supply chain system, particularly when the corresponding transitional treatment procedures for returned used products are complicated, as can be seen in numerous high-technology industries.

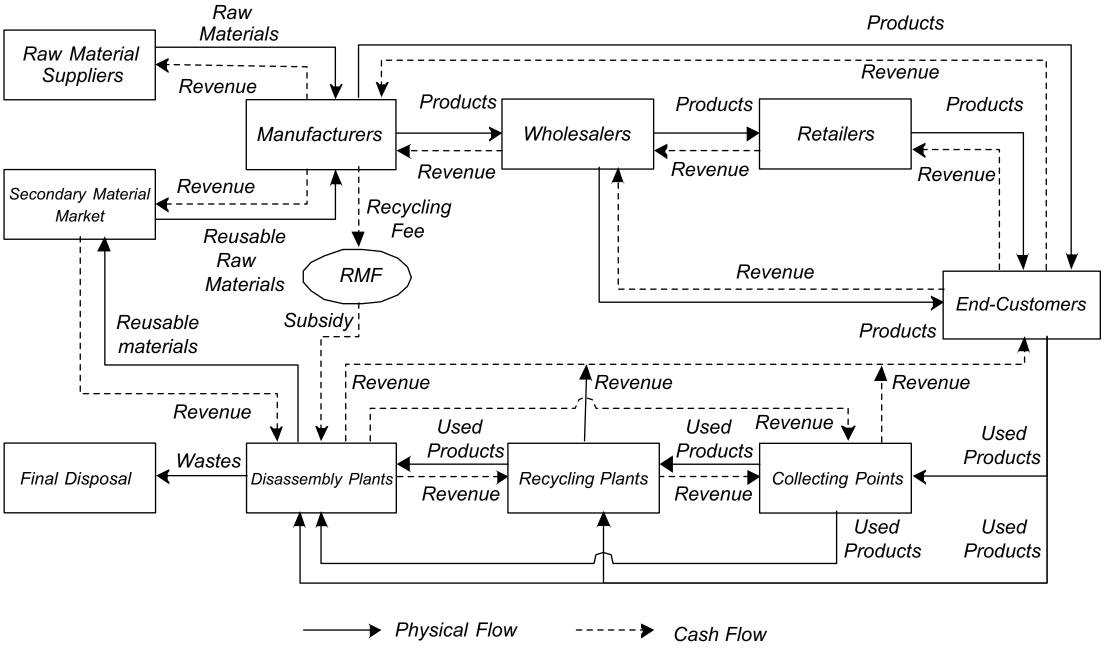

Fig. 1. Conceptual framework for integrated logistics control across a green-supply chain.

To specify the study scope and facilitate model formulation, five assumptions are postulated below.

(1) Only the single-product condition is considered in the proposed model. [2]
(2) The time-varying quantity of product demands from end-customers in any given time interval is given. [3]
(3) There is a given return ratio, referring to the proportion of the quantity of used products returned from end-customers, and through the reverse logistics chain.
(4) Facility capacities associated with chain members of the proposed integrated logistics system are known.
(5) The lead-time associated with each chain member either in the general supply chain or in the reverse supply chain is given.

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[2] Different products may have distinctive features requiring specific operational procedures, strategies, and induced operational costs in green-supply chains. To facilitate model formulation, only the single-product scenario is investigated in this study.

[3] Considering the limitations of space and study scope, the time-varying end-customer demands in each given time interval are assumed to be known, and estimated by given stochastic processes in the proposed model. Nevertheless, it is suggested that corresponding demand forecasting techniques be employed in future research for the development of an advanced G-SCM system.

4. Modeling

Given the aforementioned assumptions, a composite multi-objective optimization model [4] is formulated to seek equilibrium solutions with the goal of maximizing the systematic net profit, as aggregated from the chain-based net profits associated with the manufacturing supply chain and reverse logistics chain, respectively. The mathematical formulation of the proposed model is detailed below. All the notations for variables, including decision variables referring to the variables determined by the optimization process of the proposed model for G-SCM, are summarized in Appendix A.

According to the proposed integrated logistics system architecture (see Fig. 1), the composite multi-objective function (Ω) of the proposed model mainly contains two sub-objective functions: (1) manufacturing chain-based net profit (NP_{mc}) maximization, and (2) reverse chain-based net profit (NP_{rc}) maximization. Considering the respective effects of NP_{mc} and NP_{rc} on Ω, two corresponding weights (w_{mc} and w_{rc}) are specified, respectively, subject to the condition that the sum of w_{mc} and w_{rc} is equal to 1. Accordingly, we have the mathematical form of the proposed composite multi-objective function given by

$$\max \Omega = w_{mc} \times \mathrm{NP}_{mc} + w_{rc} \times \mathrm{NP}_{rc} \tag{1}$$

Herein, these two aggregate profits, NP_{mc} and NP_{rc}, are measured by subtracting the corresponding aggregate costs (i.e., AC_{mc} and AC_{rc}) from the respective aggregate revenues (i.e., AR_{mc} and AR_{rc}), as expressed respectively in Eqs. (2) and (3).

$$\mathrm{NP}_{mc} = \mathrm{AR}_{mc} - \mathrm{AC}_{mc} = \mathrm{AR}_{mc} - (\mathrm{APC}_{mc} + \mathrm{AMC}_{mc} + \mathrm{AIC}_{mc} + \mathrm{ATC}_{mc} + \mathrm{ARF}_{mc}) \tag{2}$$

$$\mathrm{NP}_{rc} = \mathrm{AR}_{rc} - \mathrm{AC}_{rc} = (\mathrm{AD}_{rc} + \mathrm{AS}_{rc}) - (\mathrm{ACC}_{rc} + \mathrm{ATTC}_{rc} + \mathrm{AIC}_{rc} + \mathrm{ATC}_{rc} + \mathrm{AFC}_{rc}) \tag{3}$$

As can be seen in Eq. (2), the aggregate cost associated with a given manufacturing chain (AC_{mc}) is composed of five major items. They are the corresponding aggregate costs in terms of raw-material procurement (APC_{mc}), manufacturing (AMC_{mc}), inventory (AIC_{mc}), transportation (ATC_{mc}) and aggregate recycling fees (ARF_{mc}) paid from the manufacturing layer to the corresponding EPA. Similarly, in Eq. (3), the aggregate cost associated with the corresponding reverse chain is composed of five items, i.e., the aggregate costs in terms of used-product collection (ACC_{rc}), transitional treatment (ATTC_{rc}), inventory (AIC_{rc}), transportation (ATC_{rc}), and final disposal (AFC_{rc}). In addition, considering the potential effect of subsidies from the EPA (AS_{rc}) on the

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[4] The composite multi-objective optimization approach is a well-known multiple-objective decision-making (MODM) approach, which has been extensively used in the field of operational research and related application areas to find the non-inferior solutions in the decision space constrained by the multiple objective functions under decision maker's preferences (Zadeh, 1963; Goicoechea et al., 1982; Rangan and Poola, 1997; Rardin, 1998). The feature of the proposed composite optimization method is associating different weights with specific objective functions to distinguish the corresponding effects of the specified objective functions on system optimization. Here the aforementioned weights associated with disaggregate objective functions represent the relative significance of the associated objective functions perceived by the decision makers who plan/operate/manage the system.

aggregate profit function associated with a given reverse chain, both AS_{rc} and the aggregate revenue (AD_{rc}) oriented specifically from general vendor–buyer business operations in a given reverse chain are involved to formulate the corresponding aggregate revenue (AR_{rc}). The mathematical forms of the aforementioned components shown in Eqs. (2) and (3) are further expressed as presented below. First, for Eq. (2)

$$\mathrm{AR}_{mc} = \sum_{\forall k}\left\{\left[\sum_{\forall i^1_{mc}}\sum_{\forall i^2_{mc}} r_{i^1_{mc},i^2_{mc}}(k)\times Q_{i^1_{mc},i^2_{mc}}(k)\right] + \left[\sum_{j=2}^{4}\sum_{l=j+1}^{5}\sum_{\forall i^j_{mc}}\sum_{\forall i^l_{mc}} r_{i^j_{mc},i^l_{mc}}(k)\times Q_{i^j_{mc},i^l_{mc}(k)}\right]\right\} \tag{4}$$

where the first term on the right hand side of Eq. (4) represents the aggregate profit oriented from the raw-material flows ($Q_{i^1_{mc},i^2_{mc}}(k)$) transported by the layer of raw-material supply to the layer of manufacturing; and the second term represents the aggregate profit oriented from the physical flows ($Q_{i^j_{mc},i^l_{mc}}(k)$) of the manufactured product in any given distribution channel of the corresponding manufacturing chain.

$$\begin{aligned}\mathrm{APC}_{mc} = \sum_{\forall k}\Bigg\{&\left[\sum_{\forall i^1_{mc}} c^{\mathrm{raw}}_{i_{mc}1}(k)\times Q^{\mathrm{raw}}_{i^1_{mc}}(k)\right] + \Bigg[\sum_{\forall i^1_{mc}}\sum_{i^2_{mc}} c^{\mathrm{pro}}_{i^1_{mc},i^2_{mc}}(k)\times Q_{i^1_{mc},i^2_{mc}}(k)\\ &+\sum_{\forall i^4_{rc}}\sum_{\forall i^2_{mc}} c^{\mathrm{pro}}_{i^4_{rc},i^2_{mc}}(k)\times Q_{i^4_{rc},i^2_{mc}}(k)\Bigg] + \left[\sum_{j=2}^{3}\sum_{l=j+1}^{4}\sum_{\forall i^j_{mc}}\sum_{\forall i^l_{mc}} c^{\mathrm{pro}}_{i^j_{mc},i^l_{mc}}(k)\times Q_{i^j_{mc},i^l_{mc}}(k)\right]\Bigg\}\end{aligned} \tag{5}$$

where the aggregate cost of raw-material procurement (APC_{mc}) involves three components: (1) the initialized cost of raw materials generated in the layer of raw-material supply, (2) the procurement cost oriented from the layer of manufacturing for ordering the raw materials from both the raw-material supplies of the given manufacturing chain and the secondary material market of the corresponding reverse chain, and (3) the manufactured-product procurement costs in any given distribution channels of the given manufacturing chain, as presented in order on the right-hand side of Eq. (5).

$$\mathrm{AMC}_{mc} = \sum_{\forall k}\left\{\sum_{\forall i^2_{mc}} c^{\mathrm{man}}_{i^2_{mc}}(k)\times Q^{\mathrm{man}}_{i^2_{mc}}(k)\right\} \tag{6}$$

where the aggregate manufacturing cost (AMC_{mc}) is oriented primarily from the flows of the manufactured product ($Q^{\mathrm{man}}_{i^2_{mc}}(k)$).

$$\mathrm{AIC}_{mc} = \sum_{\forall k}\left\{\left[\sum_{j=1}^{2}\sum_{\forall i^j_{mc}} c^{\mathrm{inv}^{\mathrm{raw}}}_{i^j_{mc}}(k)\times Q^{\mathrm{inv}^{\mathrm{raw}}}_{i^j_{mc}}(k)\right] + \left[\sum_{j=2}^{4}\sum_{\forall i^j_{mc}} c^{\mathrm{inv}}_{i^j_{mc}}(k)\times Q^{\mathrm{inv}}_{i^j_{mc}}(k)\right]\right\} \tag{7}$$

where the aggregate inventory cost (AIC_{mc}) of the given manufacturing chain is composed of two terms: (1) the inventory cost of raw materials oriented in the layers of both raw-material supply and manufacturing, and (2) the inventory cost of the manufactured product in any given chain member of the given manufacturing chain.

$$\mathrm{ATC}_{mc} = \sum_{\forall k} \left\{ \left[\sum_{\forall i^1_{mc}} \sum_{\forall i^2_{mc}} c^{\mathrm{tra}}_{i^1_{mc},i^2_{mc}}(k) \times Q_{i^1_{mc},i^2_{mc}}(k) \right] + \left[\sum_{j=2}^{4} \sum_{l=j+1}^{5} \sum_{\forall i^j_{mc}} \sum_{\forall i^l_{mc}} c^{\mathrm{tra}}_{i^j_{mc},i^l_{mc}}(k) \times Q_{i^j_{mc},i^l_{mc}}(k) \right] \right\} \tag{8}$$

where the aggregate transportation cost (ATC_{mc}) of the given manufacturing chain is oriented from two types of physical flows: (1) the raw materials ($Q_{i^1_{mc},i^2_{mc}}(k)$) transported from the layers of raw-material supply to manufacturing, and (2) the manufactured product ($Q_{i^j_{mc},i^l_{mc}}(k)$) transported in any given distribution channels of the given manufacturing chain, as presented in that order on the right-hand side of Eq. (8).

$$\mathrm{ARF}_{mc} = \sum_{\forall k} \sum_{\forall i^2_{mc}} f^{\mathrm{rec}} \times Q^{\mathrm{man}}_{i^2_{mc}}(k) \tag{9}$$

where the aggregate recycling fees (ARF_{mc}) are oriented from the amount of the manufactured product ($Q^{\mathrm{man}}_{i^2_{mc}}(k)$) multiplied by the corresponding unit recycling fees (f^{rec}).

Then, for Eq. (3)

$$\begin{aligned}\mathrm{AD}_{rc} = \sum_{\forall k} \Bigg\{ & \left[\sum_{l=1}^{3} \sum_{\forall i^5_{mc}} \sum_{\forall i^l_{rc}} r_{i^5_{mc},i^l_{rc}}(k) \times Q_{i^5_{mc},i^l_{rc}}(k) \right] + \left[\sum_{l=2}^{3} \sum_{\forall i^1_{rc}} \sum_{\forall i^l_{rc}} r_{i^1_{rc},i^l_{rc}}(k) \times Q_{i^1_{rc},i^l_{rc}}(k) \right] \\ & + \left[\sum_{j=2}^{3} \sum_{\forall i^j_{rc}} \sum_{\forall i^{j+1}_{rc}} r_{i^j_{rc},i^{j+1}_{rc}}(k) \times Q_{i^j_{rc},i^{j+1}_{rc}}(k) \right] + \sum_{\forall i^4_{rc}} \sum_{\forall i^2_{mc}} r_{i^4_{rc},i^2_{mc}}(k) \times Q_{i^4_{rc},i^2_{mc}}(k) \Bigg\}\end{aligned} \tag{10}$$

where the corresponding aggregate revenue (AD_{rc}) associated with the given reverse chain is composed of four terms: (1) the refund obtained by any given end customer for returning the used product, [5] (2) the revenue associated with the layer of used-product collection for selling the collected unprocessed used product to the other chain members of the given reverse chain, (3) the revenue oriented from any other chain members for selling the processed used product to another, and (4) the revenue oriented from the layer of the secondary material market for selling the processed usable raw materials to the layer of manufacturing of the given manufacturing chain. These terms are presented in order on the right-hand side of Eq. (10).

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[5] Despite the fact that the amount of used products returned from a given end customer can be assumed to follow a stochastic process or to be preset as a given value, depending on the nature of the problem specified, here we tend to define it as a time-varying decision variable, determined using the return resource constraints (see Eq. (32)) in the optimization process. That is, it is expected that the time-varying used-product returns are controllable in the proposed model. From a viewpoint of a system supplier (e.g., the green-supply chain decision-makers), the aforementioned operational condition can be achieved using some specific collection strategies, e.g., network design of local used-product return points, specific collection frequencies for end customers' returns, appropriate return policies, and regulations coupled with operational strategies of return promotions. These issues may warrant more investigation and discussion in further research.

$$\mathrm{AS}_{rc} = \sum_{\forall k} \left\{ \sum_{j=1}^{2} \sum_{\forall i_{rc}^{j}} \sum_{\forall i_{rc}^{3}} s_{i_{rc}^{3}} \times Q_{i_{rc}^{j}, i_{rc}^{3}}(k) \right\} \tag{11}$$

where the aggregate subsidies (AS_{rc}) associated with the given reverse chain are oriented from the reverse flows ($Q_{i_{rc}^{j}, i_{rc}^{3}}(k)$) of the returned used product transported to the layer of disassembly plants for government subsidies.

$$\mathrm{ACC}_{rc} = \sum_{\forall k} \left\{ \sum_{l=1}^{3} \sum_{\forall i_{mc}^{5}} \sum_{\forall i_{rc}^{l}} \left[c_{i_{mc}^{5}, i_{rc}^{l}}^{\mathrm{col}}(k) \times Q_{i_{mc}^{5}, i_{rc}^{l}}(k) \right] \right\} \tag{12}$$

where the aggregate collection cost (ACC_{rc}) is mainly oriented from the physical flows ($Q_{i_{mc}^{5}, i_{rc}^{l}}(k)$) of the returned used product collected from the end-customer layer to the layers of collection points, recycling plants and disassembly plants in the given reverse chain.

$$\mathrm{ATTC}_{rc} = \sum_{\forall k} \left\{ \sum_{j=1}^{4} \sum_{\forall i_{rc}^{j}} c_{i_{rc}^{j}}^{\mathrm{tre}}(k) \times Q_{i_{rc}^{j}}^{\mathrm{tre}}(k) \right\} \tag{13}$$

where the aggregate transitional treatment cost (ATTC_{rc}) is caused mainly due to the transitional treatment procedures executed potentially in all the reverse-chain layers, except for the layer of final disposal.

$$\begin{aligned} \mathrm{AIC}_{rc} = \sum_{\forall k} \Bigg\{ & \sum_{j=1}^{5} \sum_{\forall i_{rc}^{j}} \left[c_{i_{rc}^{j}}^{\mathrm{inv}^{\mathrm{untre}}}(k) \times Q_{i_{rc}^{j}}^{\mathrm{inv}^{\mathrm{untre}}}(k) \right] + \sum_{j=1, j \neq 3}^{4} \sum_{\forall i_{rc}^{j}} \left[c_{i_{rc}^{j}}^{\mathrm{inv}^{\mathrm{tre}}}(k) \times Q_{i_{rc}^{j}}^{\mathrm{inv}^{\mathrm{tre}}}(k) \right] \\ & + \sum_{i_{rc}^{3}} \left[c_{i_{rc}^{j}}^{\mathrm{inv}_{3\text{–}4}}(k) \times Q_{i_{rc}^{3}}^{\mathrm{inv}_{3\text{–}4}}(k) + c_{i_{rc}^{j}}^{\mathrm{inv}_{3\text{–}5}}(k) \times Q_{i_{rc}^{3}}^{\mathrm{inv}_{3\text{–}5}}(k) \right] \Bigg\} \end{aligned} \tag{14}$$

where the aggregate inventory cost (AIC_{rc}) of the given reverse chain is mainly caused by the storage of two types of physical flows, i.e., the unprocessed used product ($Q_{i_{rc}^{j}}^{\mathrm{inv}^{\mathrm{untre}}}(k)$) and the processed used product ($Q_{i_{rc}^{j}}^{\mathrm{inv}^{\mathrm{tre}}}(k)$), associated with any potential chain member of the given reverse chain. In addition, considering the two potential types of processed used product that may be stored in any given disassembly plant, i.e., one for final disposal and the other one selling to the secondary market, a specific cost term is formulated for the layer of disassembly plants, as presented in the third term on the right-hand side of Eq. (14).

$$\begin{aligned} \mathrm{ATC}_{rc} = \sum_{\forall k} \Bigg\{ & \left[\sum_{l=2}^{3} \sum_{\forall i_{rc}^{1}} \sum_{\forall i_{rc}^{l}} c_{i_{rc}^{1}, i_{rc}^{l}}^{\mathrm{tra}}(k) \times Q_{i_{rc}^{1}, i_{rc}^{l}}(k) \right] + \left[\sum_{j=2}^{3} \sum_{\forall i_{rc}^{j}} \sum_{\forall i_{rc}^{j+1}} c_{i_{rc}^{j}, i_{rc}^{j+1}}^{\mathrm{tra}}(k) \times Q_{i_{rc}^{j}, i_{rc}^{j+1}}(k) \right] \\ & + \left[\sum_{\forall i_{rc}^{3}} \sum_{\forall i_{rc}^{5}} c_{i_{rc}^{3}, i_{rc}^{5}}^{\mathrm{tra}}(k) \times Q_{i_{rc}^{3}, i_{rc}^{5}}(k) \right] + \left[\sum_{\forall i_{rc}^{4}} \sum_{\forall i_{mc}^{2}} c_{i_{rc}^{4}, i_{mc}^{2}}^{\mathrm{tra}}(k) \times Q_{i_{rc}^{4}, i_{mc}^{2}}(k) \right] \Bigg\} \end{aligned} \tag{15}$$

where the aggregate transportation cost (ATC_{rc}) involves the costs of transporting physical flows in any given distribution channels of the given reverse chain, excluding the aforementioned collection costs, which are oriented from the reverse flows associated with end customers.

$$\mathrm{AFC}_{rc} = \sum_{\forall k} \left\{ \sum_{\forall i^5_{rc}} c^{\mathrm{fin}}_{i^5_{rc}}(k) \times Q^{\mathrm{fin}}_{i^5_{rc}}(k) \right\} \tag{16}$$

As can be seen in Eq. (16), the aggregate final disposal cost (AFC_{rc}) depends on the total amount of the used product disposed in the layer of final disposal.

In addition, considering the corresponding logistics conditions either compelled by governmental regulations or limited by operating requirements, three groups of constraints, including disaggregate inventory conditions, total product demands, and total used-product return quantities, are involved in the proposed model. They are elaborated as follows.

4.1. Disaggregate inventory constraints

Inventory constraints define the relationships of the inbound and outbound logistics flows as well as the corresponding storage quantities associated with given chain members. Herein, they are specified as follows.

(1) For raw-material suppliers (*mc*-layer 1)

$$0 \leqslant Q^{\mathrm{inv}^{\mathrm{raw}}}_{i^1_{mc}}(k) = Q^{\mathrm{inv}^{\mathrm{raw}}}_{i^1_{mc}}(k-1) + Q^{\mathrm{raw}}_{i^1_{mc}}(k) - \sum_{\forall i^2_{mc}} Q_{i^1_{mc},i^2_{mc}}(k) \leqslant \Psi^{\mathrm{inv}^{\mathrm{raw}}}_{i^1_{mc}} \quad \forall(i^1_{mc},k) \tag{17}$$

where the time-varying inventory amount ($Q^{\mathrm{inv}^{\mathrm{raw}}}_{i^1_{mc}}(k)$) of raw materials associated with a given raw-material supplier i^1_{mc} in a given time interval k is equal to the sum of the corresponding inventory amount remaining in the previous time interval $k-1$ ($Q^{\mathrm{inv}^{\mathrm{raw}}}_{i^1_{mc}}(k-1)$) and the corresponding time-varying amount generated in the given time interval k ($Q^{\mathrm{raw}}_{i^1_{mc}}(k)$), minus the total outbound raw-material flow ($\sum_{\forall i^2_{mc}} Q_{i^1_{mc},i^2_{mc}}(k)$) transported to the layer of manufacturing in the given time interval k. In addition, $Q^{\mathrm{inv}^{\mathrm{raw}}}_{i^1_{mc}}(k)$ is subject to predetermined upper and lower bounds, i.e., the corresponding storage capacity ($\Psi^{\mathrm{inv}^{\mathrm{raw}}}_{i^1_{mc}}$) and 0. Therefore, Eq. (17) is proposed for the disaggregate inventory constraint associated with any given raw-material supplier i^1_{mc} in the given manufacturing chain.

(2) For product manufacturers (*mc*-layer 2)

$$\begin{aligned} 0 \leqslant Q^{\mathrm{inv}^{\mathrm{raw}}}_{i^2_{mc}}(k) = {} & Q^{\mathrm{inv}^{\mathrm{raw}}}_{i^2_{mc}}(k-1) + \left[\sum_{\forall i^1_{mc}} Q_{i^1_{mc},i^2_{mc}}(k) + \sum_{\forall i^4_{rc}} Q_{i^4_{rc},i^2_{mc}}(k) \right] \\ & - \tau^{r/m}_{i^2_{mc}} \times Q^{\mathrm{man}}_{i^2_{mc}}(k) \leqslant \Psi^{\mathrm{inv}^{\mathrm{raw}}}_{i^2_{mc}} \quad \forall(i^2_{mc},k) \end{aligned} \tag{18}$$

$$0 \leqslant Q^{\mathrm{inv}}_{i^2_{mc}}(k) = Q^{\mathrm{inv}}_{i^2_{mc}}(k-1) + Q^{\mathrm{man}}_{i^2_{mc}}(k) - \sum_{l=3}^{5} \sum_{\forall i^l_{mc}} Q_{i^2_{mc},i^l_{mc}}(k) \leqslant \Psi^{\mathrm{inv}}_{i^2_{mc}} \quad \forall(i^2_{mc},k) \tag{19}$$

Similar to the rationales of Eq. (17), the time-varying inventory amounts of both the raw materials ($Q_{i_{mc}^2}^{\text{inv}^{\text{raw}}}(k)$) and the manufactured product ($Q_{i_{mc}^2}^{\text{inv}}(k)$) associated with any given manufacturer should be subject to predetermined upper and lower bounds, i.e., their corresponding storage capacities and 0, as presented in Eqs. (18) and (19), respectively. In addition, the variations of logistics flows transformed from raw materials to products are considered, and thus the corresponding coefficient $\tau_{i_{mc}^2}^{r/m}$ is involved in Eq. (18) for the corresponding disaggregate inventory constraint of raw materials associated with any given manufacturer i_{mc}^2.

(3) For wholesalers and retailers (*mc*-layers 3 and 4)

$$0 \leqslant Q_{i_{mc}^l}^{\text{inv}}(k) = Q_{i_{mc}^l}^{\text{inv}}(k-1) + \left[\sum_{j=2}^{l-1} \sum_{\forall i_{mc}^j} Q_{i_{mc}^j, i_{mc}^l}(k)\right] - \left[\sum_{n=l+1}^{5} \sum_{\forall i_{mc}^n} Q_{i_{mc}^l, i_{mc}^n}(k)\right] \leqslant \Psi_{i_{mc}^l}^{\text{inv}}$$

$$\forall (i_{mc}^l, k), \quad l = 3 \text{ or } 4 \tag{20}$$

Similarly, considering the upper and lower bounds with respect to the disaggregate inventory amounts associated with any given wholesalers and retailers, the corresponding time-varying inventory ($Q_{i_{mc}^l}^{\text{inv}}(k)$) and its relationships with remaining inventory ($Q_{i_{mc}^l}^{\text{inv}}(k-1)$), inbound and outbound flows (i.e., the second and third terms on the right-hand side of the equation symbol of Eq. (20)) are defined, subject to the corresponding upper and lower bounds, i.e., $\Psi_{i_{mc}^l}^{\text{inv}}$ and 0.

(4) For collecting points (*rc*-layer 1)

In this layer, two types of inventory, i.e., untreated (untre for short) and treated (tre for short) inventory flows, are considered. Here treated inventory refers to the corresponding inventory of the used product which has been processed via transitional treatment procedures, e.g., rinse and classification, and repacking, required in the given *rc*-layer. Accordingly, we have Eqs. (21) and (22) proposed for the corresponding upper and lower bounds associated with the untreated and treated inventories (i.e., $Q_{i_{rc}^1}^{\text{inv}^{\text{untre}}}(k)$ and $Q_{i_{rc}^1}^{\text{inv}^{\text{tre}}}(k)$), respectively, for any given collection point, where their time-varying relationships with corresponding remaining inventories (i.e., $Q_{i_{rc}^1}^{\text{inv}^{\text{untre}}}(k-1)$ and $Q_{i_{rc}^1}^{\text{inv}^{\text{tre}}}(k-1)$, respectively) and with inbound-outbound flows are also defined.

$$0 \leqslant Q_{i_{rc}^1}^{\text{inv}^{\text{untre}}}(k) = Q_{i_{rc}^1}^{\text{inv}^{\text{untre}}}(k-1) + \left[\sum_{\forall i_{mc}^5} Q_{i_{mc}^5, i_{rc}^1}(k)\right] - Q_{i_{rc}^1}^{\text{tre}}(k) \leqslant \Psi_{i_{rc}^1}^{\text{inv}^{\text{untre}}} \quad \forall (i_{rc}^1, k) \tag{21}$$

$$0 \leqslant Q_{i_{rc}^1}^{\text{inv}^{\text{tre}}}(k) = Q_{i_{rc}^1}^{\text{inv}^{\text{tre}}}(k-1) + Q_{i_{rc}^1}^{\text{tre}}(k) - \sum_{l=2}^{3} \sum_{\forall i_{rc}^l} Q_{i_{rc}^1, i_{rc}^l}(k) \leqslant \Psi_{i_{rc}^1}^{\text{inv}^{\text{tre}}} \quad \forall (i_{rc}^1, k) \tag{22}$$

(5) For recycle plants (*rc*-layer 2)

Similarly, the corresponding upper and lower bounds with respect to both the untreated and treated inventory flows associated with any given recycle plant are taken into account, thus contributing to the following inventory boundary constraints.

$$0 \leqslant Q^{\text{inv}^{\text{untre}}}_{i^2_{rc}}(k) = Q^{\text{inv}^{\text{untre}}}_{i^2_{rc}}(k-1) + \left[\sum_{\forall i^5_{mc}} Q_{i^5_{mc},i^2_{rc}}(k) + \sum_{\forall i^1_{rc}} Q_{i^1_{rc},i^2_{rc}}(k)\right] - Q^{\text{tre}}_{i^2_{rc}}(k) \leqslant \Psi^{\text{inv}^{\text{untre}}}_{i^2_{rc}} \quad \forall(i^2_{rc},k) \tag{23}$$

$$0 \leqslant Q^{\text{inv}^{\text{tre}}}_{i^2_{rc}}(k) = Q^{\text{inv}^{\text{tre}}}_{i^2_{rc}}(k-1) + Q^{\text{tre}}_{i^2_{rc}}(k) - \sum_{\forall i^3_{rc}} Q_{i^2_{rc},i^3_{rc}}(k) \leqslant \Psi^{\text{inv}^{\text{tre}}}_{i^2_{rc}} \quad \forall(i^2_{rc},k) \tag{24}$$

(6) For disassembly plants (*rc*-layer 3)

In contrast with the above boundary constraints specified for *rc*-layers 1 and 2, the used products processed in this layer (i.e., *rc*-layer 3) may have two distribution channels: one leading to secondary material markets for further reuse (i.e., *rc*-layers 3–4), and the other one leading to final disposal (i.e., *rc*-layers 3–5). Accordingly, the corresponding inventory boundary constraints with respect to both untreated and treated inventories associated with any given disassembly plant are specified as follows.

$$\begin{aligned}0 \leqslant Q^{\text{inv}^{\text{untre}}}_{i^3_{rc}}(k) = Q^{\text{inv}^{\text{untre}}}_{i^3_{rc}}(k-1) &+ \left[\sum_{\forall i^5_{mc}} Q_{i^5_{mc},i^3_{rc}}(k) + \sum_{j=1}^{2}\sum_{\forall i^j_{rc}} Q_{i^j_{rc},i^3_{rc}}(k)\right]\\ &- Q^{\text{tre}}_{i^3_{rc}}(k) \leqslant \Psi^{\text{inv}^{\text{untre}}}_{i^3_{rc}} \quad \forall(i^3_{rc},k)\end{aligned} \tag{25}$$

$$0 \leqslant Q^{\text{inv}_{3\text{–}4}}_{i^3_{rc}}(k) = Q^{\text{inv}_{3\text{–}4}}_{i^3_{rc}}(k-1) + \tau^{3\text{–}4}_{i^3_{rc}} \times Q^{\text{tre}}_{i^3_{rc}}(k) - \sum_{\forall i^4_{rc}} Q_{i^3_{rc},i^4_{rc}}(k) \leqslant \Psi^{\text{inv}_{3\text{–}4}}_{i^3_{rc}} \quad \forall(i^3_{rc},k) \tag{26}$$

$$0 \leqslant Q^{\text{inv}_{3\text{–}5}}_{i^3_{rc}}(k) = Q^{\text{inv}_{3\text{–}5}}_{i^3_{rc}}(k-1) + \tau^{3\text{–}5}_{i^3_{rc}} \times Q^{\text{tre}}_{i^3_{rc}}(k) - \sum_{\forall i^5_{rc}} Q_{i^3_{rc},i^5_{rc}}(k) \leqslant \Psi^{\text{inv}_{3\text{–}5}}_{i^3_{rc}} \quad \forall(i^3_{rc},k) \tag{27}$$

where the condition $\tau^{3\text{–}4}_{i^3_{rc}} + \tau^{3\text{–}5}_{i^3_{rc}} = 1$ with respect to corresponding physical transformation rates must also hold.

(7) For secondary material markets (*rc*-layer 4)

Two types of inventory, i.e., untreated (untre for short) and treated (tre for short) inventory flows (i.e., $Q^{\text{inv}^{\text{untre}}}_{i^4_{rc}}(k)$ and $Q^{\text{inv}^{\text{tre}}}_{i^4_{rc}}(k)$), are considered for each given secondary material market in this layer. Here the untreated inventory flow refers to the unprocessed disassembled materials transported from disassembly plants of *rc*-layer 3, and the treated inventory flow represents those processed reusable materials which are planned to be returned to the manufacturing chain. Accordingly, the corresponding inventory boundary constraints are formulated as shown in Eqs. (28) and (29), respectively.

$$0 \leqslant Q^{\text{inv}^{\text{untre}}}_{i^4_{rc}}(k) = Q^{\text{inv}^{\text{untre}}}_{i^4_{rc}}(k-1) + \sum_{\forall i^3_{rc}} \left[Q_{i^3_{rc},i^4_{rc}}(k)\right] - Q^{\text{tre}}_{i^4_{rc}}(k) \leqslant \Psi^{\text{inv}^{\text{untre}}}_{i^4_{rc}} \quad \forall(i^4_{rc},k) \tag{28}$$

$$0 \leqslant Q^{\text{inv}^{\text{tre}}}_{i^4_{rc}}(k) = Q^{\text{inv}^{\text{tre}}}_{i^4_{rc}}(k) + \tau^{\text{tre}}_{i^4_{rc}} \times Q^{\text{tre}}_{i^4_{rc}}(k) - \sum_{\forall i^2_{mc}} Q_{i^4_{rc},i^2_{mc}}(k) \leqslant \Psi^{\text{inv}^{\text{tre}}}_{i^4_{rc}} \quad \forall(i^4_{rc},k) \tag{29}$$

(8) For final disposal locations (*rc*-layer 5)

Final disposal locations of wastes refer to the sites where useless wastes are processed with appropriate disposal measures, e.g., landfill or incineration. Therefore, only one type of inventory (i.e., useless disassembled materials transported from disassembly plants of *rc*-layer 3) is considered, and the corresponding inventory ($Q^{\mathrm{inv}^{\mathrm{untre}}}_{i^5_{rc}}(k)$) boundary constraint condition is given by

$$0 \leqslant Q^{\mathrm{inv}^{\mathrm{untre}}}_{i^5_{rc}}(k) = Q^{\mathrm{inv}^{\mathrm{untre}}}_{i^5_{rc}}(k-1) + \sum_{\forall i^3_{rc}} \left[Q_{i^3_{rc},i^5_{rc}}(k) \right] - Q^{\mathrm{fin}}_{i^5_{rc}}(k) \leqslant \Psi^{\mathrm{inv}^{\mathrm{untre}}}_{i^5_{rc}} \quad \forall (i^5_{rc}, k) \tag{30}$$

where the time-varying relationships of $Q^{\mathrm{inv}^{\mathrm{untre}}}_{i^5_{rc}}(k)$ with the corresponding remaining inventory, inbound flows, and the time-varying physical amount of final disposal are also defined, as shown in the first, second and third terms on the right-hand side of the equation symbol of Eq. (30).

4.2. Demand constraints

Demand constraints aim to specify the relationships between the end-customer total demands ($D_{mc}(k)$) and the physical flows ($Q_{i^j_{mc},i^5_{mc}}(k)$) of manufactured products transported to end-customers. According to the second assumption mentioned above, the quantity of the time-varying total end-customer demands ($D_{mc}(k)$) is given. Therefore, we have the corresponding constraints given by

$$D_{mc}(k) = \sum_{j=2}^{4} \sum_{\forall i^j_{mc}} \sum_{\forall i^5_{mc}} Q_{i^j_{mc},i^5_{mc}}(k) \geqslant 0 \quad \forall k \tag{31}$$

4.3. Return resource constraints

In contrast with the above demand constraints, return resource constraints denote the time-varying relationships between the quantities of the time-varying product demand ($D_{mc}(k)$) and the corresponding used-product return flow ($R_{rc}(k)$). Here the used-product return ratio (γ), either enforced by EPA or predetermined by the G-SCM system, is also considered. Accordingly, we have the corresponding constraints given by

$$R_{rc}(k) = \sum_{l=1}^{3} \sum_{\forall i^5_{mc}} \sum_{\forall i^l_{rc}} Q_{i^5_{mc},i^l_{rc}}(k) = \gamma \times D_{mc}(k) \geqslant 0 \quad \forall k \tag{32}$$

where $D_{mc}(k)$ can be estimated using given stochastic processes. In this study, it is assumed to follow a Poisson distribution with a given mean value, which is determined using collected survey data.

It is noteworthy that in the proposed green-supply chain system, the no-inventory condition, which mimics Just-in-Time (JIT) cases, may not happen all the time for the following two reasons. First, both the transportation costs and inventory costs in either the manufacturing chain or the reverse chain have been considered in the proposed objective function (see Eqs. (2) and (3), and related equations for their components). As extensively perceived in fields of logistics management, a trade-off relationship between transportation and inventory costs exists in real-world logistics operational cases. Therefore, such JIT cases may not happen unless specific operational strategies are employed as an aid. Second, the time-varying inventory associated with each given chain member is updated in each time interval. This can be seen in the proposed disaggregate inventory constraints (see Eq. (17) through (30)). Therefore, according to our proposed model, the optimal solutions of decision variables together with these inventory updated functions will determine the optimal inventory amount associated with each chain member under the system-optimization condition for G-SCM.

5. Numerical results

To illustrate the applicability of the proposed method, a simplified numerical study was conducted. Considering the local operational case of a well-known Taiwanese notebook computer manufacturer, which is one of the top three domestic brands in Taiwan. In this case study, we built a simplified integrated logistics network based on the logistics distribution channels of the given notebook manufacturer in the northern region of Taiwan. Using collected historical data as well as interview survey data, we estimated both the input data, e.g., the annual sales and used-product returns, as well as the primary parameters, e.g., corresponding logistics-induced operational costs for use in formulating the corresponding integrated logistics management problem. Using the proposed method, the numerical results of optimal solutions were determined and then compared to the existing operational performance of the targeted notebook manufacturer. Details of the primary procedures in the numerical study and corresponding results are presented below.

5.1. Estimates of demands and returns

In this scenario, the time-varying product demands and used-product returns in each given time interval were estimated. The aforementioned time-varying demands and returns refer to the quantities of product demands and induced used-product returns oriented from the end-customer layer (i.e., *ms*-layer 5) of the targeted notebook manufacturing supply chain in each given time interval. Here the length of a unit time interval (coded k) is one month, and the time horizon for integrated logistics management is set to be one year (coded K). Conveniently, the average monthly domestic sales volume of the targeted manufacturer in Taiwan in 2002 (the corresponding approximate value is 6152) was used as the mean of a Poisson distribution to generate the time-varying end-customer product demands, i.e., $D_{mc}(k)$, for the numerical study. In addition, the corresponding used-product return ratio (γ) was preset to be 0.25 according to the corresponding regulations of the EPA of Taiwan. Given a Poisson distribution with the preset mean value (6152), the time-varying amount of end-customer product demands, $D_{mc}(k)$, was then generated in each given time interval k, and followed by the estimation of $R_{rc}(k)$ using the estimate of $D_{mc}(k)$ multiplied by the predetermined return ratio γ. The aforementioned estimates of time-varying demands and returns are summarized in Table 1.

Table 1
Estimates of time-varying product demands and used-product returns (unit: pcs)

Estimates		
Time interval	Product demand	Used-product return
1	6290	1623
2	6263	1534
3	6049	1535
4	6115	1547
5	6163	1564
6	6107	1605
7	6153	1478
8	6149	1485
9	6151	1576
10	6055	1532
11	6231	1489
12	6095	1487
Total	73,821	18,455

5.2. Parameter settings

Estimation of supply-related parameters was completed using interview data. In general, it is difficult to estimate supply-related parameters such as the unit operational costs and revenues directly from reported statistical data because of business confidentiality. To overcome this, with the aid of EPA and the Industrial Bureau of the Taiwan Economics Ministry of Taiwan, interviews were conducted with high-level decision-makers of the targeted notebook manufacturing enterprise and its potential channel members, including the chain members in both the manufacturing and reverse chains. The interviews included both open- and closed-ended questions relating to the potential operating performance (e.g., the potential ranges of operational costs and benefits) and limitations in dealing with the corresponding logistics operational problems of the notebook computer product and used product returns (e.g., corresponding facility capacities, availability of fleet size, and vehicle dispatching frequencies). These collected raw interview data were then analyzed and processed to generate the upper and lower bounds associated with the corresponding costs and revenues associated with both the *mc*- and *rc*-layers. Then, using respective uniform distributions with respective ranges bounded by estimated upper and lower bounds, the corresponding unit costs and revenues associated with each disaggregate chain member were generated for the use of the proposed model.

Here the corresponding upper and lower bounds of these uniform distribution functions were specified using the aforementioned survey data. The estimated ranges of the corresponding unit revenues in the numerical study are summarized in Table 2; and the corresponding ranges of unit costs associated with the manufacturing supply chain and reverse logistics chain are summarized in Tables 3 and 4, respectively.

In addition, other primary parameters, e.g., transformation rates and inventory capacities, were also predetermined according to the aforementioned interview data, as summarized in Table 5.

Table 2
Estimated boundaries of unit revenues used in the numerical study

	Parameter	Unit revenues (US$)	
		Lower bound	Upper bound
mc-layer			
Layer-1: raw material supplier	$r_{i_{mc}^{1},i_{mc}^{2}}(k)$	29	55
Layer-2: manufacturer	$r_{i_{mc}^{2},i_{mc}^{3}}(k)$	360	610
Layer-3: wholesaler	$r_{i_{mc}^{3},i_{mc}^{4}}(k)$	521	825
Layer-4: retailer	$r_{i_{mc}^{4},i_{mc}^{5}}(k)$	723	1023
Layer-5: end-customer	$r_{i_{mc}^{5},i_{rc}^{l}}(k)$	0	5
rc-layer			
Layer-1: collecting point	$r_{i_{rc}^{1},i_{rc}^{l}}(k)$	4.3	6.8
Layer-2: recycle plant	$r_{i_{rc}^{2},i_{rc}^{3}}(k)$	6.1	9.5
Layer-3: disassembly plant	$r_{i_{rc}^{3},i_{rc}^{4}}(k)$	8.9	12.8
Layer-4: secondary material market	$r_{i_{rc}^{4},i_{mc}^{2}}(k)$	15.0	30.0

Table 3
Estimated boundaries of unit costs associated with the manufacturing supply chain

mc-layer	Parameter	Unit costs (US$)	
		Lower bound	Upper bound
Layer-1: raw material supplier	$c_{i_{mc}^{1}}^{\mathrm{raw}}(k)$	12	27
	$c_{i_{mc}^{1}}^{\mathrm{inv}^{\mathrm{raw}}}(k)$	1.5	2.0
	$c_{i_{mc}^{1},i_{mc}^{2}}^{\mathrm{tra}}(k)$	0.1	0.3
Layer-2: manufacturer	$c_{i_{mc}^{1},i_{mc}^{2}}^{\mathrm{pro}}(k)$	13	35
	$c_{i_{rc}^{4},i_{mc}^{2}}^{\mathrm{pro}}(k)$	15	30
	$c_{i_{mc}^{2}}^{\mathrm{man}}(k)$	68	162
	$c_{i_{mc}^{2}}^{\mathrm{inv}}(k)$	42	97
	$c_{i_{mc}^{2}}^{\mathrm{inv}^{\mathrm{raw}}}(k)$	30	70
	$c_{i_{mc}^{2},i_{mc}^{3}}^{\mathrm{tra}}(k)$	0.1	0.3
Layer-3: wholesaler	$c_{i_{mc}^{2},i_{mc}^{3}}^{\mathrm{pro}}(k)$	409	654
	$c_{i_{mc}^{3}}^{\mathrm{inv}}(k)$	52	121
	$c_{i_{mc}^{3},i_{mc}^{4}}^{\mathrm{tra}}(k)$	0.1	0.3
Layer-4: retailer	$c_{i_{mc}^{3},i_{mc}^{4}}^{\mathrm{pro}}(k)$	518	725
	$c_{i_{mc}^{4}}^{\mathrm{inv}}(k)$	65	138
	$c_{i_{mc}^{4},i_{mc}^{5}}^{\mathrm{tra}}(k)$	0.25	0.6

Table 4
Estimated boundaries of unit costs associated with the reverse logistics chain

rc-layer	Parameter	Unit costs (US$)	
		Lower bound	Upper bound
Layer-1: collecting point	$c^{\mathrm{col}}_{i^5_{mc},i^1_{rc}}(k)$	0.6	1.4
	$c^{\mathrm{tre}}_{i^1_{rc}}(k)$	0.3	1.0
	$c^{\mathrm{inv}^{\mathrm{untre}}}_{i^1_{rc}}(k)$	0.3	0.6
	$c^{\mathrm{inv}^{\mathrm{tre}}}_{i^1_{rc}}(k)$	0.3	0.6
	$c^{\mathrm{tra}}_{i^1_{rc},i^l_{rc}}(k)$	0.1	0.3
Layer-2: recycle plant	$c^{\mathrm{col}}_{i^5_{mc},i^2_{rc}}(k)$	1.4	2.3
	$c^{\mathrm{tre}}_{i^2_{rc}}(k)$	2.2	3.5
	$c^{\mathrm{inv}^{\mathrm{untre}}}_{i^2_{rc}}(k)$	0.3	0.6
	$c^{\mathrm{inv}^{\mathrm{tre}}}_{i^2_{rc}}(k)$	0.3	0.6
	$c^{\mathrm{tra}}_{i^2_{rc},i^3_{rc}}(k)$	0.1	0.3
Layer-3: disassembly plant	$c^{\mathrm{col}}_{i^5_{mc},i^3_{rc}}(k)$	1.5	2.8
	$c^{\mathrm{tre}}_{i^3_{rc}}(k)$	1.3	2.2
	$c^{\mathrm{inv}^{\mathrm{untre}}}_{i^3_{rc}}(k)$	0.3	0.6
	$c^{\mathrm{inv}_{3-4}}_{i^3_{rc}}(k)$	1.1	2.5
	$c^{\mathrm{inv}_{3-5}}_{i^3_{rc}}(k)$	0.14	0.32
	$c^{\mathrm{tra}}_{i^3_{rc},i^4_{rc}}(k)$	0.14	0.29
	$c^{\mathrm{tra}}_{i^3_{rc},i^5_{rc}}(k)$	0.06	0.14
Layer-4: secondary material market	$c^{\mathrm{col}}_{i^3_{rc},i^4_{rc}}(k)$	3.6	5.2
	$c^{\mathrm{tre}}_{i^4_{rc}}(k)$	1.5	2.6
	$c^{\mathrm{inv}^{\mathrm{untre}}}_{i^4_{rc}}(k)$	0.6	1.5
	$c^{\mathrm{inv}^{\mathrm{tre}}}_{i^4_{rc}}(k)$	1.0	2.2
	$c^{\mathrm{tra}}_{i^4_{rc},i^2_{mc}}(k)$	0.1	0.3
Layer-5: final disposal location	$c^{\mathrm{inv}^{\mathrm{untre}}}_{i^5_{rc}}(k)$	0.06	0.14
	$c^{\mathrm{fin}}_{i^5_{rc}}(k)$	0.09	0.17

Conveniently, the initial inventory condition associated with each chain member was generated here using a respective uniform distribution bounded by the range between 0 and the corresponding inventory capacity estimated.

Table 5
Summary of primary supply-related parameter

1. Transformation rate

$\tau_{i_{mc}^{2}}^{r/m}$	$\tau_{i_{rc}^{3}}^{3-4}$	$\tau_{i_{rc}^{3}}^{3-5}$	$\tau_{i_{rc}^{4}}^{\mathrm{tre}}$
1	1	1	0.2

2. Inventory capacity (unit: pcs)

(1) *mc*-layer

$\Psi_{i_{mc}^{1}}^{\mathrm{inv}^{\mathrm{raw}}}$	$\Psi_{i_{mc}^{2}}^{\mathrm{inv}^{\mathrm{raw}}}$	$\Psi_{i_{mc}^{2}}^{\mathrm{inv}}$	$\Psi_{i_{mc}^{3}}^{\mathrm{inv}}$	$\Psi_{i_{mc}^{4}}^{\mathrm{inv}}$
7000	5000	5000	500	100

(2) *rc*-layer

$\Psi_{i_{rc}^{1}}^{\mathrm{inv}^{\mathrm{untre}}}$	$\Psi_{i_{rc}^{1}}^{\mathrm{inv}^{\mathrm{tre}}}$	$\Psi_{i_{rc}^{2}}^{\mathrm{inv}^{\mathrm{untre}}}$	$\Psi_{i_{rc}^{2}}^{\mathrm{inv}^{\mathrm{tre}}}$	$\Psi_{i_{rc}^{3}}^{\mathrm{inv}^{\mathrm{untre}}}$	$\Psi_{i_{rc}^{3}}^{\mathrm{inv}_{3-4}}$	$\Psi_{i_{rc}^{3}}^{\mathrm{inv}_{3-5}}$	$\Psi_{i_{rc}^{4}}^{\mathrm{inv}^{\mathrm{untre}}}$	$\Psi_{i_{rc}^{4}}^{\mathrm{inv}^{\mathrm{tre}}}$	$\Psi_{i_{rc}^{5}}^{\mathrm{inv}^{\mathrm{untre}}}$
500	500	1000	1000	2500	1500	500	1000	800	500

3. Others

Return ratio (γ)	Unit recycle fee (f^{rec})	Unit subsidy ($s_{i_{rc}^{3}}$)	Manufacturing chain-based weight (w_{mc})	Reverse chain-based weight (w_{rc})
0.25	1.1	8.7	0.5	0.5

5.3. Analysis of numerical results

This scenario assesses the relative performance of the proposed method by comparing it with the existing operational costs given the preset input data and parameters. Herein, we assume that the weights associated with the manufacturing chain-based objective function and reverse chain-based objectives are consistent, so that both w_{mc} and w_{rc} are equal to 0.5 in this case. In addition, the unit subsidy is set to be 8.7 (US$) according to the corresponding regulations of the Taiwan EPA for 2003. Accordingly, we obtained the numerical results, as summarized in Table 6.

Table 6 indicates the relatively significant advantages of the proposed integrated logistics control method for G-SCM. As can be seen in Table 6, using the proposed model, the relative improvement in terms of the increases of the aggregate net profits in the given green-supply chain reaches as high as 21.1%, compared to the existing chain-based operational performance. [6] According to our observation from this study case, such a generalization may result mainly from the efficiency in coordinating the reverse logistics operations of chain members in different layers of the given reverse logistics chain. In addition, the chain members of the manufacturing supply chain can also benefit somewhat from the aforementioned improvement. By doing so, the overall system performance can thus be improved to a certain extent.

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[6] The existing chain-based operational performance, including corresponding logistics operational costs and revenues, was estimated using the survey data collected via interviews with the corresponding chain members. Data collected from the interview respondents were then processed and aggregated to estimate the existing chain-based operating performance, as presented in Table 6.

Table 6
Evaluation of relative system performance using the proposed model

Evaluation criterion	Net profit (US$)		
Operational alternative	*mc*-layer	*rc*-layer	Aggregate
The proposed method	25,836,372	76,843	25,913,215
The existing operational strategy	21,344,593	54,339	21,398,932
Increase in net profit	4,491,779	22,504	4,514,283
Relative improvement (%)	21.0	41.4	21.1

It is also worth mentioning that although the increased profit oriented from the reverse logistics chain is relatively small, compared to that oriented from the manufacturing chain, such profit-based improvement is still meaningful to both the private sector, e.g., a manufacturer, and the public sector, e.g., the corresponding EPA. Practically, the numerical results shown in Table 6 can make available the proposed integrated logistics operations model with benefits not only for the implementation of effective G-SCM, but also for the accomplishment of environmental pollution alleviation without extra expenses charged to any members involved in a given green-supply chain, including the corresponding EPA. Accordingly, manufacturers can be convinced more easily to coordinate all the chain members for the promotion of G-SCM.

In addition, the above comparison results also imply the necessity of appropriate used-product return policies and subsidy strategies in the reverse logistics chain system. This is particularly true with the increasing global environmental concerns. Therefore, the two corresponding parameters of (1) the return ratio (γ) and (2) the unit subsidy ($s_{i^3_{rc}}$), are worth further investigation. Note that in practice γ can be determined by either EPA or corresponding chain members (e.g., manufacturers) according to their operational policies in product recovery; in contrast, $s_{i^3_{rc}}$ may rely mainly on the corresponding environmental protection regulations imposed by the EPA.

Accordingly, we conducted respective sensitivity analyses of the aforementioned parameters to investigate the potential effects of these parameters on the performance of the given reverse logistics chain. The corresponding numerical results are summarized in Table 7, including the improved reverse chain-based net profits relative to the previous system performance obtained using the proposed method.

According to the numerical results of Table 7, there are two implications as summarized below.

(1) There seems to be an optimal solution with respect to the used-product return ratio existing in the proposed integrated logistics system. As can be seen in Table 7, the corresponding reverse chain-based net profits increase proportionally with the increase of the return ratio subject to the corresponding range of the return ratio 0 and 0.6, and then decline as the return ratio continues to increase. This generalization may also imply that extreme used-product return policies, e.g., no-return or full-return policies, may not be appropriate for improving the operational performance of used-product recovery in the given green-supply chain.

(2) The governmental subsidy policy remains as a critical determinant in influencing the performance of used-product reverse logistics chain in this case studied. The corresponding numerical results shown in Table 7 indicate that the reverse chain-based net profits increase

Table 7
Numerical results of sensitivity analyses for reverse logistics

Control parameter		Reverse chain-based net profits (US$)	Relative improvement (%): compared to US$76,843
Used-product return ratio (γ)	Unit subsidy ($s_{i^3_{rc}}$)		
0.0	8.7	0	−100.0
0.2		53,703	−30.1
0.4		116,648	51.8
0.6		151,612	97.3
0.8		−1254	−101.6
1.0		−4991	−106.5
0.25	0.0	−25,204	−132.8
	5.0	67,084	−12.7
	10.0	104,813	36.4
	15.0	142,851	85.9
	20.0	163,368	112.6
	30.0	213,854	178.3

significantly with the increase of the value of the governmental subsidy. In contrast, the existing reverse logistics chain system may suffer from the sacrifice condition in the case that the EPA provides no subsidies to the reverse logistics system.

Overall, the above numerical results have implied both the potential advantages of the proposed integrated logistics control system for G-SCM, and the significance of appropriate used-product return and subsidy strategies in determining the system performance. To improve system performance, it is absolutely necessary to coordinate all the chain members, including the EPA and members of the reverse logistics chain, involved in such an extended supply chain in the presence of global environmental concerns. Herein, the equilibrium condition among the three parties of system supervisor (e.g., EPA), supply chain operators, and the corresponding reverse logistics operators, may also be worth noting.

6. Conclusions

This paper has presented an integrated logistics operational model to coordinate the cross-functional product logistics flows and used-product reverse logistics flows in a given green-supply chain. By identifying the critical activities and related operational requirements of the proposed integrated logistics system, a composite multi-objective function together with corresponding operational constraints are formulated.

Compared to previous literature, the proposed method has two distinctive features. First, the corresponding integrated logistics operational problem of a green-supply chain is formulated with a generalized mathematical form, and thus is not limited to applications for specific industries. Such a methodological measure is rare in previous literature, and has exhibited its potential advantages in addressing complicated G-SCM problems. Second, factors oriented from the enforcement of corresponding governmental regulations for environmental protection, e.g., the subsidies for used-product recovery, return ratio, and recycle fees charged to manufacturers, are considered in the proposed model. Thus, the corresponding effects may help to determine solution alternatives to improve the performance of a green-supply chain.

Results of numerical studies have indicated that using the proposed integrated logistics operational model, the chain-based aggregate net profits of a selected notebook computer manufacturer can be improved by 21.1%, relative to the existing operational performance of the supply chain.

Nevertheless, it is suggested that appropriate used-product return and subsidy strategies should be involved to determine the system performance. Here the used-product return ratio and corresponding unit subsidy for reverse logistics can be regarded as two primary factors, oriented respectively from the sectors of the end-customer demand market and government, and significantly influencing the G-SCM performance. More specifically, the optimal solutions of used-product return ratio and unit subsidy may exist according to the corresponding numerical results of sensitivity analyses. For instance, by extending the proposed model, a nonlinear optimization-based model can be formulated to address the aforementioned issues, where the used-product return ratio and corresponding unit subsidy are specified as two decision variables in the proposed extended model. Definitely, other factors such as the end-customer willingness to return used products and the corresponding governmental budget for recycle subsidies may be appropriate subjects for further investigation. Model extension involving the goal of minimizing environmental pollution-oriented risks is also our research interest. From the viewpoint of a system supplier, (e.g., the green supply chain decision makers), the success of the proposed G-SCM system may also rely on appropriate used-product collection strategies, e.g., specification of local used-product return points and collection frequencies for end customers' returns, specific return policies and regulations, and strategies for return promotions. These may warrant further investigation and discussion in future research. Furthermore, measures to determine the equilibrium condition among the three parties of system supervisor (e.g., EPA), supply chain operators, and the corresponding reverse logistics operators, may also warrant more investigation.

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Appendix A. Definitions of model variables and parameters

Definitions of variables and parameters shown in the proposed method are summarized below.

Notation	Definition
AC_{mc}	the aggregate cost associated with a given manufacturing chain (*mc* for short)
AC_{rc}	the aggregate cost associated with a given reverse chain (*rc* for short)
ACC_{rc}	the aggregate collection cost of the corresponding used products associated with a given reverse chain (*rc* for short)
AD_{rc}	the aggregate revenue oriented specifically from general vendor-buyer business operations in a given reverse chain (*rc* for short)
AFC_{rc}	the aggregate final disposal cost of the corresponding used products associated with a given reverse chain (*rc* for short)
AIC_{mc}	the aggregate inventory cost associated with a given manufacturing chain (*mc* for short)
AIC_{rc}	the aggregate inventory cost associated with a given reverse chain (*rc* for short)
AMC_{mc}	the aggregate manufacturing cost associated with a given manufacturing chain (*mc* for short)
APC_{mc}	the aggregate raw-material procurement cost associated with a given manufacturing chain (*mc* for short)
AR_{mc}	the aggregate revenue associated with a given manufacturing chain (*mc* for short)
AR_{rc}	The aggregate revenue associated with a given reverse chain (*rc* for short)
ARF_{mc}	the aggregate recycling fees paid from the manufacturing layer (i.e., layer 2) of a given manufacturing chain (*mc* for short) to the corresponding EPA
AS_{rc}	The aggregate subsidies associated with a given reverse chain (*rc* for short) from EPA
ATC_{mc}	the aggregate transportation cost associated with a given manufacturing chain (*mc* for short)
ATC_{rc}	the aggregate transportation cost associated with a given reverse chain (*rc* for short)
ATTC_{rc}	the aggregate transitional treatment cost of the corresponding used products associated with a given reverse chain (*rc* for short)
$c^{\text{col}}_{i^5_{mc},i^l_{rc}}(k)$	the time-varying unit cost for collecting (col for short) the time-varying amount of a given used product returned from a given end-customer i^5_{mc} in layer 5 of the given manufacturing chain (*mc* for short) to a given chain member i^l_{rc} in layer l of the given used-product reverse logistics chain (*rc* for short) in a given time interval k
$c^{\text{fin}}_{i^3_{rc},i^5_{rc}}(k)$	the time-varying unit cost of final disposal (fin for short) associated with the time-varying amount of a given used product returned from a given disassembly plant (i^3_{rc}) in layer 3 to a given final disposal location (i^5_{rc}) in layer 5 of the given used-product reverse logistics chain (*rc* for short) in a given time interval k
$c^{\text{inv}}_{i^j_{mc}}(k)$	the time-varying unit inventory (inv for short) cost for storing a given product associated with a given chain member (i^j_{mc}) in layer j of the given manufacturing chain (*mc* for short) in a given time interval k
$c^{\text{inv}^{\text{raw}}}_{i^j_{mc}}(k)$	the time-varying unit inventory (inv for short) cost for storing the raw materials (raw for short) of a given product, associated with a given chain member (i^j_{mc}) in layer j of the given manufacturing chain (*mc* for short) in a given time interval k

Appendix A (*continued*)

Notation	Definition
$c^{\mathrm{inv}^{\mathrm{tre}}}_{i^j_{rc}}(k)$	the time-varying unit inventory (inv for short) cost for storing a given used product that has been treated (tre for short) by a given chain member (i^j_{rc}) in layer j of the given used-product reverse logistics chain (*rc* for short) in a given time interval k
$c^{\mathrm{inv}^{\mathrm{untre}}}_{i^j_{rc}}(k)$	the time-varying unit inventory (inv for short) cost for storing a given used product that has not been treated (untre for short) by a given chain member (i^j_{rc}) in layer j of the given used-product reverse logistics chain (*rc* for short) in a given time interval k
$c^{\mathrm{inv}_{3\text{–}4}}_{i^3_{rc}}(k)$	the time-varying unit inventory (inv for short) cost for storing a given disassembled used product that is processed in a given disassembly plant (i^3_{rc}) in a given time interval k, and is planned to be transported to a given secondary market (i^4_{rc}) in layer 4 of the given used-product reverse logistics chain (*rc* for short)
$c^{\mathrm{inv}_{3\text{–}5}}_{i^3_{rc}}(k)$	the time-varying unit inventory (inv for short) cost for storing a given disassembled used product that is processed in a given disassembly plant (i^3_{rc}) in a given time interval k, and is planned to be transported to a given final disposal location (i^5_{rc}) in layer 5 of the given used-product reverse logistics chain (*rc* for short)
$c^{\mathrm{man}}_{i^2_{mc}}(k)$	the time-varying unit cost for manufacturing (man for short) a given product produced by a given manufacturer (i^2_{mc}) in layer 2 of the given manufacturing chain (*mc* for short) in a given time interval k
$c^{\mathrm{pro}}_{i^j_{mc},i^l_{mc}}(k)$	the time-varying unit cost for the procurement (pro for short) of the time-varying amount of physical flow from a given chain member i^j_{mc} in layer j to another given chain member i^l_{mc} in layer l of the given manufacturing chain (*mc* for short) in a given time interval k
$c^{\mathrm{pro}}_{i^4_{rc},i^2_{mc}}(k)$	the time-varying unit cost for the procurement (pro for short) of the time-varying amount of physical flow from a given member of the secondary material market (i^4_{rc}) in layer 4 of the given used-product reverse logistics chain (*rc* for short) to a given manufacturer (i^2_{mc}) in layer 2 of the given manufacturing chain (*mc* for short) in a given time interval k
$c^{\mathrm{raw}}_{i^1_{mc}}(k)$	the time-varying unit cost for holding the time-varying amount of the raw materials (raw for short) associated with a given raw-material supplier (i^1_{mc}) in layer 1 of the given manufacturing chain (*mc* for short) in a given time interval k
$c^{\mathrm{tra}}_{i^j_{mc},i^l_{mc}}(k)$	the time-varying unit cost for transporting (tra for short) of the time-varying amount of physical flow from a given chain member i^j_{mc} in layer j to another given chain member i^l_{mc} in layer l of the given manufacturing chain (*mc* for short) in a given time interval k
$c^{\mathrm{tra}}_{i^4_{rc},i^2_{mc}}(k)$	the time-varying unit cost for transporting (tra for short) of the time-varying amount of physical flow from a given secondary material market i^4_{rc} in layer 4 of the given used-product reverse logistics chain (*rc* for short) to a given manufacturer i^2_{mc} in layer 2 of the given manufacturing chain (*mc* for short) in a given time interval k

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Appendix A (*continued*)

Notation	Definition
$c^{\text{tra}}_{i^j_{rc},i^l_{rc}}(k)$	the generalized form of the time-varying unit cost for transported (tra for short) the time-varying amount of a given used product from a given chain member i^j_{rc} in layer j to another given chain member i^l_{rc} in layer l of the given used-product reverse logistics chain (*rc* for short) in a given time interval k ($\forall j,k,l$)
$c^{\text{tre}}_{i^j_{rc}}(k)$	the time-varying unit cost for transitional treatment (tre for short) of the time-varying amount of the given used product associated with a given chain member (i^j_{rc}) in layer j of the given used-product reverse logistics chain (*rc* for short) in a given time interval k
$D_{mc}(k)$	the quantity of time-varying end-customer demands in the given manufacturing chain (*mc* for short) in a given time interval k
f^{rec}	the recycling fees charged by the corresponding EPA for manufacturing a given unit amount of the given product
NP_{mc}	the sub-objective function in terms of manufacturing chain-based (*mc* for short) aggregate profit
NP_{rc}	the sub-objective function in terms of reverse chain-based (*rc* for short) aggregate profit
$Q^{\text{inv}}_{i^j_{mc}}(k)$	a decision variable referring to the time-varying inventory (inv for short) amount of a given product stored by a given chain member (i^j_{mc}) in layer j of the given manufacturing chain (*mc* for short) in a given time interval k
$Q^{\text{inv}^{\text{raw}}}_{i^j_{mc}}(k)$	the time-varying inventory (inv for short) amount of the raw materials (raw for short) stored by a given chain member (i^j_{mc}) in layer j of the given manufacturing chain (*mc* for short) in a given time interval k
$Q^{\text{fin}}_{i^5_{rc}}(k)$	a decision variable referring to the time-varying final disposal (fin for short) amount of useless disassembled materials executed in a given final disposal location (i^5_{rc}) in layer 5 of the given used-product reverse logistics chain (*rc* for short) in a given time interval k
$Q^{\text{inv}^{\text{tre}}}_{i^j_{rc}}(k)$	the time-varying inventory (inv for short) amount of a given used product that has been treated (tre for short) by a given chain member (i^j_{rc}) in layer j of the given used-product reverse logistics chain (*rc* for short) in a given time interval k
$Q^{\text{inv}^{\text{untre}}}_{i^j_{rc}}(k)$	the time-varying inventory (inv for short) amount of a given used product that has not been treated (untre for short) by a given chain member (i^j_{rc}) in layer j of the given used-product reverse logistics chain (*rc* for short) in a given time interval k
$Q^{\text{inv}_{3\text{–}4}}_{i^3_{rc}}(k)$	the time-varying inventory (inv for short) amount of a given disassembled used product in a given time interval k that is processed in a given disassembly plant (i^3_{rc}), and is planned to be transported to a given secondary market (i^4_{rc}) in layer 4 of the given used-product reverse logistics chain (*rc* for short) for further reuse
$Q^{\text{inv}_{3\text{–}5}}_{i^3_{rc}}(k)$	the time-varying inventory (inv for short) amount of a given disassembled used product in a given time interval k that is processed in a given disassembly plant (i^3_{rc}), and is planned to be transported to a given final disposal location (i^5_{rc}) in layer 5 of the given used-product reverse logistics chain (*rc* for short)

Appendix A (*continued*)

Notation	Definition
$Q^{\text{man}}_{i^2_{mc}}(k)$	a decision variable referring to the time-varying amount of a given product manufactured (man for short) by a given manufacturer (i^2_{mc}) in layer 2 of the given manufacturing chain (*mc* for short) in a given time interval *k*
$Q^{\text{raw}}_{i^1_{mc}}(k)$	a decision variable referring to the time-varying amount of the raw materials (raw for short) generated by a given raw-material supplier (i^1_{mc}) in layer 1 of the given manufacturing chain (*mc* for short) in a given time interval *k*
$Q^{\text{tre}}_{i^j_{rc}}(k)$	a decision variable referring to the time-varying transitional treatment (tre for short) amount of the given used product associated with a given chain member (i^j_{rc}) in layer j of the given used-product reverse logistics chain (*rc* for short) in a given time interval *k*
$Q_{i^j_{mc},i^l_{mc}}(k)$	the generalized form of a decision variable referring to the time-varying amount of the physical flow transported from a given chain member i^j_{mc} in layer *j* to another given chain member i^l_{mc} in layer *l* of the given manufacturing chain (*mc* for short) in a given time interval *k* ($\forall j,k,l$)
$Q_{i^5_{mc},i^l_{rc}}(k)$	a decision variable referring to the time-varying amount of the physical flow returned from a given end-customer (i^5_{mc}) in layer 5 of the given manufacturing chain (*mc* for short) to a given chain member (i^l_{rc}) in layer *l* of the given used-product reverse logistics chain (*rc* for short) in a given time interval *k*
$Q_{i^4_{rc},i^2_{mc}}(k)$	a decision variable referring to the time-varying amount of the physical flow transported from a given secondary-material supplier (i^4_{rc}) in layer 4 of the given used-product reverse logistics chain (*rc* for short) to a given manufacturer (i^2_{mc}) in layer 2 of the given manufacturing chain (*mc* for short) in a given time interval *k*
$Q_{i^j_{rc},i^l_{rc}}(k)$	the generalized form of a decision variable referring to the time-varying amount of the physical flow transported from a given chain member (i^j_{rc}) in layer *j* to another given chain member (i^l_{rc}) in layer *l* of the given used-product reverse logistics chain (*rc* for short) in a given time interval *k* ($\forall j,k,l$)
$R_{rc}(k)$	the time-varying amount of the given used product returned from end customers to the given reverse chain (*rc* for short) in a given time interval *k*
$r_{i^j_{mc},i^l_{mc}}(k)$	the generalized form of the time-varying unit revenue for selling the time-varying amount of physical flow from a given chain member (i^j_{mc}) in layer *j* to another given chain member (i^l_{mc}) in layer *l* of the given manufacturing chain (*mc* for short) in a given time interval *k* ($\forall j,k,l$)
γ	the predetermined used-product return ratio
$r_{i^j_{rc},i^l_{rc}}(k)$	the generalized form of the time-varying unit revenue for selling the time-varying amount of physical flow from a given chain member (i^j_{rc}) in layer *j* to another given chain member (i^l_{rc}) in layer *l* of the given used-product reverse logistics chain (*rc* for short) in a given time interval *k* ($\forall j,k,l$)

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Appendix A (*continued*)

Notation	Definition
$r_{i^5_{mc},i^l_{rc}}(k)$	the time-varying unit revenue for recycling the time-varying amount of physical flow from a given end-customer (i^5_{mc}) in layer 5 of the given manufacturing chain (*mc* for short) to a given chain member (i^l_{rc}) in layer *l* of the given used-product reverse logistics chain (*rc* for short) in a given time interval *k*
$r_{i^4_{rc},i^2_{mc}}(k)$	the time-varying unit revenue for selling the time-varying amount of physical flow from a given secondary-material supplier (i^4_{rc}) in layer 4 of the given used-product reverse logistics chain (*rc* for short) to another given manufacturer (i^2_{mc}) in layer 2 of the given manufacturing chain (*mc* for short) in a given time interval *k*
$s_{i^3_{rc}}$	the unit subsidy of environmental protection offered by EPA to a given disassembly plant (i^3_{rc}) in layer 3 of the given used-product reverse logistics chain (*rc* for short)
w_{mc}	the weight associated with the manufacturing chain-based sub-objective function
w_{rc}	the weight associated with the reverse chain-based sub-objective function
Ω	the proposed composite multi-objective function
Ψ°_{*}	the generalized form of the facility capacity associated with a given chain member "∗" for the corresponding inventory item "∘"
$\tau^{r/m}_{i^2_{mc}}$	A coefficient referring to the transformation rate with respect to a given amount of raw materials relative to an unit manufactured product (*r*/*m* for short)
$\tau^{3-4}_{i^3_{rc}}$	A coefficient referring to the transformation rate with respect to a given amount of reusable disassembled materials (i.e., those reusable materials planned to be transported from *rc*-layers 3 to 4; 3–4 for short) relative to an unit amount of the given used product
$\tau^{3-5}_{i^3_{rc}}$	A coefficient referring to the transformation rate with respect to a given amount of useless disassembled materials (i.e., those useless materials planned to be transported from *rc*-layers 3 to 5; 3–5 for short) relative to an unit amount of the given used product
$\tau^{\mathrm{tre}}_{i^4_{rc}}$	A coefficient referring to the transformation rate with respect to a given amount of reusable disassembled materials treated (tre for short) by a given secondary material market (i^4_{rc}) relative to an unit amount of untreated reusable disassembled materials

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