Sustainability **2014**, *6*, 9027-9056; doi:10.3390/su6129027

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

Profit Analysis and Supply Chain Planning Model for Closed-Loop Supply Chain in Fashion Industry

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External Editors: Tsan-Ming Choi and Yongjian Li

Received: 23 September 2014; in revised form: 12 November 2014 / Accepted: 26 November 2014 / Published: 9 December 2014

Abstract: In recent decades, due to market growth and use of synthetic fiber, the fashion industry faces a rapid increase of CO_2 emission throughout the production cycle and raises environmental issues in recovery processing. This study proposes a closed-loop supply chain (CLSC) structure in fashion industry and develops its planning model as multi-objective mixed integer linear programming to find an optimal trade-off between CLSC profit and CO_2 emission. The planning model is associated with the profit analysis of each member in CLSC to find the optimal price of products on CLSC network. The model determines optimal production, transportation, and inventory quantities on CLSC network. The proposed models are validated using numerical experiments and sensitivity analyses, and from the results some managerial insights are addressed.

Keywords: closed-loop supply chain; fashion industry; profit analysis; supply planning model; sustainable supply chain management; CO_2 emission

1. Introduction

Since Brundtland Commission report in 1987 [1] drew huge attention to the importance of sustainable development as an inevitable challenge to the world, researchers, practitioners, and policy makers have made considerable efforts to improve and realize it in their own fields by giving sustainability priority.

Especially, in industrial context, Tonelli *et al.* [2] argue that sustainable development is a means for industrial organizations to survive. They addressed sustainable approaches for future industry, suggested actions and recommendation for educators, researchers, industrialists and policy makers. Supply chain management has no exception. Under the name of sustainable supply chain, the importance of the environmental performance of products and processes for sustainable manufacturing and service operations increasingly is being recognized [3]. For performance measurement of sustainable supply chain, Taticchi *et al.* [4] reviewed most critical literatures on the topic and provided key insights on the current status and future direction of sustainable supply chain in both industry and academia. Also, Kim, *et al.* [5] analytically justified the necessity of sustainable supply chain using the concept of supply chain surplus. However, even the perceived importance of sustainability issues has increased considerably in the literature of SCM (Supply Chain Management) and OM (Operation Management), the research on the impact of SCM and OM on the environment is tiny when compared to other topics, let alone sustainability as a whole [6]. We are still in the early stage of environmental sustainability in most supply chain practices. One of the major progresses may be found in closed-loop supply chain (CLSC). Using a combination of forward and reverse supply network, CLSC can reduce environmental impacts. Especially, as the fashion industry faces vast challenges as well as opportunities in the reduction of its environmental impact globally [7], efficient design of CLSC may considerably mitigate not only environmental pollutions generated through supply chain network, but also increase economic benefits. The most important methods in the fashion industry to pursue environmental sustainability objectives are, (1) use of organic fibers to reduce environmental damages; (2) reusing and recycling materials; (3) vintage practices and secondhand; (4) clean technologies; (5) green certifications; and (6) green product and process design [8]. Of these methodologies, in this study, we focus on reusing and recycling materials, and green certification as CER (Certified Emissions Reduction) credits in the context of CLSC. In this paper, we propose a comprehensive closed-loop supply chain structure for fashion industry and develop a CLSC planning model associated with profit analysis of each member in order to achieve an optimal trade-off between total profit and CO_2 emission on CLSC network. We consider a CLSC consisting of raw material suppliers, three stages of manufacturers—yarn, fabric, apparel—on forward supply chain, and three types of recovery options—repair, remanufacturing, recycling—on reverse supply chain.

As one fundamental CLSC research, Guide *et al.* [9] pointed out that recoverable manufacturing systems inherently increase uncertainty due to seven complicating characteristics in which traditional manufacturing can greatly different from. In this regard, Guide and van Wassenhove [10] defined CLSC management as the design, control and operations of a system to maximize value creation over the entire lifecycle of a product with dynamic recovery of value from different types and volumes of returns over time. They overviewed the rapidly evolving field of CLSC from business perspectives and categorized CLSC networks to five evolutionary phases as follows: (1) the golden age of remanufacturing as a technical problem; (2) from remanufacturing to valuing the reverse logistics process; (3) coordinating the reverse supply chain; (4) closing the loop; and (5) prices and markets. According to these phases, our study is associated with the latter three phases. Most CLSC planning researches fall into the second phase using a classic OR optimization approach with the objectives of either profit maximization or cost minimization. A good overview on quantitative models for recovery production planning and inventory control is given by Fleischmann *et al.* [11] who survey the recently emerged field of reverse logistics and subdivide the field into three main areas, namely distribution planning, inventory control, and production planning, which are also applicable to forward supply chain. Mutha and Pokharel [12] developed nine-echelon reverse logistics network model with reprocessing, remanufacturing, and disposal activities, and the model enables companies to use only the portion of existing capacities for reverse logistics so that new products and remanufacture products are flexibly produced in capacity-wise. Dat *et al.* [13] proposed a reverse logistics network with recycling and repair to minimize total processing costs of various types of electrical and electronic products. Kusumastuti *et al.* [14] and Lee and Dong [15] used facility location-allocation models to develop CLSC network model for repair service of computer products and recovery process of end-of-lease computers, and Fleischmann *et al.* [16] also employed a facility location model to design a generic recovery network. All these are cost-minimization models. Sheu *et al.* [17] suggested an integrated CLSP logistics operational model for maximizing forward- and reverse-chain profits using multi-objective LP (Linear Programming), and pointing out that the optimal used-product return ratio and corresponding unit subsidy may exist and can be considered for further improvement of CLSC network design. Kim *et al*. [18] formulated a strategic supplying decision model in remanufacturing network by maximizing total cost savings measured by the gap between the purchasing cost from the external supplier and the remanufacturing process cost for collected products and their parts. The research on various recovery paths and options can be found in CLSC literatures. Amin and Zhang [19] configured three types of return-recovery pairs on a similar remanufacturing network to that of Kim *et al*. [18] and proposed a mixed integer-programing model to maximize total profits on network. Ostlin *et al.* [20] comprehensively identified seven different types of structural closed-loop relationships between remanufacturers and core suppliers/customers, and suggested the strong and weak points of those relationships for better understanding of CLSC management. Inventory and production planning (I&PP) models on CLSC network are also classical operational management topics and the literatures are growing rapidly [21]. Jayaraman [22] developed a LP-based aggregate production planning model called RAPP (Remanufacturing Aggregate Production Planning) to optimally determine the number of units to be reused, refurbished, remanufactured, recycled, and disposed in CLSC environment with cost minimization. He also discussed demand management by determining selling price to maximize overall profit, but no specific approach was addressed how demands are determined accordingly. Many variants of CLSC planning model are found in CLSC with multi-stage logistics, multi-products, and uncertainty [23–25]. For distribution planning in CLSC, for example, Zhou and Wang [26] considered a CLSC network with repair and remanufacturing, formulated a distribution planning using mixed integer LP for cost minimization, and solved by branch and bound technique. Most previous CLSC optimization models are designed for the electrical and electronic products, such as computer, home appliance, and, recently, cellular phone, and products of automobile industry, while few researches are found in fashion industry (See, e.g., [13–15,27–29]).

Rather than configuration and modeling of CLSC network in generalization context, most researches on CLSC in *fashion industry* are focused on implementing environmental sustainability and assessing environmental impacts (*i.e.*, CO_2 emission) on supply chain in their own case-specific context. As a matter of fact, due to globalization of fashion industry, design teams, manufacturing facilities, and markets are no longer at the same region and the roles are divided by countries where their own culture, rules, infrastructure entail different structure of business systems. This trend encourages researchers in fashion industry to employ case-based approach as the prevailing methodology (See e.g., [8,30–41]), while to the authors' knowledge no relevant researches are found using the analytic model of CLSC in fashion business. In view of objectives, profit maximization and emission minimization are inherently the conflicting nature of tasks in sustainable supply chain so that desirable trade-offs are required in most cases, so are the cases in fashion industry [6,7]. According to the sustainable business model archetypes by Bocken *et al.* [39], our model belongs to "maximize material and energy efficiency" and "create value from waste" archetypes of technological group in the sustainable business model. As a result, CLSC network and low carbon manufacturing constructs our business model in fashion industry. Also, since our model is to determine the max-profit and min- CO_2 emissions using analytical (mathematical) method, it is considered as one kind of decision support tool in sustainable supply chain management, which is comprehensively reviewed and analyzed by Taticchi *et al.* [42].

Our literature review reveals that little research are found in configuring and modeling of CLSC network in fashion industry, and most researches are based on case-specific analysis. We propose a comprehensive CLSC optimization model to determine production, transportation, and inventory quantities of each member in CLSC network with the multiple objectives of CSLC profit maximization and emission minimization for environmental sustainability. The price parameters are determined using profit analysis models and, possibly, ideal market demands are estimated.

The rest of this paper is organized as follows. In the following section, we define the structure of CLSC networks in fashion industry with illustrative examples. Section 3 presents profit analysis models for each CLSC network to determine the optimal selling prices for CSLC products. Following the profit models, a generalized CLSC planning model using multi-objectives mixed integer programming is formulated in Section 4. Section 5 is devoted to numerical and sensitivity analyses for validation of models. Finally, conclusions and future research are presented in Section 6.

2. Structure of Closed-Loop Supply Chain (CLSC) in Fashion Industry

In general, the forward supply chain in fashion and apparel industry consists of the following members: raw material supplier, yarn manufacturer, fabric manufacturer, apparel manufacturer, and customer, as shown in Figure 1a. Closed-loop supply chain involves collectors who obtain end-of-life products from customers, reprocess them, and provide recovered products to manufacturer or customer in supply chain as shown in Figure 1b. The collectors are classified by recovery options. In general CLSC, five options are used, such as repair, remanufacturing, refurbishing, cannibalization, and recycling [43]. Since refurbishing and cannibalization are not applicable to fashion industry, we only consider the remained three options: repair, remanufacturing, and recycling. Repair involves the fixing and/or replacement of broken parts and requires only limited product disassembly and reassembly. As a result, repaired products are usually downgraded in quality. Remanufacturing is to completely disassemble used products, sub-assemble approved parts, and assemble remanufactured products. Sometimes, remanufacturing uses technological upgrades and the products are as good as new products in quality. Recycling process reuses materials from used products and components in order to make new parts or products. Thus, recycling results in the loss of identity and functionality of original products. Table 1 summarizes the three recovery options by type of collectors and level of disassembly. Level of disassembly is the level of components that are produced by disassembling the end-of-life products.

Figure 1. Forward *vs.* closed-loop supply chain in fashion industry. (**a**) Forward supply chain; (**b**) Closed-loop supply chain.

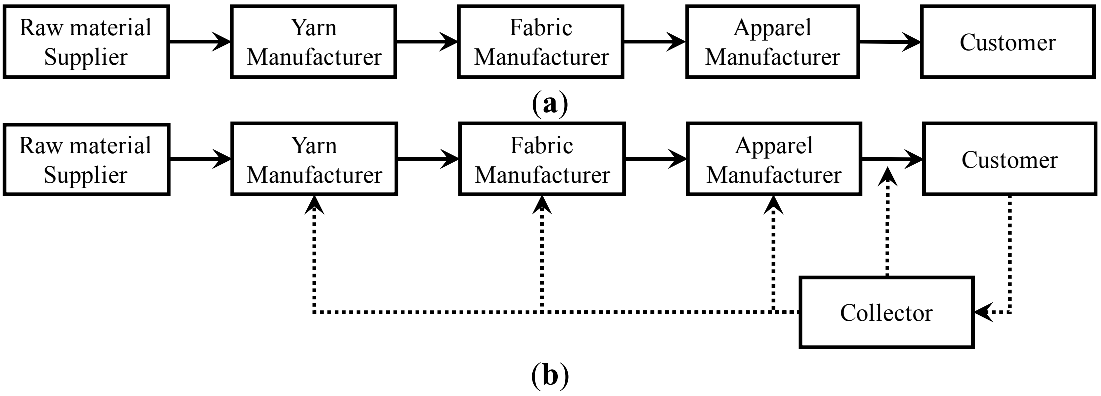


Table 1. Comparison of recovery options in apparel manufacturing.

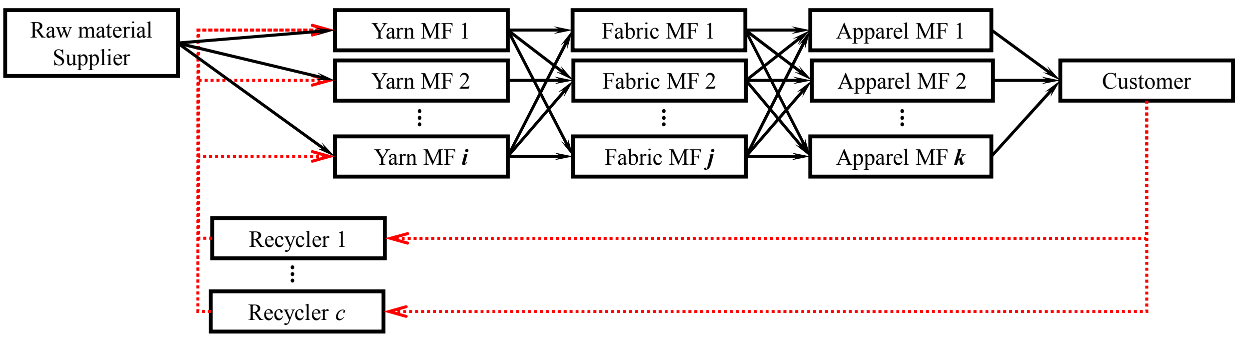
	Recycling	**Remanufacturing**	**Repairing**
Collector	Recycler	Remanufacturer	Repairer
Level of Disassembly	To raw material To semi-yarn product	To yarn product To semi-fabric product	To fabric product To semi-apparel product

According to recovery options, we define three types of CLSC in fashion industry: recycling, remanufacturing, and repair CLSC.

2.1. Recycling CLSC

In recycling CLSC, as shown in Figure 2, recycler collects end-of-life products (apparels) from customers and produce raw materials for yarn manufacturer. Thus, recyclers in fashion industry compete with raw material suppliers. For sustainable supply chain, yarn manufacturer uses the recycled materials with the first priority and then from raw material suppliers in order to meet the demand.

Figure 2. Recycling CLSC in fashion industry.

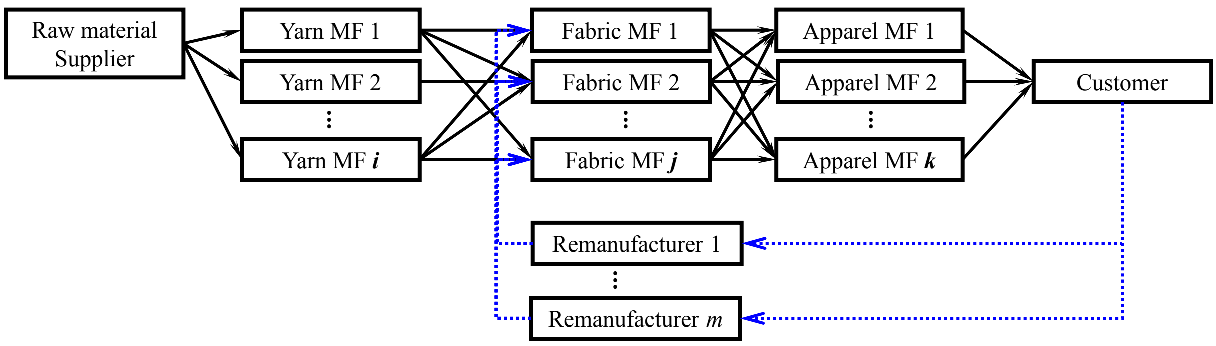


For example of recycling CLSC, Nylon 66 yarn is a synthetic fiber extensively used for carpet in commercial interior applications, and recycled for producing molding goods such as engine cover and electron rice cooker. Nylon 66 is melted into a liquid plastic form and recycled in mostly downgraded quality. Acrylic fiber is also another example of recycling CLSC. Acrylic fiber chips are collected, dissolved by the solvent in the fiber facility, and regenerated in acrylic fiber. In Japan, eco-mark is given on the products using the recycled acrylic fiber.

2.2. Remanufacturing CLSC

The purpose of remanufacturing is to bring used products up to quality standards that are as rigorous as those for new products [31]. In remanufacturing CLSC, remanufacturer collects the end-of-life apparels from customers and remanufactures semi-fabric or yarn products as shown in Figure 3. In this case, the collector competes with yarn manufacturers for yarn supply. Sustainable supply chain forces fabric manufacturers to use remanufactured fabrics with the higher priority than fabrics supplied by yarn manufacturers.

Figure 3. Remanufacturing CLSC in fashion industry.

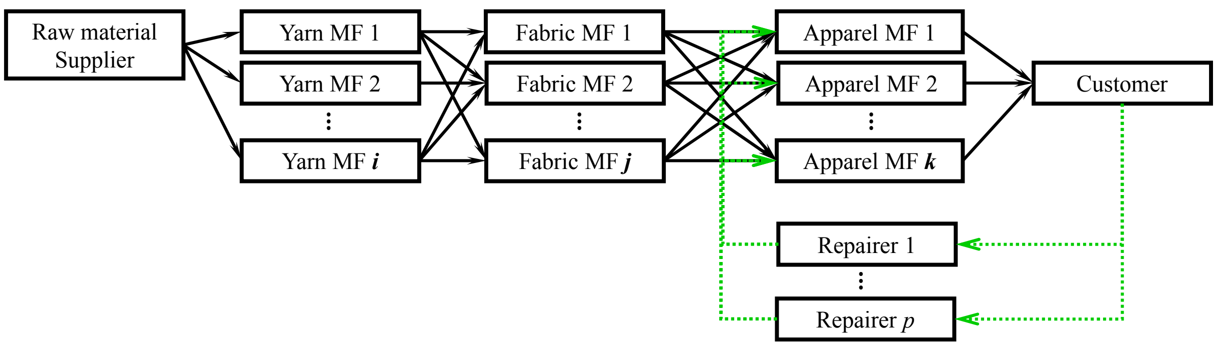


BASF, the German global chemical company, plays as a remanufacturer in carpet industry. They collect used carpets, cut into chips, and remanufacture Nylon 6 as yarn product.

2.3. Repair CLSC

In repair CLSC, as shown in Figure 4, repairer collects the end-of-life apparels from customers, fixes the defects or disassembles, and supplies the finish parts or products to apparel manufacturers. Thus, repairers in fashion industry compete with fabric suppliers. Sustainable supply chain also forces repairers to implement the use of repaired fabrics with the higher priority than the existing fabric manufacturers.

Figure 4. Repair CLSC in fashion industry.

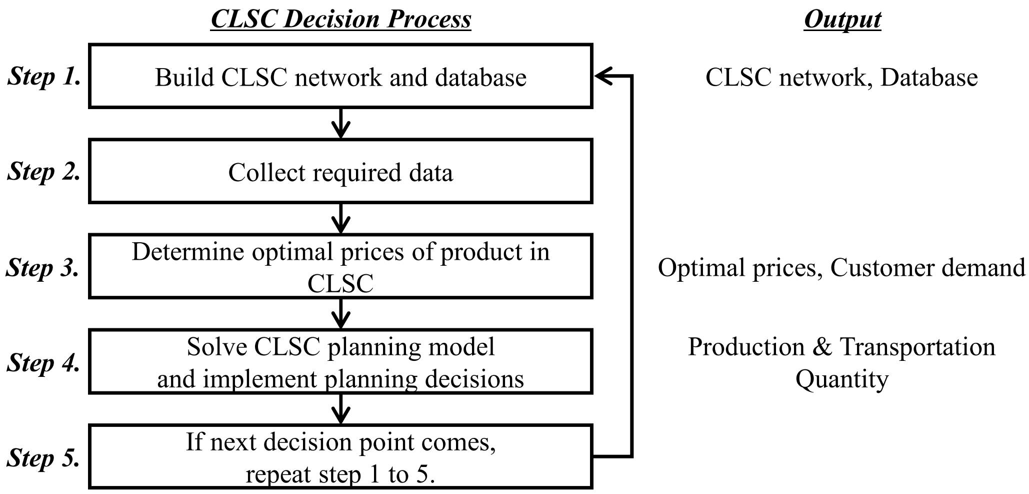


In India, repair process starts with inspection and sorting end-of-life clothes to decide their value potential, and recondition—repair, re-stitch, wash—them for sale via aftermarket retailers [37]. Similar repair process and distribution channel can be found in Zambia where most of the used clothing sold in local markets is imported from Western countries [38]. Repairers in fashion industry are operated more often by separate retailers.

2.4. Overview of CLSC Decision Process

In the previous sections, we defined three types of CLSC based on recovery options. All CLSCs pursue the maximal profits of each member involved in CLSC and also minimal damages to environment throughout supply chain operations. This section describes a decision process by which the objectives of CLSC are achieved. The process may be implemented in periodical or irregular manner. In short, CLSC decision process tries to find optimal price, production amount, transportation quantity, and inventory of all products in supply chain. The results can be used to make strategic decision on the market and implement supply chain operations efficiently. Figure 5 shows our decision process for CLSC planning.

Figure 5. Decision process for CLSC planning.



Step 1 constructs an appropriate CLSC network and setup the master data on the CLSC network. Then, all the necessary data are gathered in step 2. Using the current structure of CLSC and its relevant data, in step 3, we find optimal price for products in CLSC to maximize each member's total profit, and determine the ideal demands for each member in CLSC. In step 4, CLSC planning model is solved in order to maximize total profit and minimize CO_2 emission generated through supply chain activities. Then, optimal production, inventory, and transportation quantities are implemented in CLSC. When the next decision point comes, all previous steps are repeated with the updated CLSC network.

3. Profit Analysis in CLSC

In this section, we present a model for maximizing the profit of each member in CLSC. Before proceeding, we need to make key assumptions on CLSC environment and define nomenclatures used throughout this paper.

3.1. Assumptions and Notations

The following assumptions are made for CLSC in fashion industry.

(A1) All costs incurred in CLSC fall into three categories: production cost, material cost and transportation cost. Production cost includes labor and operation cost. Transportation costs are paid by the receiver.

(A2) Each member in CLSC pursues maximizing its own profit and tries to minimize the environmental damages as well.

(A3) We consider five members of CLSC including raw material supplier, yarn, fabric, and apparel manufacturer, and collector.

(A4) Regarding bill-of-materials (BOM) structure, one unit of apparel product consumes *a* units of fabric and *b* units of yarn products. Then one unit of fabric requires *b/a* units of yarn product.

(A5) The linear demand function is given as $D(A) = \Phi - \beta \cdot A$ and $\Phi > \beta \cdot A$, A is the selling price of product, Φ is primary demand (also called "base demand") when selling price is 0, and β is price-demand sensitivity coefficient [3,44,45], *i.e.*, the ratio of demand change to price change. Since the linear demand function reflects the behavior of market where the demand increases (decreases) as the price decreases (increases), β is interpreted as the ratio of increased (decreased) amount of demand to decreased (increased) amount of price so that the β value is always positive.

(A6) CO_2 emission is proportional to production and transportation volume.

Indices, decision variables, and parameters used in this paper are summarized as end of paper.

3.2. Profit Analysis

The purpose of profit analysis is to find the optimal prices for each member to maximize its profit in CLSC environment and derive its own ideal market size (*i.e.*, demand) for CLSC planning.

3.2.1. Profit Analysis for Recycling CLSC

3.2.1.1. Apparel Manufacturer

The demand of each apparel manufacturer *k* is given as $D_{k,t} = S_{k,t}\phi_{A,t} - \beta_{A,t}AP_{k,t}$ and total demand of apparel manufacturers becomes $D_{A,t} = \sum_k (S_{k,t}\phi_{A,t} - \beta_{A,t}AP_{k,t})$ which equals to total customer demand ($D_{d,t}$). Then we have a profit function of apparel manufacturer *k* as follows:

$$TP_{k,t}^{C}(AP_{k,t}, FP_{j,t}) = (S_{k,t}\phi_{A,t} - \beta_{A,t}AP_{k,t})(AP_{k,t} - l_{k,t} - o_{k,t} - a(\overline{FP}_{j,t} + \bar{T}_{jk,t}) - Inv_{k,t}/D_{k,t}) \quad (1)$$

Equation (1) is total profit of apparel manufacturer *k* by computing the product of sales quantity and unit profit. Total profit function used in this paper is in the form of the product of total demand and unit profit. Total demand is obtained from the linear demand function as addressed in assumption (A5), and unit profit is computed by subtracting all unit costs from unit selling price. Unit profit is computed by subtracting all unit costs from unit selling price. $Inv_{k,t}/D_{k,t}$ indicates investment cost for purchasing CERs required per unit product. $\overline{FP}_{j,t}$ and $\bar{T}_{jk,t}$ are average unit purchasing cost and average unit transportation cost from fabric manufacturer j, respectively, *i.e.*, $\overline{FP}_{j,t} = \sum_j FP_{j,t}/J$ $(j \in N, \forall t)$ and $\bar{T}_{jk,t} = \sum_j T_{jk,t}/J$ $(j \in N, \forall k, t)$. Using the first and second derivatives, we can easily find the profit function in Equation (1) is concave and has the maximal point, as shown in the following equations:

$$\frac{dTP_{k,t}^{C}}{dAP_{k,t}} = S_{k,t}\phi_{A,t} - \beta_{A,t}\left(2AP_{k,t} - PC_{k,t} - a\left(\overline{FP}_{j,t} + \bar{T}_{jk,t}\right)\right) \tag{2}$$

$$\frac{d^2TP_{k,t}^{C}}{dAP_{k,t}^2} = -2\beta_{A,t} < 0(\because \beta_{A,t} > 0) \tag{3}$$

By equating the first derivative in Equation (2) to zero, we find the optimal price as follows:

$$AP_{k,t}^{*}\left(FP_{j,t}\right) = \frac{S_{k,t}\phi_{A,t} + \beta_{A,t}\left(PC_{k,t} + a\left(\overline{FP}_{j,t} + \bar{T}_{jk,t}\right)\right)}{2\beta_{A,t}} \tag{4}$$

where $PC_{k,t} = l_{k,t} + o_{k,t}$, FP_j is the optimal price of fabric manufacturer j.

3.2.1.2. Fabric Manufacturer

The demand of each fabric manufacturer j is given as $D_{j,t} = S_{j,t}\phi_{F,t} - \beta_{F,t}FP_{j,t}$ and total demand of fabric manufacturers is computed as $D_{F,t}(= \sum_j\left(S_{j,t}\phi_{F,t} - \beta_{F,t}FP_{j,t}\right))$. According to assumption (A4), BOM structure between apparel and fabric manufacturer gives $aD_{A,t} = D_{F,t}$. Thus a profit function of fabric manufacturer j is given as follows:

$$TP_{j,t}^{C}\left(FP_{j,t}, YP_{i,t}\right) = \left(S_{j,t}\phi_{F,t} - \beta_{F,t}FP_{j,t}\right)\left(FP_{j,t} - l_{j,t} - o_{j,t} - \frac{b}{a}\left(\overline{YP}_{i,t} + \bar{T}_{ij,t}\right) - Inv_{j,t}/D_{j,t}\right) \tag{5}$$

$\overline{YP}_{i,t}$ and $\bar{T}_{ij,t}$ are average purchasing cost and average transportation cost from yarn manufacturer i, respectively. Similar to apparel manufacturer, Equation (5) is concave function and we can find the optimal price to maximize the profit function as follows:

$$FP_{j,t}^{*} = \frac{S_{j,t}\phi_{F,t} + \beta_{F,t}(PC_{j,t} + \frac{b}{a}(\overline{YP}_{i,t} + \bar{T}_{ij,t}))}{2\beta_{F,t}} \tag{6}$$

3.2.1.3. Yarn Manufacturer

As similar to previous cases, the profit function of fabric manufacturer j is given as Equation (7) and its optimal price is derived as Equation (8).

$$\begin{aligned} TP_{i,t}^{C}\left(YP_{i,t}, CP_{c,t}\right) &= \left(S_{i,t}\phi_{Y,t} - \beta_{Y,t}YP_{i,t}\right) \\ &\times \left(YP_{i,t} - l_{i,t} - o_{i,t} - \lambda_{C,t}\left(\overline{CP}_{c,t} + \bar{T}_{ci,t}\right) - \left(1 - \lambda_{C,t}\right)(m_{ri,t} + T_{ri,t})) - Inv_{i,t}/D_{i,t}\right) \end{aligned} \tag{7}$$

$$YP_{i,t}^{*}(CP_{c,t}) = \frac{S_{i,t}\phi_{Y,t} + \beta_{Y,t}(PC_{i,t} + \lambda_{C,t}\left(\overline{CP}_{c,t} + \bar{T}_{ci,t}\right) + (1 - \lambda_{C,t})(m_{ri,t} + T_{ri,t}))}{2\beta_{Y,t}} \tag{8}$$

In Equation (8), yarn manufacturer buys $\lambda_{C,t}$ ratio of end-of-life materials from recycler, and $(1 - \lambda_{C,t})$ ratio from raw material suppliers. The total cost reflects this situation.

3.2.1.4. Recycler

Similarly, the total profit of recycler and its optimal price are derived as Equations (9) and (10), respectively.

$$TP_{c,t}^{C}\left(CP_{c,t}\right) = (S_{c,t}\phi_{C,t} - \beta_{C,t}CP_{c,t})\left(CP_{c,t} - l_{c,t} - o_{c,t} - RC_{c,t} - Inv_{c,t}/D_{c,t}\right) \quad (9)$$

$$CP_{c,t}^{*} = \frac{S_{c,t}\phi_{C,t} + \beta_{C,t}(PC_{c,t} + RC_{c,t})}{2\beta_{Y,t}} \quad (10)$$

Note that the demand of recycler is, $D_{C,t} = \sum_c (S_{c,t}\phi_{C,t} - \beta_{C,t}CP_{c,t}) = b\lambda_{C,t}D_{A,t}$.

3.2.1.5. Sequence of Finding Optimal Prices

In determining optimal prices of each member, we see that the optimal prices of all members except recycler are represented as a function of their supplier's optimal price. This is because the material purchasing cost of the current manufacturer is the same as the selling price of its supplier. For example, the material purchasing cost of apparel manufacturer becomes the selling price of fabric manufacturer. This means that if the optimal selling price of their supplier is not determined, their own optimal selling price cannot be determined. Therefore, we need a feasible sequence of computation to successfully find all optimal prices. Fortunately, the optimal price of recycler is not dependent on the other member's selling price, and instead it uses given collection cost, $RC_{c,t}$. Since the collection cost is considered as the material cost of recycler, and we can compute $CP_{c,t}^{*}$ using equation (10). Therefore, the feasible sequence of finding optimal prices is as follows. Compute $CP_{c,t}^{*} \rightarrow YP_{i,t}^{*}(CP_{c,t}^{*}) \rightarrow FP_{j,t}^{*}(YP_{i,t}^{*}) \rightarrow AP_{k,t}^{*}(FP_{j,t}^{*})$.

3.2.2. Profit Analysis for Remanufacturing CLSC

Similar way to recycling CLSC model, total profit functions of each member in remanufacturing CLSC are easily obtained, and the optimal prices of each member are determined using the concaveness property of profit function. The results are summarized as follows:

3.2.2.1. Apparel Manufacturer

$$D_{A,t} = \sum_{k} (S_{k,t}\phi_{A,t} - \beta_{A,t}AP_{k,t}) = D_{d,t}$$

$$TP_{k,t}^{C}\left(AP_{k,t}, FP_{j,t}\right) = (S_{k,t}\phi_{A,t} - \beta_{A,t}AP_{k,t})\left(AP_{k,t} - PC_{k,t} - a(\overline{FP}_{j,t} + \bar{T}_{jk,t})\right) - Inv_{k,t}$$

$$AP_{k,t}^{*}(FP_{j,t}) = \frac{S_{k,t}\phi_{A,t} + \beta_{A,t}(PC_{k,t} + a(\overline{FP}_{j,t} + \bar{T}_{jk,t}))}{2\beta_{A,t}}$$

3.2.2.2. Fabric Manufacturer

$$D_{F,t} = \sum_j (S_{j,t}\phi_{F,t} - \beta_{F,t}FP_{j,t}) = aD_{A,t}$$

$$TP^M_{j,t}(FP_{j,t}, YP_{i,t}, MP_{m,t}) = (S_{j,t}\phi_{F,t} - \beta_{F,t}FP_{j,t})$$

$$\times \left(FP_{j,t} - PC_{j,t} - \frac{b}{a}\lambda_{M,t}(\overline{MP}_{m,t} + \bar{T}_{mj,t}) - \frac{b}{a}(1-\lambda_{M,t})(\overline{YP}_{i,t} + \bar{T}_{ij,t})\right) - Inv_{j,t}$$

$$FP^*_{j,t}(YP_{i,t}, MP_{m,t})$$

$$= \frac{S_{j,t}\phi_{F,t} + \beta_{F,t}(PC_{j,t} + \frac{b}{a}\lambda_{M,t}(\overline{MP}_{m,t} + \bar{T}_{mj,t}) + \frac{b}{a}(1-\lambda_{M,t})(\overline{YP}_{i,t} + \bar{T}_{ij,t}))}{2\beta_{F,t}}$$

3.2.2.3. Yarn Manufacturer

$$D_{Y,t} = \sum_i (S_{i,t}\phi_{Y,t} - \beta_{Y,t}YP_{i,t}) = b(1-\lambda_{M,t})D_{A,t}$$

$$TP^C_{i,t}(YP_{i,t}) = (S_{i,t}\phi_{Y,t} - \beta_{Y,t}YP_{i,t})(YP_{i,t} - PC_{i,t} - m_{ri,t} - T_{ri,t}) - Inv_{i,t}$$

$$YP^*_{i,t} = \frac{S_{i,t}\phi_{Y,t} + \beta_{Y,t}(PC_{i,t} + m_{ri,t} + T_{ri,t})}{2\beta_{Y,t}}$$

3.2.2.4. Remanufacturer

$$D_{M,t} = \sum_m (S_{m,t}\phi_{M,t} - \beta_{m,t}MP_{m,t}) = b\lambda_{M,t}D_{A,t}$$

$$TP^M_{m,t}(MP_{m,t}) = (S_{m,t}\phi_{M,t} - \beta_{M,t}MP_{m,t})(MP_{m,t} - PC_{m,t} - CC_{m,t}) - Inv_{m,t}$$

$$MP^*_{m,t} = \frac{S_{m,t}\phi_{M,t} + \beta_{M,t}(PC_{m,t} + CC_{m,t})}{2\beta_{M,t}}$$

The optimal prices of yarn manufacturer and remanufacturer (*i.e.*, $YP^*_{i,t}$ and $MP^*_{m,t}$) are directly computed using the cost parameters, $m_{ri,t}$ and $CC_{m,t}$. The feasible sequence of finding optimal prices in this model is as follows: compute $YP^*_{i,t}$ and $MP^*_{m,t} \rightarrow FP^*_{j,t}(YP^*_{i,t}) \rightarrow AP^*_{k,t}(FP^*_{j,t})$.

3.2.3. Profit Analysis for Repair CLSC

Instead of recycler and remanufacturer, this CLSC model has repairers who supply the repaired products to apparel manufacturer. With the similar way to previous models, we have the following results:

3.2.3.1. Apparel Manufacturer

$$D_{A,t} = \sum_{k} (S_{k,t}\phi_{A,t} - \beta_{A,t}AP_{k,t}) = D_{d,t}$$

$$TP^{P}_{k,t}(AP_{k,t}, FP_{j,t}, PP_{p,t}) = (S_{k,t}\phi_{A,t} - \beta_{A,t}AP_{k,t})$$

$$\times \left(AP_{k,t} - PC_{k,t} - a\lambda_{P,t}\left(\overline{PP}_{p,t} + \bar{T}_{pk,t}\right) - a(1-\lambda_{P,t})(\overline{FP}_{j,t} + \bar{T}_{jk,t})\right) - Inv_{k,t}$$

$$AP^{*}_{k,t}(FP_{j,t}, PP_{p,t}) = \frac{S_{k,t}\phi_{A,t} + \beta_{A,t}(PC_{k,t} + a\lambda_{P,t}\left(\overline{PP}_{p,t} + \bar{T}_{pk,t}\right) + a(1-\lambda_{P,t})(\overline{FP}_{j,t} + \bar{T}_{jk,t}))}{2\beta_{A,t}}$$

3.2.3.2. Fabric Manufacturer

$$D_{F,t} = \sum_{j} (S_{j,t}\phi_{F,t} - \beta_{F,t}FP_{j,t}) = a(1-\lambda_{P,t})D_{A,t}$$

$$TP^{P}_{j,t}(FP_{j,t}, YP_{i,t}) = (S_{j,t}\phi_{F,t} - \beta_{F,t}FP_{j,t})\left(FP_{j,t} - PC_{j,t} - \frac{b}{a}(\overline{YP}_{i,t} + \bar{T}_{ij,t})\right) - Inv_{j,t}$$

$$FP^{*}_{j,t}(YP_{i,t}) = \frac{S_{j,t}\phi_{F,t} + \beta_{F,t}(PC_{j,t} + \frac{b}{a}(\overline{YP}_{i,t} + \bar{T}_{ij,t}))}{2\beta_{F,t}}$$

3.2.3.3. Yarn Manufacturer

$$D_{Y,t} = \sum_{i} (S_{i,t}\phi_{Y,t} - \beta_{Y,t}YP_{i,t}) = b(1-\lambda_{P,t})D_{A,t}$$

$$TP^{P}_{i,t}(YP_{i,t}) = (S_{i,t}\phi_{Y,t} - \beta_{Y,t}YP_{i,t})(YP_{i,t} - PC_{i,t} - m_{ri,t} - T_{ri,t}) - Inv_{i,t}$$

$$YP^{*}_{i,t} = \frac{S_{i,t}\phi_{Y,t} + \beta_{Y,t}(PC_{i,t} + m_{ri,t} + T_{ri,t})}{2\beta_{Y,t}}$$

3.2.3.4. Repairer

$$D_{P,t} = \sum_{p} (S_{p,t}\phi_{P,t} - \beta_{P,t}PP_{p,t}) = a\lambda_{P,t}D_{A,t}$$

$$TP^{P}_{p,t}(PP_{p,t}) = (S_{p,t}\phi_{P,t} - \beta_{P,t}PP_{p,t})(PP_{p,t} - PC_{p,t} - CC_{p,t}) - Inv_{p,t}$$

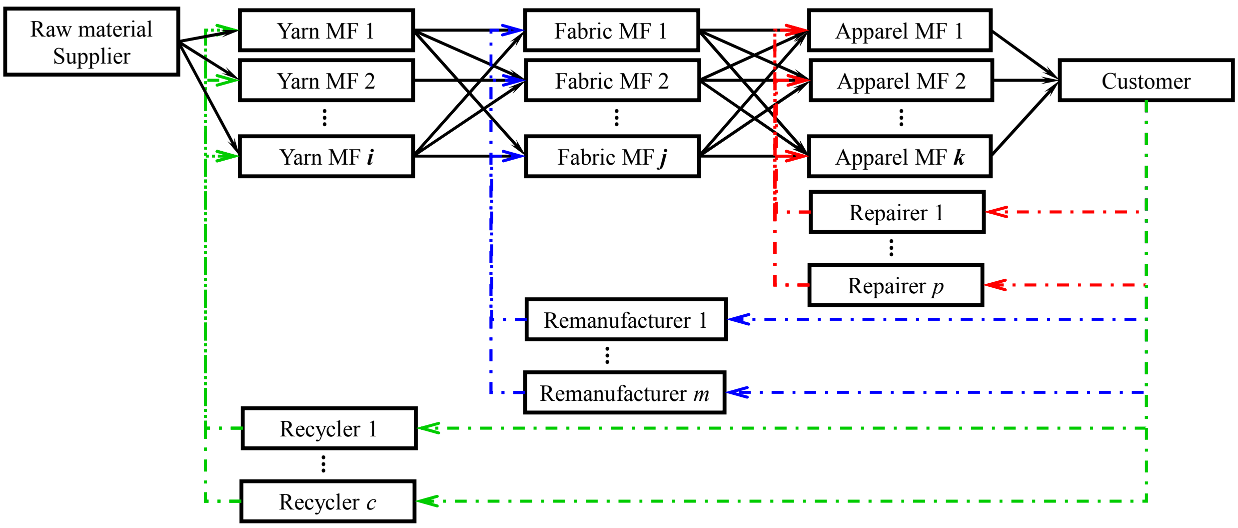
$$PP^{*}_{p,t} = \frac{S_{p,t}\phi_{P,t} + \beta_{P,t}(PC_{p,t} + CC_{p,t})}{2\beta_{P,t}}$$

The optimal prices of yarn manufacturer and repairer (*i.e.*, $YP^*_{i,t}$ and $PP^*_{p,t}$) are directly computed using known cost parameters. Beginning with these computations, a feasible sequence of finding optimal prices is as follows. Compute $YP^*_{i,t}$, $PP^*_{p,t}$, $MP^*_{m,t}$, and $CP^*_{c,t}$ $\rightarrow$ $FP^*_{j,t}(YP^*_{i,t})$ $\rightarrow$ $AP^*_{k,t}(FP^*_{j,t}, PP^*_{p,t})$.

3.2.4. Profit Analysis of Model *G*: Generalized CLSC

In this section, we present a *Generalized CLSC* model, which includes all three recovery options: repair, recycling, and remanufacturing. As shown in Figure 6, end-of-life products are collected by repairer, remanufacturer, and recycler, processed with each recovery option, and supplied to yarn, fabric, and apparel manufacturer, respectively. Return ratios by collector type ($\lambda_{C,t}$, $\lambda_{M,t}$, and $\lambda_{P,t}$) characterize this CLSC. For example, if all return ratios are positive, the CLSC uses all recovery options. If $\lambda_{C,t} = \lambda_{M,t} = 0$, and $\lambda_{P,t}$ is positive, it is repair CLSC.

Figure 6. *Generalized CLSC* in fashion industry.



For *Generalized CLSC* model, the results of profit analysis are summarized as follows.

3.2.4.1. Apparel Manufacturer

$$D^G_{A,t} = \sum_k (S_{k,t}\phi_{A,t} - \beta_{A,t}AP^G_{k,t}) = D^G_{d,t}$$

$$TP^G_{k,t}(AP^G_{k,t}, FP^G_{j,t}, PP^G_{p,t}, \lambda_{P,t}) = (S_{k,t}\phi_{A,t} - \beta_{A,t}AP^G_{k,t})$$

$$\times \left(AP^G_{k,t} - PC_{k,t} - a\lambda_{P,t}\left(\overline{PP}^G_{p,t} + \bar{T}_{pk,t}\right) - a(1-\lambda_{P,t})\left(\overline{FP}^G_{j,t} + \bar{T}_{jk,t}\right)\right) - Inv_{k,t}$$

$$AP^{G*}_{k,t}(FP^G_{j,t}, PP^G_{p,t}, \lambda_{P,t})$$

$$= \frac{S_{k,t}\phi_{A,t} + \beta_{A,t}(PC_{k,t} + a\lambda_{P,t}\left(\overline{PP}^G_{p,t} + \bar{T}_{pk,t}\right) + a(1-\lambda_{P,t})(\overline{FP}^G_{j,t} + \bar{T}_{jk,t}))}{2\beta_{A,t}}$$

3.2.4.2. Fabric Manufacturer

$$D_{F,t}^{G}(\lambda_{P,t}) = \sum_{j}(S_{j,t}\phi_{F,t} - \beta_{F,t}FP_{j,t}^{G}) = a(1-\lambda_{P,t})D_{A,t}^{G}$$

$$TP_{j,t}^{G}\left(FP_{j,t}^{G}, YP_{i,t}^{G}, MP_{m,t}^{G}, \lambda_{M,t}\right) = \left(S_{j,t}\phi_{F,t} - \beta_{F,t}FP_{j,t}^{G}\right)$$
$$\times\left(FP_{j,t}^{G} - PC_{j,t} - \frac{b}{a}\lambda_{M,t}\left(\overline{MP}_{m,t}^{G} + \bar{T}_{mj,t}\right) - \frac{b}{a}(1-\lambda_{M,t})\left(\overline{YP}_{i,t}^{G} + \bar{T}_{ij,t}\right)\right) - Inv_{j,t}$$

$$FP_{j,t}^{G*}(YP_{i,t}^{G}, MP_{m,t}^{G}, \lambda_{M,t}) = \frac{S_{j,t}\phi_{F,t} + \beta_{F,t}(PC_{j,t} + \frac{b}{a}\lambda_{M,t}\left(\overline{MP}_{m,t}^{G} + \bar{T}_{mj,t}\right) + \frac{b}{a}(1-\lambda_{M,t})\left(\overline{YP}_{i,t}^{G} + \bar{T}_{ij,t}\right))}{2\beta_{F,t}}$$

3.2.4.3. Yarn Manufacturer

$$D_{Y,t}^{G}(\lambda_{M,t}, \lambda_{P,t}) = \sum_{i}(S_{i,t}\phi_{Y,t} - \beta_{Y,t}YP_{i,t}^{G}) = b(1-\lambda_{M,t}-\lambda_{P,t})D_{A,t}^{G}$$

$$TP_{i,t}^{G}\left(YP_{i,t}^{G}, CP_{c,t}^{G}, \lambda_{C,t}\right) = \left(S_{i,t}\phi_{Y,t} - \beta_{Y,t}YP_{i,t}^{G}\right)$$
$$\times\left(YP_{i,t}^{G} - PC_{i,t} - \lambda_{C,t}(\overline{CP}_{c,t}^{G} + \bar{T}_{ci,t}) - (1-\lambda_{C,t})(m_{ri,t} + T_{ri,t})\right) - Inv_{i,t}$$

$$YP_{i,t}^{G*}(CP_{c,t}^{G}, \lambda_{C,t}) = \frac{S_{i,t}\phi_{Y,t} + \beta_{Y,t}(PC_{i,t} + \lambda_{C,t}\left(\overline{CP}_{c,t}^{G} + \bar{T}_{ci,t}\right) + (1-\lambda_{C,t})(m_{ri,t} + T_{ri,t}))}{2\beta_{Y,t}}$$

3.2.4.4. Recycler

$$D_{C,t}^{G}(\lambda_{C,t}) = \sum_{c}(S_{c,t}\phi_{C,t} - \beta_{C,t}CP_{c,t}^{G}) = b\lambda_{C,t}D_{A,t}^{G}$$
$$TP_{c,t}^{G}(CP_{c,t}^{G}) = (S_{c,t}\phi_{C,t} - \beta_{C,t}CP_{c,t}^{G})\left(CP_{c,t}^{G} - PC_{c,t} - CC_{c,t}\right) - Inv_{c,t}$$
$$CP_{c,t}^{G*} = \frac{S_{c,t}\phi_{C,t} + \beta_{C,t}(PC_{c,t} + CC_{c,t})}{2\beta_{Y,t}}$$

3.2.4.5. Remanufacturer

$$D_{M,t}^{G}(\lambda_{M,t}) = \sum_{m}(S_{m,t}\phi_{M,t} - \beta_{m,t}MP_{m,t}^{G}) = b\lambda_{M,t}D_{A,t}^{G}$$
$$TP_{m,t}^{G}(MP_{m,t}^{G}) = (S_{m,t}\phi_{M,t} - \beta_{M,t}MP_{m,t}^{G})\left(MP_{m,t}^{G} - PC_{m,t} - CC_{m,t}\right) - Inv_{m,t}$$

$$MP_{m,t}^{G*} = \frac{S_{m,t}\phi_{M,t} + \beta_{M,t}(PC_{m,t} + CC_{m,t})}{2\beta_{M,t}}$$

3.2.4.6. Repairer

$$D_{P,t}^{G}(\lambda_{P,t}) = \sum_{p}(S_{p,t}\phi_{P,t} - \beta_{P,t}PP_{p,t}^{G}) = a\lambda_{P,t}D_{A,t}^{G}$$

$$TP_{p,t}^{G}(PP_{p,t}^{G}) = (S_{p,t}\phi_{P,t} - \beta_{P,t}PP_{p,t}^{G})\left(PP_{p,t}^{G} - PC_{p,t} - CC_{p,t}\right) - Inv_{p,t}$$

$$PP_{p,t}^{G*} = \frac{S_{p,t}\phi_{P,t} + \beta_{P,t}(PC_{p,t} + CC_{p,t})}{2\beta_{P,t}}$$

The optimal prices for all recovery collectors are directly computed using given cost parameters. Also, yarn manufacturer can compute its optimal price using recycler's optimal price and recycling ratio. Then the other two optimal prices are determined in sequence of fabric and apparel manufacturer. The feasible sequence of determining optimal prices is summarized as follows. Compute $PP_{p,t}^{*}$, $MP_{m,t}^{*}$, $CP_{c,t}^{*} \rightarrow YP_{i,t}^{G*}(CP_{c,t}^{G}, \lambda_{C,t}) \rightarrow FP_{j,t}^{G*}(YP_{i,t}^{G}, MP_{m,t}^{G}, \lambda_{M,t}) \rightarrow AP_{k,t}^{G*}(FP_{j,t}^{G}, PP_{p,t}^{G}, \lambda_{P,t})$.

4. CLSC Planning Model

In this section, using the *Generalized CLSC*s and profit model, we propose a CLSC planning model. Based on the proposed CLSC network, we find the optimal prices using profit models and can determine the ideal demand of apparel products in CLSC. In practical business environment, customer demands of apparel product are provided by market analysis and survey. Then CLSC planning model determines production and transportation quantities meeting the demand on CLSC network in order to maximize total CLSC profit and minimize CO_2 emission throughout the entire CLSC network.

Our CLSC planning model is formulated as multi-objective mixed integer linear programming. We have two objectives in pursuit of economic benefits and environmental sustainability: *i.e.*, to maximize total profits of CLSC and to minimize CO_2 emissions on the network. Demand data are obtained using the linear demand function addressed in assumption (A5), which is a function of optimal price determined by the profit models presented in Section 3. The main constraints are production capacity and capital investments for CERs.

Maximize:

$$w_1 TP - w_2 TCE \tag{11}$$

$$TP = TP_A + TP_F + TP_Y + TP_C + TP_M + TP_P \tag{12}$$

$$TCE = \sum_{r,i,t} TE_{ri,t}x_{i,t} + \sum_{k,d,t} PE_{k,t}AQ_{kd,t} + \sum_{j,k,t}\left(PE_{j,t} + TE_{jk,t}\right)FQ_{jk,t} + \sum_{i,j,t}\left(PE_{i,t} + TE_{ij,t}\right)YQ_{ij,t} + \sum_{c,i,t}\left(PE_{c,t} + TE_{ci,t}\right)CQ_{ci,t} \tag{13}$$

$$+\sum_{m,j,t}(PE_{m,t}+TE_{mj,t})MQ_{mj,t}+\sum_{p,k,t}(PE_{p,t}+TE_{pk,t})PQ_{pk,t}$$

Subject to

$$TP_Y=\sum_{i,j,t}YP^*_{i,t}YQ_{ij,t}-\sum_{i,j,t}PC_{i,t}YQ_{ij,t}-\left(\sum_{r,i,t}m_{ri,t}rQ_{ri,t}+\sum_{c,i,t}CP^*_{c,t}CQ_{ci,t}\right)$$
$$-\left(\sum_{r,i,t}T_{ri,t}rQ_{ri,t}+\sum_{c,i,t}T_{ci,t}CQ_{ci,t}\right)-\sum_{i,t}h_{i,t}IV_{i,t}-\sum_{i,t}Inv_{i,t}x_{i,t} \quad (14)$$

$$TP_F=\sum_{j,k,t}FP^*_{j,t}FQ_{jk,t}-\sum_{j,k,t}PC_{j,t}FQ_{jk,t}-\left(\sum_{i,j,t}YP^*_{i,t}YQ_{ij,t}+\sum_{m,j,t}MP^*_{m,t}MQ_{mj,t}\right)$$
$$-\left(\sum_{i,j,t}T_{ij,t}YQ_{ij,t}+\sum_{m,j,t}T_{mj,t}MQ_{mj,t}\right)-\sum_{j,t}h_{j,t}IV_{j,t}-\sum_{j,t}Inv_{j,t}x_{j,t} \quad (15)$$

$$TP_A=\sum_{k,d,t}AP^*_{k,t}AQ_{kd,t}-\sum_{k,d,t}PC_{k,t}AQ_{kd,t}-\left(\sum_{j,k,t}FP^*_{j,t}FQ_{jk,t}+\sum_{p,k,t}PP^*_{p,t}PQ_{pk,t}\right)$$
$$-\left(\sum_{j,k,t}T_{jk,t}FQ_{jk,t}+\sum_{p,k,t}T_{pk,t}PQ_{pk,t}\right)-\sum_{k,t}h_{k,t}IV_{k,t}-\sum_{k,t}Inv_{k,t}x_{k,t} \quad (16)$$

$$TP_C=\sum_{c,i,t}CP^*_{c,t}CQ_{ci,t}-\sum_{c,i,t}PC_{c,t}CQ_{ci,t}-\sum_{c,i,t}RC_{c,t}CQ_{ci,t}-\sum_{c,t}h_{c,t}IV_{c,t}-\sum_{c,t}Inv_{c,t}x_{c,t} \quad (17)$$

$$TP_M=\sum_{m,j,t}MP^*_{m,t}MQ_{mj,t}-\sum_{m,j,t}PC_{m,t}MQ_{mj,t}-\sum_{m,j,t}RC_{m,t}MQ_{mj,t}-\sum_{m,t}h_{m,t}IV_{m,t}-\sum_{m,t}Inv_{m,t}x_{m,t} \quad (18)$$

$$TP_P=\sum_{p,k,t}PP^*_{p,t}PQ_{pk,t}-\sum_{p,k,t}PC_{p,t}PQ_{pk,t}-\sum_{p,k,t}RC_{p,t}PQ_{pk,t}-\sum_{p,t}h_{p,t}IV_{p,t}-\sum_{p,t}Inv_{p,t}x_{p,t} \quad (19)$$

$$\sum_k AQ_{kd,t}\ge D_{d,t} \qquad \forall d,t \quad (20)$$

$$IN_{k,t-1}+\frac{1}{a}\left(\sum_j FQ_{jk,t}+\sum_p PQ_{pk,t}\right)=\sum_d AQ_{kd,t}+IN_{k,t} \qquad \forall k,t \quad (21)$$

$$IN_{j,t-1}+\frac{a}{b}\left(\sum_i YQ_{ij,t}+\sum_m MQ_{mj,t}\right)=\sum_k FQ_{jk,t}+IN_{j,t} \qquad \forall j,t \quad (22)$$

$$IN_{i,t-1}+\left(\sum_r rQ_{ri,t}+\sum_c CQ_{ci,t}\right)=\sum_j YQ_{ij,t}+IN_{i,t} \qquad \forall i,t \quad (23)$$

$$IN_{c,t-1}+b\lambda_{C,t}\sum_d D_{d,t}=\sum_i CQ_{ci,t}+IN_{c,t} \qquad \forall c,t \quad (24)$$

$$IN_{m,t-1}+b\lambda_{M,t}\sum_d D_{d,t}=\sum_j MQ_{mj,t}+IN_{m,t} \qquad \forall m,t \quad (25)$$

$$IN_{p,t-1}+a\lambda_{P,t}\sum_P D_{d,t}=\sum_k PQ_{pk,t}+IN_{p,t} \qquad \forall p,t \quad (26)$$

$$\sum_d AQ_{kd,t}\le PCP_{k,t}x_{k,t} \qquad \forall k,t \quad (27)$$

$$\sum_k FQ_{jk,t}\le PCP_{j,t}x_{j,t} \qquad \forall j,t \quad (28)$$

$$\sum_j YQ_{ij,t}\le PCP_{i,t}x_{i,t} \qquad \forall i,t \quad (29)$$

$$\sum_i CQ_{ci,t}\le PCP_{c,t}x_{c,t} \qquad \forall c,t \quad (30)$$

$$\sum_j MQ_{mj,t}\le PCP_{m,t}x_{m,t} \qquad \forall m,t \quad (31)$$

$$\sum_k PQ_{pk,t} \leq PCP_{p,t}x_{p,t} \qquad \forall p,t \qquad (32)$$

$$\sum_j PE_{i,t}YQ_{ij,t} + \sum_r TE_{ri,t}rQ_{ri,t} + \sum_c TE_{ci,t}\,CQ_{ci,t} \leq RE_{i,t} \qquad \forall i,t \qquad (33)$$

$$\sum_k PE_{j,t}FQ_{jk,t} + \sum_i TE_{ij,t}YQ_{ij,t} + \sum_m TE_{mj,t}\,MQ_{mj,t} \leq RE_{j,t} \qquad \forall j,t \qquad (34)$$

$$\sum_d PE_{k,t}AQ_{kd,t} + \sum_j TE_{jk,t}FQ_{jk,t} + \sum_p TE_{pk,t}\,PQ_{pk,t} \leq RE_{k,t} \qquad \forall k,t \qquad (35)$$

$$\sum_i PE_{c,t}CQ_{ci,t} \leq RE_{c,t} \qquad \forall c,t \qquad (36)$$

$$\sum_j PE_{m,t}MQ_{mj,t} \leq RE_{m,t} \qquad \forall m,t \qquad (37)$$

$$\sum_k PE_{p,t}PQ_{pk,t} \leq RE_{p,t} \qquad \forall p,t \qquad (38)$$

$$YQ_{ij,t}, FQ_{jk,t}, AQ_{kd,t}, CQ_{ci,t}, MQ_{mj,t}, PQ_{pk,t} \in R \qquad \forall i,j,p,k,c,m,p,d,t \qquad (39)$$

$$x_{i,t}, x_{j,t}, x_{k,t}, x_{c,t}, x_{m,t}, x_{p,t}, \in \{0,1\} \qquad \forall i,j,p,k,c,m,p,t \qquad (40)$$

Equation (12) is total profit of CLSC and Equation (13) is total CO_2 emissions generated by production and transportation by CLSC members. Equation (11) is a weighted objective function to be maximized and accordingly maximizes total profit and minimizes CO_2 emissions. Constraints (14)–(19) define the variables in the objective function (11) and represent the profits of each CLSC member. Constraint (20) indicates that the total amount of products supplied by apparel manufacturers should meet their customer demands. Constraints (21)–(26) are the balance equations for inventories of all members in each time period in CLSC. Constraints (27)–(32) ensure the production limits by production capacity. Constraints (33)–(38) limit CO_2 emission generated by each manufacturer within upper bound restriction. Each manufacturer has the responsibility for CO_2 emission from its own production and transportation from suppliers. Constraints (39) and (40) impose the integer and binary conditions on decision variables.

5. Experimental Analysis

In this section, we investigate the proposed CLSC models by numerical experiments and sensitivity analyses. We assume a generalized CLSC model including all recovery options so that the proposed CLSC models can be comprehensively tested. The model is validated using numerical data set and results, and in order to get managerial insights some significant parameters are variously changed and post-optimal analyses are performed. Because the assumed environments are located in Korea, won (₩) is used as a monetary unit.

5.1. Data Preparation

For numerical study, we assume a *Generalized CLSC* consisting of four manufacturers for each of apparel, fabric, and yarn manufacturer, and two recovery collectors for each of recycler, remanufacturer, and repairer, and single raw material supplier. We also assume a single-period planning without loss of planning property because a single period can be easily extended to multiple periods and the resultant inventories are updated in each period. Each manufacturer has equally 25% of market share as $S_{i,j\ and\ k} = 0.25$ and each recovery collector also has equally 50% of market share as $S_{c(m\ and\ p} = 0.5$. For simplicity of analysis, we assume one-to-one BOM ratio, *i.e.*, $a = b = 1$. We also consider that all recovery options occur in CLSC, as $\lambda_C = \lambda_M = \lambda_P = 0.1$. For demand function, we set $\phi_{i,j\ and\ k} = 32{,}000$, $\beta_{i,j\ and\ k} = 0.02$, $\phi_{c,m\ and\ p} = 3200$, and $\beta_{c,m\ and\ p} = 0.016$. Raw material cost is ₩52,000/unit, and investment cost for CO_2 emission is ₩10,000 per tCO_2. Tables 2–5 summarizes the required data set.

Table 2. Data set: *PC*, *Inv*, *PE* and *RE* for manufacturers.

Apparel manufacturer	PC_k **(₩/unit)**	Inv_k **(M₩)**	PE_k **(kgCO₂/unit)**	RE_k **(tCO₂)**
k = 1	1200	22.0	928	2200
k = 2	1400	23.5	916	2350
k = 3	1600	20.9	904	2090
k = 4	2000	24.3	880	2430
Fabric manufacturer	PC_j (₩/unit)	Inv_j (M₩)	PE_j (kgCO₂/unit)	RE_j (tCO₂)
j = 1	220	16.2	786.8	1620
j = 2	200	11.0	788.0	1100
j = 3	180	14.0	789.2	1400
j = 4	160	19.0	790.4	1900
Yarn manufacturer	PC_i (₩/unit)	Inv_i (M₩)	PE_i (kgCO₂/unit)	RE_i (tCO₂)
i = 1	43	12.5	597.42	1250
i = 2	26	18.0	598.44	1800
i = 3	38	19.0	597.72	1900
i = 4	43	17.0	597.42	1700

Table 3. Data set: *PC*, *RC*, *Inv*, *PE* and *RE* for recovery collectors.

Recycler	PC_c **(₩/unit)**	RC_c **(₩/unit)**	Inv_c **(M₩)**	PE_i **(kgCO₂/unit)**	RE_c **(tCO₂)**
c = 1	950	1050	4.5	343	450
c = 2	450	1200	4.2	373	420
Remanufacturer	PC_m (₩/unit)	RC_m (₩/unit)	Inv_m (M₩)	PE_i (kgCO₂/unit)	RE_m (tCO₂)
m = 1	765	680	7.8	354.1	780
m = 2	740	950	8.9	355.6	890
Repairer	PC_p (₩/unit)	RC_p (₩/unit)	Inv_p (M₩)	PE_i (kgCO₂/unit)	RE_p (tCO₂)
p = 1	340	930	4.2	379.6	420
p = 2	380	800	3.6	377.2	360

Table 4. Data set: *T* and *TE.*

T_{jk} **(₩/unit)**	**k = 1**	**k = 2**	**k = 3**	**k = 4**	TE_{jk} **(kgCO₂/unit)**	**k = 1**	**k = 2**	**k = 3**	**k = 4**
j = 1	7550	7700	3750	8320	j = 1	367.50	345.00	937.50	252.00
j = 2	7700	7500	3820	8300	j = 2	345.00	375.00	927.00	255.00
j = 3	7450	7600	3830	8310	j = 3	382.50	360.00	925.50	253.50
j = 4	7300	7600	3800	8270	j = 4	405.00	360.00	930.00	259.50
T_{pk}	k = 1	k = 2	k = 3	k = 4	TE_{pk}	k = 1	k = 2	k = 3	k = 4
p = 1	2780	2300	3300	4040	p = 1	1083.00	1155.00	1005.00	894.00
p = 2	2620	2342	3500	3960	p = 2	1107.00	1148.70	975.00	906.00

Table 4. *Cont.*

T_{jk} (₩/$unit$)	k = 1	k = 2	k = 3	k = 4	TE_{jk} $kgCO_2$ /$unit$)	k = 1	k = 2	k = 3	k = 4
T_{ij}	j = 1	j = 2	j = 3	j = 4	TE_{ij}	j = 1	j = 2	j = 3	j = 4
i = 1	2100	2250	2160	1800	i = 1	685.00	662.50	676.00	730.00
i = 2	1700	2300	2165	1830	i = 2	745.00	655.00	675.25	725.50
i = 3	2000	2150	2190	1840	i = 3	700.00	677.50	671.50	724.00
i = 4	1800	2100	2185	1870	i = 4	730.00	685.00	672.25	719.50
T_{mj}	j = 1	j = 2	j = 3	j = 4	TE_{mj}	j = 1	j = 2	j = 3	j = 4
m = 1	1400	4000	2105	1500	m = 1	790.00	400.00	684.25	775.00
m = 2	1460	4300	2095	1700	m = 2	781.00	355.00	685.75	745.00
T_{ri}	i = 1	i = 2	i = 3	i = 4	TE_{ri}	i = 1	i = 2	i = 3	i = 4
r = 1	700	640	880	170	r = 1	695.00	704.00	668.00	774.50
T_{ci}	i = 1	i = 2	i = 3	i = 4	TE_{ci}	i = 1	i = 2	i = 3	i = 4
c = 1	920	540	590	200	c = 1	662.00	719.00	711.50	770.00
c = 2	760	600	710	190	c = 2	686.00	710.00	693.50	771.50

Table 5. Optimal price for manufacturers and collectors.

Apparel MF	**Optimal price (₩)**	**Fabric MF**	**Optimal price (₩)**	**Yarn MF**	**Optimal price (₩)**
$k = 1$	344,107	$j = 1$	305,393	$i = 1$	226,324
$k = 2$	344,233	$j = 2$	305,654	$i = 2$	226,275
$k = 3$	342,677	$j = 3$	305,531	$i = 3$	226,393
$k = 4$	344,932	$j = 4$	305,343	$i = 4$	226,053
Repairer	Optimal price (₩)	Re-manufacturer	Optimal price (₩)	Recycler	Optimal price (₩)
$p = 1$	50,635	m=1	50,723	c=1	51,000
$p = 2$	50,590	m=2	50,845	c=2	50,825

5.2. Numerical Results

For numerical experiments, we used EXCEL2010 program for profit analysis and OPL STUDIO 12.2 of ILOG for solving CLSC planning model. Table 5 summarizes the optimal prices for manufacturers and recovery collectors as the results of profit model. As a result, total demand of apparel manufacturers is determined as $D_d = D_A = 4480$ units, and with 10% return ratio, the amount of returned products are 448 units for each collector.

By solving CLSC planning model, we get the results of Tables 6 and 7. It is observed that the demand of apparel manufacturers are all satisfied and the returned end-of-life products for each collector are also fully processed and recovered. The subsequent production and transportation of fabric and yarn manufacturers are determined according to the demand of apparel products and the amount of recovered products. As a result, raw material suppliers provide 3137 units, recycle manufacturers process 448 units, and total 3585 units are supplied to yarn manufacturers. In turn, yarn manufacturers produce 3585 units, remanufacturers process 448 units of the returned products, then total 4033 units are delivered to fabric manufacturers. Finally, with 448 units of repaired products, apparel manufacturers receive total 4480 units of fabric materials. CLSC model computes 1123.72M₩ of total profit and 15,407.691 t CO_2 of total CO_2 emission.

We also observe that investment cost for purchasing CERs prevents the members in CLSC from making only profit-wise decision. For example, even though the production cost of repairer 2 is much higher than repairer 1, repairer 2 has the lower investment cost of CO_2 emission and processes all of returned products.

Table 6. Production quantity for manufacturers and collectors.

Apparel manufacturer	**Production Quantity**	**Fabric manufacturer**	**Production Quantity**	**Yarn manufacturer**	**Production Quantity**
$k = 1$	1118	$j = 1$	1076	$i = 1$	1358
$k = 2$	1115	$j = 2$	752	$i = 2$	1450
$k = 3$	1146	$j = 3$	953	$i = 3$	777
$k = 4$	1101	$j = 4$	1252	$i = 4$	0
Repairer	Production Quantity	Remanufacturer	Production Quantity	Recycler	Production Quantity
$p = 1$	0	$m = 1$	448	$c = 1$	0
$p = 2$	448	$m = 2$	0	$c = 2$	448

Table 7. Transportation quantity for manufacturers and collectors.

FQ_{jk}	**k = 1**	**k = 2**	**k = 3**	**k = 4**	YQ_{ij}	**j = 1**	**j = 2**	**j = 3**	**j = 4**
j = 1	0	0	1076	0	i = 1	496	0	505	357
j = 2	0	667	70	15	i = 2	580	0	0	870
j = 3	0	0	0	953	i = 3	0	751	0	26
j = 4	1118	0	0	134	i = 4	0	0	0	0
PQ_{pk}	k = 1	k = 2	k = 3	k = 4	MQ_{mj}	j = 1	j = 2	j = 3	j = 4
p = 1	0	0	0	0	m = 1	0	0	448	0
p = 2	0	448	0	0	m = 2	0	0	0	0
rQ_{ri}	i = 1	i = 2	i = 3	i = 4	CQ_{ci}	i = 1	i = 2	i = 3	i = 4
r = 1	910	1450	777	0	c = 1	0	0	0	0
					c = 2	448	0	0	0

5.3. Sensitivity Analyses

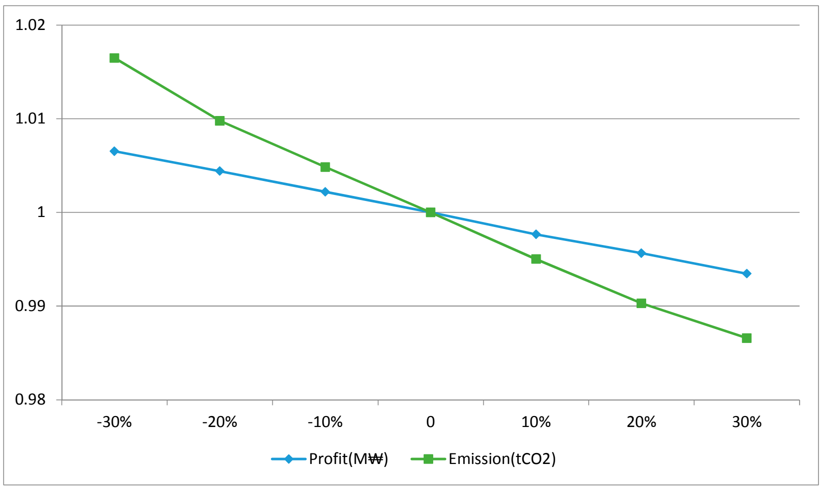
Most medium- and large-size Korean apparel companies have oversea facilities in China or Southeast Asian countries for the benefits of low production costs. Therefore, oversea production strategy is very significant in cost-wise and market competitiveness. Also the efficient supply of raw material is crucial to production stability and profit management. We investigate the effects of two cost factors, production and raw material cost, using sensitivity analysis through our CLSC models. On the other hand, in terms of sustainability in CLSC, the issues are related to recovery processes and CO_2 emissions on the CLSC network. The choice of recovery options affects both profit and emission results, and trade-off between profit maximization and reduction of CO_2 emission is always problematic to most apparel companies in

Korea. We explore the effects of choice of recovery options and trade-off production strategies in view of sustainable CLSC.

5.3.1. Production Cost

This analysis, more or less, reflects the recent changes of labor environment in China. The most significant observable change in China is that the minimum wage system and social insurance system has been introduced, which is quite big progress in China's labor environment. This change directly results in the increase of production cost and decrease of profits. To numerically see the effects of this, we computed the total profits and CO_2 emissions using our CLSC model according to the change of production cost by 10% from −30% to 30%. Figure 7 shows the rate of changes of total profit and CO_2 emission. We see the trade-off relationship between two objectives as represented in our CLSC planning model. Also, the result shows that for example a decrease of only 0.5% in total profit with 30% increase of production cost. This implies that the profit model maximizes total profit by determining a new optimal selling price according to the new production cost parameter. With our data set, we observe that the profit is considerably robust to the change of production cost. Consequently, increase of production cost results in the decrease of profit and decrease of CO_2 emission. This happens in the following sequence: increase of production cost → decrease of net profit → increase of selling price → decrease of net demand → decrease of production → decrease of CO_2 emission. However, decrease of profit is not desirable to a firm at the benefit of CO_2 emission reduction. Strategically, a firm needs to make considerable efforts for technological innovations in material resourcing, manufacturing processes, and transportation activities in more sustainable way. Also, in our data set, we observe that the rate of change of CO_2 emission is more sensitive to the change of production cost than total profit.

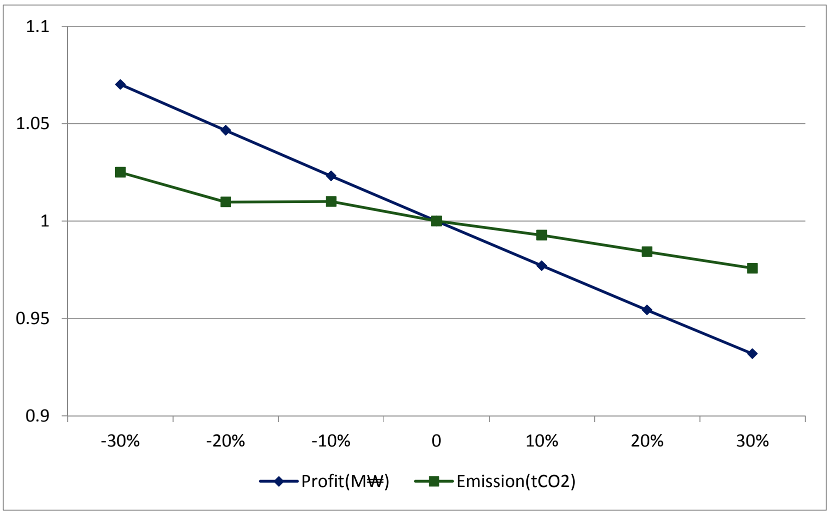
Figure 7. Change rate of total profit and CO_2 emission according to change of production cost.



5.3.2. Raw Material Cost

In fashion industry, raw material cost is not stable and hardly predictable. Even, regardless of types of yarn, the proportion of raw material cost to selling price of yarn varies a lot by yarn manufacturers [46]. This is because the production cost of raw material varies by all time and logistics cost as well. In the case of the Korean fashion industry, since most yarn production occurs in oversea plants, the selling price of raw material depends on not only raw material production cost but also oil price, tariff, and currency exchange rate. In this section, we investigate the effect of raw material cost on CLSC performance. Figure 8 shows the rate of changes of total profit and CO_2 emission according to change of raw material cost by 10% from −30% to 30%. Similar to Figure 7, we see the trade-off relationship between total profit and CO_2 emission in our CLSC planning model. As a similar results to previous analysis with production cost, the increase of raw material cost results in the decrease of profit and decrease of CO_2 emission. This happens in the following sequence: increase of raw material cost → increase of selling price of yarn → increase of material cost and selling price of fabric → increase of material cost of apparel → decrease of net profit →increase of selling price → decrease of net demand → decrease of production → decrease of CO_2 emission. The situation is similar to the previous case and technological improvements in supply chain activities need to be key strategic direction to achieve high sustainability. Unlike the case in the previous section, we observe that the rate of change of CO_2 emission is less sensitive to raw material cost than total profit. This indicates that change of raw material cost results in more effects on total profit than on CO_2 emission. Also, the change of raw material cost gives more effects on both profit and CO_2 emission than production cost does, which means that Korean apparel firms need to be more attentive to the change of raw material market when the increasing trend of production cost exists.

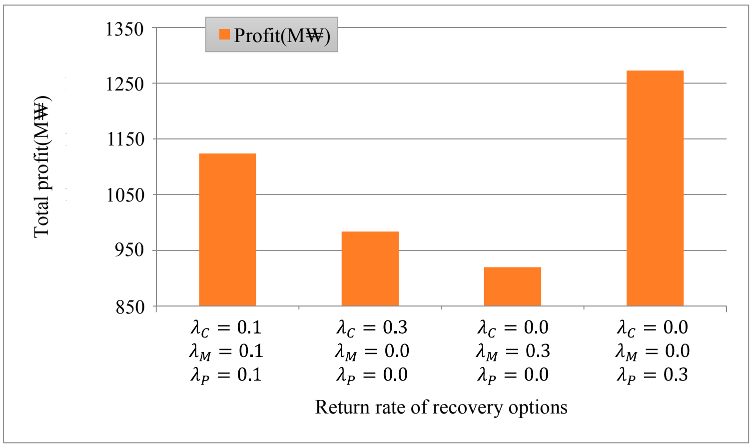
Figure 8. Change rate of total profit and CO_2 emission according to change of raw material cost.



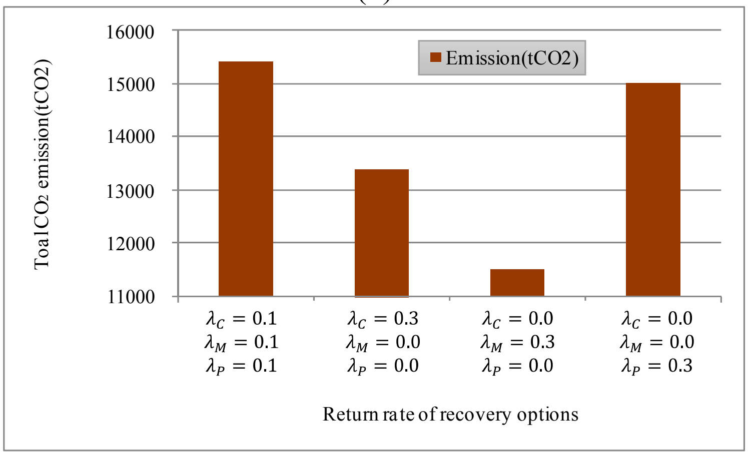
5.3.3. Recovery Options

For this analysis, we assume that three recovery options can produce the same quality of recovered products in terms of functionality. We try to find which option or which combination of options can be the best for CLSC performance. Given 30% of return ratio, four different scenarios were tested: $(\lambda_C, \lambda_M, \lambda_P) = (0.1, 0.1, 0.1), (0.3, 0, 0), (0, 0.3, 0), (0,0,0.3)$. Figure 9a,b shows the results. We observe that only-repair option gives the highest profit while only-remanufacturing option results in the least CO_2 emission. For comparison of four strategies, we consider a performance measure as the amount of CO_2 emission per million won of profit (t CO_2/M₩). As shown in Table 8, using only-repair option gives the best performance and using all options shows the worst. From the analysis, we see that the proper use of recovery options can make significant difference on CLSC performance.

Figure 9. Performance of recovery option strategies. (**a**) Profit; (**b**) CO_2 emission.



(**a**)



(**b**)

Table 8. Comparison of recovery option strategies.

Strategy ($\lambda_C, \lambda_M, \lambda_P$)	CO_2 Emission Per Profit (t CO_2/M₩)
(0.1, 0.1, 0.1)	13.7113
(0.3, 0.0, 0.0)	13.6050
(0.0, 0.3, 0.0)	12.5256
(0.0, 0.0, 0.3)	11.7921

5.3.4. Weight of Objective Functions

This analysis explores the trade-off relationship between profit and CO_2 emission by changing the weights in the objective function of CLSC planning model. Since there is no change in price, demand is fixed. We tested five cases—five different set of weights as (w_1, w_2) = (0, 1), (0.25, 0.75), (0.5, 0.5), (0.75, 0.25), (1, 0). After solving CLSC planning model, as shown in Figure 10, the results are obtained as an efficient-frontier curve (*i.e.*, *Pareto* optimal) of total profit and CO_2 emission. Obviously, Case 1 shows the smallest CO_2 emission but the lowest profit and Case 5 shows the reverse result, and the other three cases are in between two extreme results. However, as shown in Table 9, we observe that Case 1 is the largest CO_2 emission per profit, and Case 5 is the least. The choice of strategy depends on which criterion is employed. For example, Case 5 seems to be the best in terms of environmental efficiency but it still produces the largest amount of CO_2 emission. A decision maker needs to be extremely cautious of multi-criteria trade-off decision.

Figure 10. The efficient-frontier curve of profit and CO_2 emission.

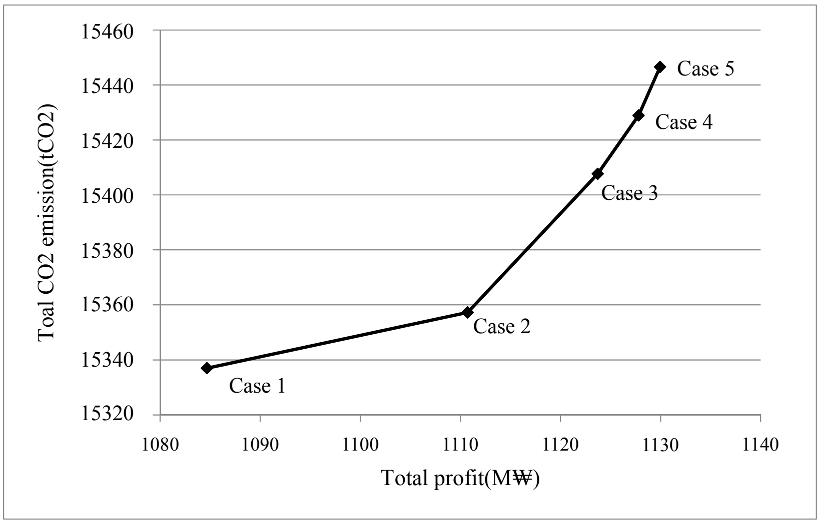


Table 9. Performances of CLSC with different weights on profit and CO_2 emission.

(w_1, w_2)	(0,1)	(0.25, 0.75)	(0.5, 0.5)	(0.75, 0.25)	(1, 0)
Emission(t CO_2)	15337.00	15357.30	15407.69	15428.98	15446.60
Profit(M₩)	1084.70	1110.72	1123.72	1127.81	1129.94
Emission/Profit	14.14	13.83	13.71	13.68	13.67

6. Conclusions and Future Research

In fashion industry, it is inherently problematic for its CLSC to achieve both economic benefits and environmental sustainability through CLSC activities. Firstly, this paper provided a structure of CLSC network in fashion industry. The proposed CLSC network characterizes the manufacturers and collectors who take back the end-of-life apparel goods, recover, and supply them to forward chain. The manufacturers are on forward chain and classified into yarn, fabric, and apparel manufacturing. The collectors are on reverse chain and classified by recovery options of repair, remanufacturing, and recycling. The return rate of each collector reflects its own market size and determines processing capacity as well. Secondly, for the pursuit of profitable CLSC, profit models have been derived to find optimal selling prices for each member. These prices can be used to estimate their own ideal market sizes with the assumption of linear demand function, although actual demands are realized by customers. Thirdly, trade-off between CLSC profits and environmental sustainability has been implemented by CLSC planning model. With the weighted objective function of CLSC profit maximization and CO_2 emission minimization, our planning model is formulated by multi-objectives mixed integer programming. The optimal selling prices obtained from profit models are used in CLSC planning model for taking the most profitable situation.

The numerical experiments using real-scale data were performed to see how properly the proposed models work. From the analysis of results, our observations are summarized as follows.

- Regarding trade-off between profit and emission, with our data set, the most profitable strategy also provides the best environmental efficiency in terms of tCO_2/M₩. Even though this particular case may not be generalized, we see that technological innovation can make the CLSC more profitable in exchange for the smaller increase rate of CO_2 emission.
- In the results, CO_2 emission is less sensitive to raw material cost than CLSC profit is. Also, raw material cost gives the larger effects on both profit and CO_2 emission than production cost does. This implies that the choice of cost drivers may bring significant results to profit and emission in different way.
- Proper combination of recovery options can make significant improvements on CLSC performances. This also implies that different objectives of CLSC require different combination of recovery options.
- Regarding the weights in the objective function of planning model, it is obvious that the choice of weights significantly affects CLSC performances. However, it should be note that proper choice of weights is extremely difficult because the resultant performances are more than just computing numbers and they may bring up different interpretations and implications. Instead, using the model, Pareto optimal weight sets are visibly obtained on the efficient-frontier curve of profit and CO_2 emission.

As future research and also the limitation of this paper, Quick Response (QR) system needs to be integrated in CLSC network, as *fast fashion* is overwhelmingly in demand in recent years. Global business operations and shortened product lifecycle in fashion industry force firms to be more responsive to customer demands than ever [47,48]. Introduction of QR may significantly affect CLSC network in fourfold: recovery lead-time, product proliferation, collection rate of end-of-life goods, and objectives of CLSC, all of which are the critical success factors of CLSC. Implementing QR in CLSC is truly challenging because it requires the higher degree of synchronization of forward and backward supply chain to achieve both efficiency and sustainability of CLSC. It is quite worth exploring the academic and practical problems of QR in CLSC because the problems encompass most of the issues in sustainable supply chain.

Acknowledgments

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (NRF-2012R1A1A2009054).

Author Contributions

Jisoo Oh wrote the manuscript and participated in all phases. Bongju Jeong conceived the theme of this study, guided the whole research process, and responded to the reviewers. All authors have read and approved the final manuscript.

Notation

Indices

i	Index of yarn manufacturer (i = 1, 2, 3, …, I)
j	Index of fabric manufacturer (j = 1, 2, 3, …, J)
k	Index of apparel manufacturer (k = 1, 2, 3, …, K)
c	Index of recycler (c = 1, 2, 3, …, C)
m	Index of remanufacturer (m=1, 2, 3, …, M)
p	Index of repairer (p = 1, 2, 3, …, P)
r	Index of raw material supplier (r = 1)
d	Index of demand zone(d = 1)
t	Index of time period (t = 1, 2, 3, …, T)

Decision variables (for profit analysis model) & Parameters (for CLSC planning model)

$AP_{k,t}$	Selling price of apparel manufacturer k in period t
$FP_{j,t}$	Selling price of fabric manufacturer j in period t
$YP_{i,t}$	Selling price of yarn manufacturer i in period t
$CP_{c,t}$	Selling price of recycler c in period t
$MP_{m,t}$	Selling price of remanufacturer m in period t
$PP_{p,t}$	Selling price of repairer p in period t

Decision variables (for CLSC planning model)

$YQ_{ij,t}$	Transportation quantity from yarn manufacturer i to fabric manufacturer j in period t
$FQ_{jk,t}$	Transportation quantity from fabric manufacturer j to apparel manufacturer k in period t
$AQ_{kd,t}$	Transportation quantity from apparel manufacturer k to demand zone d in period t
$CQ_{ci,t}$	Transportation quantity from recycler c to yarn manufacturer I in period t
$MQ_{mj,t}$	Transportation quantity from remanufacturer m to fabric manufacturer j in period t
$PQ_{pk,t}$	Transportation quantity from repairer p to apparel manufacturer k in period t
$rQ_{ri,t}$	Transportation quantity from raw material supplier r to yarn manufacturer i in period t
$IV_{i(j,k,c,m\ or\ p),t}$	Inventory quantity for manufacturer i, j, k, c, m, p in period t
$x_{i(j,k,c,m\ or\ p),t}$	1: if production occurs at $i(j, k, c, m\ p)$ in period t 0: otherwise

Parameters

$S_{i(j,k,c,m\ or\ p),t}$	Market share ratio for manufacturer *i, j, k, c, m, p* in period *t* $\sum_{i(j,k,c,m\ or\ p)} S_{i(j,k,c,m\ or\ p)} = 1$
$\phi_{A(F,Y,C,M\ or\ P),t}$	Primary demand of each member (apparel, fabric, yarn, recycler, remanufacturer, repairer) in period *t*
$\beta_{A(F,Y,C,M\ or\ P),t}$	Price-demand sensitivity coefficient of each member (apparel, fabric, yarn, recycler, remanufacturer, repairer) in period *t*
$D_{A(F,Y,C,M\ P or\ d),t}$	Demand quantity each member (apparel, fabric, yarn, recycler, remanufacturer, repairer, customer) in period *t*
N	Set of all connected manufacturer
$PC_{i(j,k,c,m\ or\ p),t}$	Production and operation cost per unit for manufacturer *i, j, k, c, m, p* in period *t* ($PC_{i(j,k,c,m\ or\ p)} = l_{i(j,k,c,m\ or\ p)} + o_{i(j,k,c,m\ or\ p)}$)
$RC_{c,(m\ or\ p),t}$	Collection cost per unit for each recovery manufacturer *c, m, or p* in period *t*
$m_{ri,t}$	Raw material cost per unit from *r* raw material supplier to *i* manufacturer in period *t*
$l_{i(j,k,c,m\ or\ p),t}$	Labor cost per unit for manufacturer *i, j, k* in period *t*
$o_{i(j,k,c,m\ or\ p),t}$	Operation cost per unit for manufacturer *i, j, k, c, m, p* in period *t*
$T_{ri(ij,jk,ci,mj,pk\ or\ kd),t}$	Transportation cost per unit from *r* to *i, i* to *j, j* to *k, c* to *i, m* to *j, p* to *k, k* to *d* in period *t*
$Inv_{i(j,k,c,m\ or\ p),t}$	Investment cost per CO_2 ton for CERs(Certified Emission Reductions) for manufacturer *i, j, k, c, m, p* in period *t*
$\lambda_{C(M\ or\ P),t}$	Return ratio for each recovery type (recycle, remanufacturing, repair) in period *t*
$h_{i(j,k,c,m\ or\ p),t}$	Holding cost per unit for manufacturer *i, j, k, c, m, p* in period *t*
$PE_{i(j,k,c,m\ or\ p),t}$	CO_2 emission of production per unit for manufacturer *i, j, k, c, m, p* in period *t*
$TE_{ri(ij,jk,ci,mj\ or\ pk),t}$	CO_2 emission of transportation per unit from *r* to *i, i* to *j, j* to *k, c to i, m* to *j, p* to *k* in period *t*
$PCP_{i(j,k,c,m\ or\ p),t}$	Production capacity for manufacturer *i, j, k, c, m, p* in period *t*
$RE_{i(j,k,c,m\ or\ p),t}$	Upper bound (restriction) for CO_2 emission for manufacturer *i, j, k, c, m, p* in period *t*

Conflicts of Interest

The authors declare no conflict of interest.

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