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How Effective Is Reverse Cross-Docking and Carbon Policies in Controlling Carbon Emission from the Fashion Industry?

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Abstract: The present consumer behavior is manipulated by "fast fashion", where purchasing new, trendy, affordable clothes is preferred over recycling old ones. This changing mannerism has escalated the GHG emissions from the fashion industry. Energy-intensive raw material production, preparation, and processing contribute to considerable emissions. The management of the returned goods from the primary market and further processing through the secondary outlets indulge in reverse logistics. In this paper, efforts are made to minimize the total cost and the carbon emission amount during the process of managing the return articles from the primary market to the reverse distribution center, further processing of the articles at the secondary outlet, and the return of the unsold or excess articles from the secondary outlet. Reverse cross-docking has been implemented in managing the return articles, while environmental concerns over GHG emissions have been addressed by investing in green technology under a strict carbon cap policy. In this research, return articles from the primary and secondary markets, rework of the returned articles, and disposal of the impaired returned articles have been considered. The carbon emission cost at all stages of transportation, rework, or disposal has also been incorporated into this model. A constrained mixed integer linear programming model is proposed and solved considering green investment. A numerical example has been formulated to investigate the effect of green technology on the total cost. The results portray that, though the total cost increases by nearly 2% due to investment in green technology, it ensures a considerable drop of 23% in the carbon emission amount. Also, the result is successful in establishing that reverse cross-docking is a better option than traditional warehousing in terms of minimizing the cost.

Keywords: fast fashion; reverse logistic; carbon emission; green investment; circular economy

MSC: 90B05; 90B06

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Citation: Mukherjee, T.; Sangal, I.; Sarkar, B.; Almaamari, Q.; Alkadash, T.M. How Effective Is Reverse Cross-Docking and Carbon Policies in Controlling Carbon Emission from the Fashion Industry?. *Mathematics* **2023**, *11*, 2880. https://doi.org/10.3390/math11132880

Academic Editor: María del Carmen Valls Martínez

Received: 21 May 2023
Revised: 15 June 2023
Accepted: 20 June 2023
Published: 27 June 2023

1. Introduction

Over the centuries, the fashion industry has evolved into a deep-rooted, multibillion-dollar global enterprise. The rapid increase in world population, global income, as well as improvements in the living standards of the people, have proliferated the consumption and production of clothes [1]. The inclination of the present generation to the latest fashion, as well as the ascent of new innovations, the rise of worldwide free enterprise, the improvement of the industrial system of production, and the expansion of retail outlets, for example, retail chains, have enabled clothing to be efficiently manufactured in standard sizes and sold at fixed costs. The cheap prices of clothes in the recent decade have proliferated the consumption and global production of clothing. However, the modest prices hide a high natural expense. Economical, inferior quality pieces of clothing have implied to customers that purchasing another outfit is more affordable than getting their garments fixed. This drift in consumption behavior from reuse to purchasing new clothes has prompted heaps of discarded and unsold clothes. The unsold pieces end up in the inventory, contributing to the retailers' inventory holding costs and carbon emissions. It is a well-established fact that the fate of a textile product is either landfilling, incineration (burning of the waste), recycling (changing to a new product), reselling as new, reuse internally, or remanufacturing with added value [2,3], thus making a substantial contribution to greenhouse gases. Each year, more than 92 × 106 t of clothing trash is produced due to fast fashion evolution and people's wasteful lives. It is recycled in only 14% of the total, and the rest is thrown on land [4].

It is surprising to note that the style business transmits a similar amount of GHGs each year as the whole economies of France, Germany, and the United Kingdom jointly produce. A report by McKinsey [5] shows that the fashion industry was responsible for 2.1 billion metric tons of greenhouse gas discharges in 2018, around 4 percent of the worldwide aggregate. High numbers of synthetic, petroleum-based clothes made by fast fashion businesses are produced in developing nations, resulting in significant emissions and textile waste. The thought that the fashion industry is expected to witness a rise in growth due to shifting population and consumption behavior has kept environmentalists awake at night, raising concern over the increasing emission of GHGs and pollution. The clothing industry accounts for 1.7×10^9 t of emissions, utilizes 1.5×10^{12} L of water, and is responsible for polluting the ocean with a considerable amount of microplastics, whose value is more than 190×10^9 t [4]. Over 70% of the outflows in an apparel and footwear value chain come from upstream activities, where 38% of the emissions are contributed, especially by energy-escalated raw material manufacturing, 8% from yarn preparation, 6% from fabric preparation, and 15% from wet processes [5]. While transport, packaging, retail operations, usage, and end-of-use operations contribute to the rest of the 30% of carbon emissions, as shown in Figure 1.

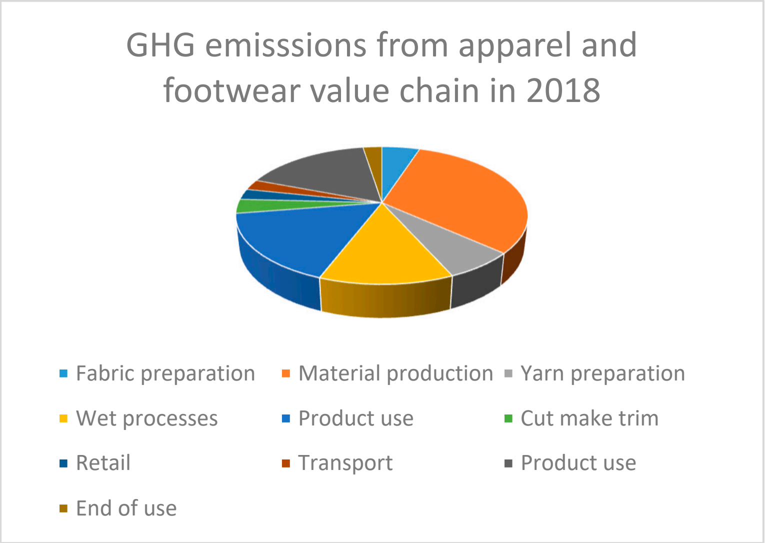


Figure 1. GHG emissions from the apparel and footwear value chain.

This compels the companies to search for better abatement efforts like decarbonized garment manufacturing, decarbonized material processing, reduction in manufacturing waste, minimizing retail returns, reducing waste generated due to unsold retail stock, increased use of sustainable transport, and innovation of smart technologies [6] to reduce the carbon emission amount. Some companies are using the textile waste to produce thermal energy [7]. Green technology innovation is also playing a crucial role in enhancing carbon emission performance [8,9]. Even meaningful efforts were made to correlate the environment, business, and energy through various carbon policies [10]. Carbon costs, carbon tax policies, carbon cap and trade policies, and strict carbon cap policies have been introduced by the government and regulatory organizations to curb carbon emissions.

A considerable amount of research has been put forward on carbon emission, strategies to limit carbon footprint in smart production systems [11], implying carbon tax policy on inventory models with imperfect quality items [12], carbon tax and cap policy on sustainable production models [13], as well as the effect of carbon emissions on sustainable supply chain models [14,15]. However, mathematical models of carbon emissions from the fashion industry are very limited, though they contribute a noticeable amount of GHG. It is noteworthy that the inventory holding at the primary market or secondary outlet stores as well as the transportation modes contribute to carbon emissions, so changes in modes of transportation [16], improvements in the fuel mix, and the introduction of planned logistic strategies like reverse logistics and reverse cross-docking can facilitate the abatement efforts. The return flows of manufactured goods, materials, or equipment from purchasers to the logistics network are referred to as reverse logistics. Manufactured items, for example, could be sent to customers from the supplier or the manufacturer. Remanufactured, reused, recovered, or recycled commodities, resources, and/or equipment are all possibilities [17,18]. Hence, from the point of recapturing value or legitimate disposal of the returned goods or manufacturing waste [19], proper planning [20], implementing, and controlling the efficient flow, along with the financially savvy flow of raw materials, in-process inventory [21], finished products, and related information from the place of utilization to the point of origin, are obligatory. Sectors dealing with seasonal demand efficiently search for ways of catching value from the RL frameworks as returns too considerably affect the profitability of the business [22]. The introduction of environmental laws increased the natural awareness of clients, and cutthroat competition has prompted the improvement of various models and answers for RL exercises [23]. It is amazing that applying cross-docking in forward operations has been perceived as a significant field of performance management; however, ways to deal with this methodology in both forward and reverse settings (at the same time) are far from adequate [24]. Understanding this gap, the aim of this paper is to apply cross-docking in the reverse logistic framework, managing the return of articles from primary markets and channeling them to secondary outlets while minimizing the total cost and carbon emissions of the whole transaction.

The remainder of our research is described as forthcoming. Section 2 elaborates on the literature review based on fast fashion, reverse logistics, carbon emissions, green technology investment, and the circular economy. A brief description of the features of reverse cross-docking is recorded in Section 3. Section 4 exhibits the problem description along with the symbols and assumptions relevant to the mathematical model. A mathematical model is discussed in Section 5. To justify the model, a numerical experiment is demonstrated in Section 6, followed by solutions, sensitivity analysis, theoretical implications, and managerial implications in the subsections. Eventually, the study is concluded by the findings in Section 7.

2. Literature Review

The relevant literature under the framework of keywords has been exhibited in the subsections.

2.1. Fast Fashion

Fast fashion has been an interesting exploration topic in the literature over the past couple of years. Fast fashion profoundly highlights two important features (a) faster response and short lead time with reference to inventory management; and (b) the latest fashion trends [25]. However, a large portion of the current studies are observational and case-oriented in nature. Only a couple of papers are focused on analytical optimization models to explore the functional issues associated with fast fashion. Concentrating on fast fashion products, Caro and Gallien [26] pioneered a fascinating study on the assortment optimization problem. They developed a stochastic model establishing the demand forecast, the available inventory of each size of clothing, and store inventory management policy as parameters to predict the sale of an article in a single outlet. Knowing that demand forecasting is a challenging task and highly influences inventory management, fast fashion companies need to wisely plan their product assortment and optimize inventory policies [27]. Fast fashion retailing strategies often trigger impulsive purchases by the consumer, which cripples the modern apparel industry with high return rates [28] and massive levels of waste and greenhouse gas emissions. Thus, to cope with the diversified customer demand and cut logistic costs, an integrated optimization problem merging collaborative shipping with fashion clothing assortment packing was proposed by Wang et al. [29]. Furthermore, to regulate the carbon emissions from fast-fashion enterprises, Mason et al. [30] suggested embracing the theory of planned behavior, considering consumers' participation in recycling as a directing variable.

2.2. Reverse Logistics

The success of a supply chain model revolves around a proper logistical structure. In conventional logistical approaches, products are transferred from the manufacturer to the customer across wholesalers and retailers in forward distribution. Organizations dealing with seasonal demand for goods have to plan reverse logistics to retrieve the unsold items. These organizations pull unsold items from the primary market stores for additional appropriation in RL networks [31]. Though there exists a sufficient amount of literature on reverse logistics and return management, research actually describing and focusing on the return process is minimal. Cullinane and Cullinane [32] in their article discussed the structural complexity of reverse logistics apart from suggesting measures to reduce carbon footprint. Dondo and Mendez [33] studied the distribution and recovery problems in a multi-echelon supply chain network. They applied a column generation-based decomposition approach to effectively plan the operational activities in a forward and reverse logistic setting. Kumar et al. [34] proposed a forward-reverse logistic multi-period, multi-echelon model. They aimed to maximize profit aside from obtaining an efficient vehicle route. Reverse logistic operations in general are complex and bounded by high uncertainties. Considering this aspect, Ghanbarzadeh-Shams et al. [35] studied a multi-period production planning problem with multi-product accounting from multiple sites in the carpet industry. Reddy et al. [36] investigated a multi-period green reverse logistic design based on the practical parameters of carbon footprints, inventory factors, and multi-period settings. Transportation and production at the facilities being the prime causes of carbon emissions, they investigated the effect of vehicle type on emission amounts and aimed to minimize the total cost by reducing the carbon emission cost.

Reverse Cross-Docking

Cross-docking is a logistic strategy focused on transferring goods from the supplier to the customer, eliminating the intermediate process of storage. Cross-docking includes the integration of different middle forms like accepting the inbound items, deconsolidation, sorting, union, and, at long last, stacking the solidified items in outbound shipments to reach the clients [37]. Most of the logistic models within a cross-dock focus on reducing the total cost, the material handling cost [38], or the material flow [39] in forward distribution. However, with return process management turning into a significant field in different organizations, the extension of the benefits of cross-docking with reverse logistics has broadened accordingly [40]. Zuluaga et al. [41] in their paper formulated a linear programming model to showcase the impact of reverse cross-docking on goods with seasonal demand. The results of their proposed model successfully established the fact that reverse cross-docking can escalate the effectiveness of reverse logistics in terms of cost reduction, time savings, and improvement of information management. Rezaei and Kheirkhah [24] proposed an integrated multi-product supply network and showed how cross-docking can be productively carried out in forward/reverse settings. They formulated a mixed-integer programming model designed to minimize the total cost. The performance of the model was assessed by contrasting the use of forward/reverse cross-docking with that of the classical approach. Gunwan et al. [40] applied cross-docking with reverse logistics in a four-level supply chain model comprising suppliers, cross-dock, customers, and outlets and aimed to minimize the cost of moving goods.

2.3. Carbon Emission

The textile industry, which creates a significant environmental footprint from cultivation to the manufacturing of fabrics to the landfill disposal of post-consumer items, is facing enormous environmental and resource challenges as a result of growing concerns over environmental and social sustainability, energy and water consumption, pollution, scarcity of natural resources, and emissions of greenhouse gases. Sixty-three percent of textile fibers are made of synthetic fibers and polymers derived from petroleum, such as nylon, acrylic, polyester, and polypropylene, whose manufacturing and disposal result in significant carbon dioxide emissions [1]. The processes of clothing production, manufacturing, and transportation in the textile, fashion, and apparel industries produce 8–10% of GHG emissions and generate waste [42,43]. Sustainability trends in the TAF industries were reviewed in depth by Abbate et al. [44] in their report. For the textile and apparel sectors, a sustainable circular three-layer supply chain model with a single supplier-manufacturer and numerous retailers was created by Ezhilarasan and Mishra [4]. To achieve environmental sustainability in the textile and apparel industries, zero-waste approaches for the valorization of pre-consumer textile scrap, green technology, and carbon emission reduction approaches were implemented at the manufacturer stage, while water purification technology, green technology, and concepts to minimize carbon emissions were introduced at the supplier stage. Muthu [45] in his work addressed the idea and foundations of quantifying one's carbon footprint, the tools used to do so, and how they apply to the supply chain for textiles and garments. The main difficulties in determining the carbon footprint of textile items were also covered by him in his work.

Carbon Policies

The increased consciousness about the impact of greenhouse gases on the environment has impelled researchers to scrutinize various issues related to operation management. It is inventory management that has widely benefited from sustainable development. The researchers retrospected the carbon emission amount from various operations under specific regulations in sustainable inventory management and enlisted the major carbon policies as Carbon cost/tax policy, carbon cap and trade policy, and strict carbon-cap policy [46]. Under the carbon cost/tax policy, every unit of carbon emission is recorded, and organizations are penalized financially [47]. An upper limit of the carbon emission amount from companies is predetermined under the carbon cap and trade policy. Also, companies can buy carbon credit from outside in case of more carbon production than the estimated or regulated amount and at the same time trade in or keep it as an unused allowance in case their carbon emission falls below the given limit [48]. Liu et al. [49] presented a model considering the carbon trade mechanism and inspected the effect of carbon emission reduction cost-sharing policy on the profit margin of the supply chain model. A strict carbon cap policy is another effective policy to control carbon emissions. However, the stringent nature of the policy makes it challenging for companies and associations to abide by it. Ghosh et al. [50] proposed two constrained mixed-integer programming models under a strict carbon cap policy to provide an understanding of the prudent choice of investing in green technology or otherwise. The investment in green technology leads to a reduction in total supply chain costs. Mishra et al. [51] introduced a carbon cap and tax policy based on a sustainable economic production quantity model. Based on the objectives of the highest cycle time, the most economical green technology investment, and the lowest duration of the fraction period in a positive inventory level, the solution established that for partial backlog cases, the SEPQ carbon tax and cap model is more cost-effective.

Considering both linear and non-linear price-dependent demand, they further investigated the effect of controllable carbon emissions on sustainable inventory management.

In order to achieve zero emissions within 2050, TAF industries are introducing various carbon policies. de Oliveira Neto et al. [52] propagated cleaner production as an approach in the textile industry to check if CP introduced economic and environmental advantages and contributed to sustainable development goals. In order to reduce the carbon emissions from the fashion, apparel, and textile industries, carbon circularity has evolved into an immensely popular innovation [53]. The introduction of sustainable fashion products is another abatement effort put forward by fashion companies to protect the environment and control carbon emissions [54]. In her research work, Jhanji [55] studied the life cycle assessment tools and techniques for measuring the environmental impact of goods, processes, and services. By using LCA tools and techniques, the environmental performance of items in terms of energy use, greenhouse gas emissions, water footprints, and contaminants may be assessed. Due to its emphasis on the entire life cycle of the product, including the procurement of raw materials, material processing, manufacturing, distribution, use, repair, maintenance, disposal, and recycling, LCA also provides a holistic perspective and is essential in improving the environmental performance ranking of textiles.

2.4. Green Investment

As organizations are progressively becoming cognizant of climate change, numerous associations have begun putting resources into green speculations [56]. Optimal investment in green technologies has been able to reduce carbon emissions in the supply chain to a certain extent [57]. This has compelled the authors to consider the green interest in various supply chain models while studying green investment and carbon policies simultaneously. Considering the textile and clothing sector Ezhilarasan and Mishra [4] developed a sustainable circular three-layer supply chain model where they discussed the use of green technology to cut back on emissions costs at the supplier and manufacturing levels. Bai et al. [58] applied carbon cap and trade regulation along with green technology investment to a vendor-managed inventory of a supply chain model with one manufacturer and two retailers. They presented an optimization model with an upper limit on the profit penalty for decentralization and stated that a revenue-sharing contract can curb the emissions and elevate the profit of the decentralized framework. Bazan et al. [59] proposed a classically coordinated model and vendor-managed inventory closed-loop supply chain model under the emissions-tax policy and considered it a green investment. They addressed three high-priority environmental concerns in their models: energy consumption during manufacturing and remanufacturing processes, emission of GHG during production and transportation, and frequency of remanufacturing used goods. Sepehri et al. [13] presented a sustainable production inventory model considering imperfect quality items. As manufacturing processes and the deterioration of items are solely responsible for carbon emissions, they studied three different models, considering investment in preservation technology, investment in improving quality, and carbon reduction technologies. Through the results of their model, they successfully established the fact that investment in quality improvement ensures an increase in total profit. As the fast fashion industry contributes heavily to greenhouse gases, the pioneers have adopted sustainability to curb the emission rate and shift to sustainable supply chain management. In his review, Wren [60] analyzed the present strategies that the fast fashion houses carry out to adopt sustainable supply chain management, the gaps in the current practices, and the major initiatives that need to be embraced to diminish the environmental impact of their supply chain in the near future.

2.5. Circular Economy

One of the largest worldwide issues is achieving sustainable economic growth with little harm to the environment. The escalating levels of production, consumption, and economic expansion have depleted the system's resources, generating a financial crisis and contamination of the environment. The circular economy has a positive impact on carbon emissions. Hence, the principle of circular economy is being applied to the fashion and textile industries as well [1]. Tsironis and Tsagarakis proposed a circular economy in the fashion and textile industries from the social media point of view [61]. Saccani et al. [62] in their paper suggested a circular supply chain orchestration strategy in order to comprehend responses to circular economy adoption hurdles in the textile and fashion supply chains. Khan et al. [63] explored this relationship between the circular economy and carbon emissions by applying the rolling window approach and stated that there exists a reciprocal link between them. It is now understood that environmental sustainability thrives on the concept of the 3 Rs: reduce, restore, and recycle. To increase environmental sustainability in their operations and supply chains, many prominent firms, including Apple and Dell, to mention a few, have embraced CE. Global business leaders are increasingly focusing on the transition to circular supply chain management (CSCM). However, this being a comparatively new research area, a comprehensive, integrated view of CSCM was missing. Farooque et al. [64] organized existing supply chain sustainability terminology into categories and then conceptualized a general definition of CSCM. Mauss et al. [65] in their research suggested a change management model by incorporating the ideas from expert interviews and translating the theory from the extensive literature in order to achieve a circular economy. They mentioned the challenges that manufacturing organizations have to encounter in order to implement a circular economy.

A lot of research on the circular economy has been focused either on a theoretical concept or on statistical analysis. Debnath and Sarkar [66] designed a sustainable supply chain model, considering step-wise waste reduction and nullification from the concept of the circular economy. They introduced the idea of price discounts in order to minimize waste generation at the retailer's end, and they recycled them to feed livestock, thus nullifying the waste. Due to rising volumes of end-of-life and end-of-use product returns, reverse logistics is anticipated to play a significant role in CSCM. In the CE, renewable energy will replace fossil fuels in the power supply chain and logistical operations. Mallick et al. [67] presented a conceptual framework outlining the core activities, drivers and barriers, stakeholder participation, and performance management in RL based on an organized evaluation of the literature. A framework like this would help businesses assess various methods and tactics, as well as the benefits and drawbacks of creating and implementing RL and moving towards a circular economy.

2.6. Research Gaps and Contributions

The management of supply chains in the textile and apparel industries has been the subject of numerous research papers and sustainability models. But most of the research in this sector enabled a forward system of logistics with a prime focus on minimizing the total supply chain cost. Though there has been extensive research on supply chain models, very little research from the perspective of the fashion industry is available.

- Previous research has seldom explored the effect of green technology investment on the total cost of a reverse logistics model relevant to the fashion industry.
- Most of the models in TAF industries are theoretical models aiming to achieve sustainable development goals.

For contributing to the recognized research gap and constructing a sustainable reverse logistic framework, this elaboration returns to the paper proposed by Ghosh et al. [50] and Zuluaga et al. [41].

These papers were thoroughly investigated to propose a novel integrated model focusing on minimizing the total cost and the carbon emission amount during the process of collecting the returned articles from the primary market and redistributing the returned articles to secondary outlets. A reverse cross-docking strategy has been used during the product transference.

- The model attempted to evaluate the carbon amount emitted during the various stages of transportation of the return articles, rework of the unsold articles, land filling, and inventory holding at the reverse distribution center following a strict carbon cap policy.
- The model presented its result under the pretext of two scenarios, one considering green investment and the other not considering green investment.

3. Features of Reverse Cross-Docking

It is entirely understood that the unsold articles after a makeover through rework or recycling would be ready to contribute to business revenues. In conventional logistical approaches, products are transferred from the manufacturer to the customer across wholesalers and retailers in forward distribution. But in the reverse setting, the orders from secondary outlets are unknown. The surplus unsold pieces are packed in boxes at the primary stores and sent to the reverse distribution center. So, channeling the return goods demands a systemic logistical approach. A reverse cross-docking framework, which is a part of reverse logistics, deals with the immediate exchange of returned items coming from essential business sectors to secondary outlets through active outbound vehicles without holding the items in inventory. The standard structure of the return process in the RL network and reverse cross-docking has been sketched and shown in Table 1.

The matching percentage of a box denotes how nearly the contents of the box i match the ideal product assortment of the secondary outlet j [41]. It is calculated as

$$MP_{ij} = 1 - \frac{nof\ of\ articles\ a\ in\ box\ i\ which\ does\ not\ match\ with\ the\ ideal\ product\ assortment\ of\ outlet\ j}{Total\ number\ of\ goods\ in\ box\ i}$$

Table 1. Comparison of reverse logistic with reverse cross-docking.

Criteria	Reverse Logistic	Reverse Cross-Docking
Box content	**Unknown** Given an average measure of unsold items from organizations with occasional demand, these organizations pull out unsold items from the primary market stores for additional appropriation in RL networks [31].	**Known** The supply information from market store is shared with ReDc. The unsold products from the primary market, at the end of the sales season, are packed in cartons and sent to the ReDc with labelled information about the product.
Labelling–Box destination	**Non existent** the boxes are open, the goods quality are inspected then classified, sorted and stored in inventory untill further reassignment through secondary outlets.	**Defined and placed by the ReDc** Demand information from the secondary outlet are obtained through ideal product assortment and shared with ReDc. The cartons are labelled accordingly and dispatched without being opened.
Cost- effectiveness	**Low** The counting of return items on individual basis rather than lot size contributes to high processing cost in reverse settings apart from inventory holding cost.	**High** The boxes are not opened but are directly dispatched. So processing cost and inventory holding cost are ignored.

The flexibility of the secondary outlet to accept return goods is judged by the tolerance percentage (TP). It is a constant parameter with values ranging from 0% to 100% that decides the level of mismatch of the box items that is permissible by the secondary outlets. Based on ideal product assortment, content of the box, matching percentage of the box, the tolerance percentage of the outlets, the final destination of the returned boxes of clothes from primary market could be secondary outlets through cross-docking or could be directed to traditional warehouses (Table 2).

Table 2. Box assignment.

Approach	**Matching Percentage** (MP_{ij})	**Tolerance Percentage (*TP*)**	**Cost**
Cross-docking	High	Low	Crossdocking cost is more and return cost is less.
	High	High	Crossdocking cost is more and return cost is less
	Low	High	More unwanted items being sent, increase in cross-docking and return cost.
Traditional warehousing	Low	Low	Increases traditional warehousing cost.

4. Problem Description

In this study, apart from the total cost, we examine the amount of carbon emitted during various stages of managing the returned clothes from the primary market to the reverse distribution center and to secondary outlets. Two mathematical models have been designed in this study. The first model aimed to find the total cost and the carbon emission amount while transferring the return articles from primary markets to a reverse distribution center and further processing those articles through secondary outlets following a reverse crossdocking framework (refer to Figure 2). The second mathematical model was conceptualized to understand the effect of green technology investment on the total cost as well as the amount of carbon emitted during the same process. In a previous study regarding reverse cross-docking [41], the total cost applicable to the assignment decision was optimized considering the parameters traditional warehousing cost, cross-docking cost, return cost, tolerance percentage, and return probability. In this study, the model has been formulated by considering one extra parameter apart from the above-listed parameters, namely carbon emission. The carbon emission cost corresponding to activities like inventory holding at the reverse distribution center, recycling of the fabrics or rework of the turned articles, landfilling, or incineration of the discarded clothes has been incorporated in this model, apart from the carbon emission cost due to transportation. Transportation is one of the major contributors to greenhouse gases [68]. In this model, we have contemplated the carbon emission cost during the transportation of the return articles from the primary market to ReDc, from secondary outlets to ReDc, from ReDc to the local remanufacturing/recycling workshop, as well as the carbon emission cost corresponding to the transportation from ReDc to the nearest landfill. The carbon emission cost during the transfer of returned articles to secondary outlets from ReDc through cross-docking has been included in the cross-docking cost. Thus, the prime focus of this model is to minimize the total cost of the reverse logistic model by considering the carbon emission amount and its effect. Abbreviations list represents the notations, which include indices, decision variables, and parameters used in the model formulation. Section 4.1 explains the assumptions of this problem.

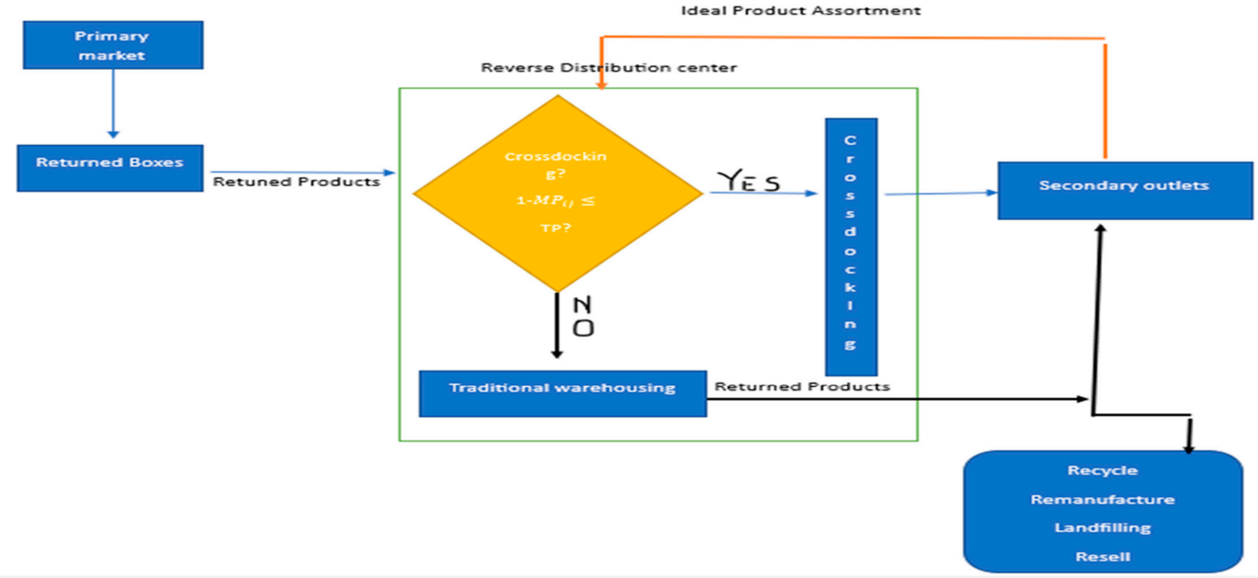


Figure 2. Reverse cross-docking model.

4.1. Assumptions

The following arrangement of assumptions is made to define the boundaries in the model's formulation and frame the proposed model.

1. The respective supply and demand information from the primary stores and secondary outlets about the products is readily available at the reverse distribution center. The boxes are labeled with their contents, the quantity of the item, and its type. Also, five secondary outlets have been considered in the reverse logistic network;
2. Recycle, remanufacture, inventory, transportation, and cleaning of the fabrics are the prime causes of carbon emissions in the fashion industry. The amount of carbon emitted due to transportation is a function of truck velocity and is dependent on the amount of load carried and the nature of vehicles [50]. In this model, we have excluded the amount of carbon emitted due to the cleaning of the fabrics;
3. Based on the matching percentage of the box with the product requirement from the secondary outlet, the boxes are directed to cross-docking. Those boxes that are not resent through cross-docking are opened and become part of warehouse inventory. All the boxes returned from the primary market are exercised through either cross-docking or traditional warehousing [41];
4. The return probability of unsold, excess items to the ReDc that were sent to secondary outlets is calculated by considering the mean of the returnable products in the history. The total lot sent for rework is fully processed. There is no loss of items in the process;
5. Though the total traditional warehousing cost is more than the cross-docking cost, depending on the number of boxes being processed, the cost for every individual box is the same. The return cost is calculated on every article [41]. The traditional warehousing cost is inclusive of the inventory holding cost;
6. The amount of green investment influences the level of carbon emission reduction [50]. We have assumed that biodiesel has been used as a fuel in the vehicles, which is an investment in green technology.

5. Mathematical Model

This mathematical model was designed to minimize the total cost and the carbon emission amount in a reverse logistic context when articles are transferred from primary markets to secondary outlets via a reverse distribution center. The first term of the objective function is the return cost of the unsold articles. The cumulative return cost has two subcosts. The return cost of unsold articles from the primary market to the ReDc and the return cost of unsold articles from the secondary outlet *j* which were sent in excess to the outlet and do not match their product requirements, are returned back to the reverse distribution center.

$$\left(\sum_{a=1}^{A}\sum_{i=1}^{I} C_{ai} + \sum_{j=1}^{J}\sum_{a=1}^{A} GS_{aj} * p_{aj}\right) RC_a \tag{1}$$

The second term corresponds to the traditional warehousing cost when the return articles are addressed to the traditional warehouses from the reverse distribution center due to the high unmatching percentage and low flexibility of the secondary outlets. The traditional warehousing cost includes the inventory holding cost.

$$\sum_{i=1}^{I} BT_i * TWC_i \tag{2}$$

$$\sum_{j=1}^{J}\sum_{i=1}^{I} BA_{ij} * CDC_i \tag{3}$$

The fourth term of the function explains the rework cost when the unsold articles are sent back to the reverse distribution center from the secondary outlet. The articles are then processed through other channels for rework, recycling, or remanufacturing.

$$(1-\mu_r)\sum_{j=1}^{J}\sum_{a=1}^{A} GS_{aj} * p_{aj}) * C_r \tag{4}$$

The fifth term of the function embodies the transportation cost due to the shifting of the returned unsold particles from the secondary outlet to the local repair or remanufacturing store and the delivery of the finished reworked product to the ReDc. The transportation cost is measured by the number of units transferred and the hour of service.

$$\left[(1-\mu_r)\sum_{j=1}^{J}\sum_{a=1}^{A} GS_{aj} * p_{aj}\right] * \frac{L_r}{V} * (T_n + T_{n'}) \tag{5}$$

The sixth term of the function represents the carbon tax levied due to carbon emissions during the processes of transportation of the returned articles, repair, landfilling, and inventory holding at the reverse distribution center (Refer Appendix A for carbon emission amount). Therefore, CE costs can be given as:

$$C_t(CE_{dc} + CE_r + 4CE_t + CE_l) \tag{6}$$

$$\begin{gathered} C_t\ \{(a_0 + a_1V + a_2V^3 + \tfrac{a_3}{V^2})[L_{dc} * \sum_{a=1}^{A}\sum_{i=1}^{I} C_{ai} + \\ \sum_{a=1}^{A}\sum_{j=1}^{J} (L_j * GS_{aj} * p_{aj}) + 2(1-\mu_r)\sum_{j=1}^{J}\sum_{a=1}^{A} GS_{aj} * \\ p_{aj} * L_r + L_l * \mu_r\sum_{j=1}^{J}\sum_{a=1}^{A} GS_{aj} * p_{aj}] + [(1-\mu_r)\sum_{j=1}^{J}\sum_{a=1}^{A} GS_{aj} * \\ p_{aj} * CE_r + \mu_r\sum_{j=1}^{J}\sum_{a=1}^{A} GS_{aj} * p_{aj} * CE_l + \sum_{a=1}^{A}\sum_{i=1}^{I} C_{ai} + \\ \sum_{j=1}^{J}\sum_{a=1}^{A} GS_{aj} * p_{aj} * CE_{dc}]\} \end{gathered} \tag{7}$$

5.1. The Final Objective Function of the Model Based on Strict Carbon Cap Policy without Investing in Green Technology

$$\begin{gathered} TC = \left(\sum_{a=1}^{A}\sum_{i=1}^{I} C_{ai} + \sum_{j=1}^{J}\sum_{a=1}^{A} GS_{aj} * p_{aj}\right) * RC_a + \sum_{i=1}^{I} BT_i * \\ TWC_i + \sum_{j=1}^{J}\sum_{i=1}^{I} BA_{ij} * CDC_i + (1-\mu_r)\sum_{j=1}^{J}\sum_{a=1}^{A} GS_{aj} * \\ p_{aj} * C_r + (1-\mu_r)\sum_{j=1}^{J}\sum_{a=1}^{A} GS_{aj} * p_{aj} * \tfrac{L_r}{V} * (T_n + T_{n'}) + \\ C_t(CE_{dc} + CE_r + 4CE_t + CE_l) \end{gathered} \tag{8}$$

The constraint of the designed model are listed as follows:

5.1.1. Carbon Emission Constraint

$$\begin{aligned}&\{(a_0+a_1V+a_2V^3+\tfrac{a_3}{V^2})[L_{dc}\ast\textstyle\sum_{a=1}^{A}\sum_{i=1}^{I}C_{ai}+\\&\textstyle\sum_{a=1}^{A}\sum_{j=1}^{J}(L_j\ast GS_{aj}\ast p_{aj})+2(1-\mu_r)\sum_{j=1}^{J}\sum_{a=1}^{A}GS_{aj}\ast\\&p_{aj}\ast L_r+L_l\ast\mu_r\textstyle\sum_{j=1}^{J}\sum_{a=1}^{A}GS_{aj}\ast p_{aj}]+[(1-\\&\mu_r)\textstyle\sum_{j=1}^{J}\sum_{a=1}^{A}GS_{aj}\ast p_{aj}\ast CE_r+\mu_r\sum_{j=1}^{J}\sum_{a=1}^{A}GS_{aj}\ast p_{aj}\ast\\&CE_l+\sum_{a=1}^{A}\sum_{i=1}^{I}C_{ai}+\sum_{j=1}^{J}\sum_{a=1}^{A}GS_{aj}\ast p_{aj}\ast CE_{dc}]\}\\&\le\ \hat{C}\end{aligned}\tag{9}$$

Constraint (9) explains the carbon emission amount without green technology investment. In strict carbon cap policy, the carbon emission amount should be within the given limit; failing to comply with the suggested cap imposes a heavy penalty.

5.1.2. Product Availability Constraint

$$\sum_{i=1}^{I}C_{ai}-\sum_{j=1}^{J}O_{aj}=\sum_{j=1}^{J}\sum_{i=1}^{I}SP_{aij}-\sum_{i=1}^{I}\sum_{j=1}^{J}LP_{aij}\ \ \forall a\tag{10}$$

Constraint (10) computes the amount of the excess or deficient articles in box *i* with respect to the ideal product assortment of outlet *j*. In the case of SP_{aij} attaining a positive value, it implies that there are excess articles *a* in box *i* apart from the ordered quantity by outlet *j*. If LP_{aij} adopts a positive value, then there is a shortage of articles *a* ordered by outlet *j* in box *i*. SP_{aij} obtaining a positive value implies LP_{aij} being zero, and vice versa.

$$\left(\sum_{i=1}^{I}C_{ai}\ast BA_{ij}\right)-\sum_{j-1}^{J}O_{aj}=\sum_{j=1}^{J}\sum_{a=1}^{A}(GS_{aj}-GL_{aj})\ \forall a\tag{11}$$

For every article *a* and secondary outlet *j*, Constraint (11) calculates the global surplus GS_{aj} or global deficiency LP_{aij} in comparison with the ideal demand O_{aj}. This calculation includes the contents of all boxes assigned to outlet *j*.

$$\mathrm{E}[\widehat{RP_{aj}}]=GS_{aj}\ast p_{aj}\ \ \forall j\tag{12}$$

Constraints Equation (12) estimates the number of unsold, defective articles that are returned from the outlets to the reverse distribution center.

5.2. Product Assortment Constraint

$$MP_{ij}=1-\frac{\sum_{a=1}^{A}SP_{aij}}{\sum_{a=1}^{A}C_{ai}}\ \ \forall i,j\tag{13}$$

Constraints Equation (13) represents the matching percentage of box *i* with respect to the ideal product assortment of outlet *j*.

$$BA_{ij}\le TP+MP_{ij}\quad\forall i,j\tag{14}$$

Constraint (14) explains the conditions for *a* box to be assigned for cross-docking.

$$\sum_{j=1}^{J}BA_{ij}+BT_i=1\quad\forall i\tag{15}$$

Equation (15) certifies that every box is checked. They are either assigned to secondary outlet *j* through crossdocking or to traditional warehousing.

5.3. Binary Decision Variables

$$BT_i,BA_{ij}\in\{0.1\}\tag{16}$$

$$LP_{aij}, SP_{aij}, MP_{ij} \geq 0 \tag{17}$$

5.4. Formulation of the Objective Function Considering Strict Carbon Cap Policy and Green Investment

$$\begin{aligned}\mathrm{TC} = {} & \left(\sum_{a=1}^{A}\sum_{i=1}^{I} C_{ai} + \sum_{j=1}^{J}\sum_{a=1}^{A} GS_{aj} * p_{aj}\right) RC_a + \sum_{i=1}^{I} BT_i * TWC_i + \\ & \sum_{j=1}^{J}\sum_{i=1}^{I} BA_{ij} * CDC_i + \left[(1-\mu_r)\sum_{j=1}^{J}\sum_{a=1}^{A} GS_{aj} * p_{aj}\right] * C_r + (1- \\ & \mu_r)\sum_{j=1}^{J}\sum_{a=1}^{A} GS_{aj} * p_{aj} * \frac{L_r}{V} * (T_n + T_{n'}) + C_t(CE_{dc} + CE_r + 4CE_t + CE_l) + I\end{aligned} \tag{18}$$

The eighth term of the objective function is I which presents the green technology investment to reduce carbon emissions. Here, the investment has been considered for the partial setup concerning the primary market, reverse distribution center, secondary outlets, and rework center.

The carbon reduction function for green technology has been referred from [50].

$$F(I) = \mu I - \sigma I^2 \tag{19}$$

Here I is the number of monetary units invested per partial setup, μ denotes the carbon reduction efficiency factor, and σ denotes the decreasing return parameter.

Carbon Emission Constraint

$$\begin{aligned} & \Big\{\left(a_0 + a_1 V + a_2 V^3 + \frac{a_3}{V^2}\right)\Big[L_{dc} * \sum_{a=1}^{A}\sum_{i=1}^{I} C_{ai} + \sum_{a=1}^{A}\sum_{j=1}^{J}\left(L_j * GS_{aj} * p_{aj}\right) \\ & + 2(1-\mu_r)\sum_{j=1}^{J}\sum_{a=1}^{A} GS_{aj} * p_{aj} * L_r + L_l * \mu_r \sum_{j=1}^{J}\sum_{a=1}^{A} GS_{aj} * p_{aj}\Big] \\ & + \Big[(1-\mu_r)\sum_{j=1}^{J}\sum_{a=1}^{A} GS_{aj} * p_{aj} * CE_r + \mu_r \sum_{j=1}^{J}\sum_{a=1}^{A} GS_{aj} * p_{aj} * CE_l + \\ & \sum_{a=1}^{A}\sum_{i=1}^{I} C_{ai} + \sum_{j=1}^{J}\sum_{a=1}^{A} GS_{aj} * p_{aj} * CE_{dc}\Big]\Big\} - \left(\mu I - \sigma I^2\right) \leq \hat{C}\end{aligned} \tag{20}$$

6. Numerical Example

This section provides numerical examples where the numerical values have been adopted from Ghosh et al. [50] and Sepehri et al. [13] and adjusted in accordance with our explanation. Hence, the values for the parameters are given as

$$\begin{aligned} & V = 50\ \mathrm{km/h},\ \widehat{\mathrm{C}} = 20{,}000\ \mathrm{Kg\ of\ CO_2/per\ partial\ setup},\ a_0 = 1567 * 10^{-6}, \\ & \mathrm{a}_1 = -17.6 * 10^{-6},\ a_2 = 0.00117 * 10^{-6},\ a_3 = 36{,}067 * 10^{-6},\ \sigma = 0.01,\ \mu = 4, \\ & \mu_a = 0.3,\ L_{dc} = 200\ \mathrm{km},\ L_r = 300\ \mathrm{km},\ L_l = 250\ \mathrm{km},\ L_j = \{200, 250, \\ & 225, 300, 350\}\ \mathrm{km},\ CE_r = 20\ \mathrm{kg/unit},\ CE_l = 0.5\ \mathrm{kg/unit},\ CE_{dc} = 1.0 \\ & \mathrm{kg/unit},\ C_r = 5\ \$,\ T_n = 5\ \$/\mathrm{unit/h},\ RC_a = 4\ \$/\mathrm{unit},\ TWC_i = 12\ \$/\mathrm{box}, \\ & CDC_i = 10\ \$/\mathrm{box},\ C_t = 1\ \$/\mathrm{kg}, \mathrm{I} = 60\ \$\end{aligned} \tag{21}$$

6.1. Solution and Discussion

The constrained MILP model developed has been solved using the computational software OCTAVE 5.2.0 and the numerical values of the parameters mentioned above. GNU octave is a programming language that is faster than other programming languages. It is user friendly, free, and open source software that helps solve linear problems easily. For TC and CE, we have considered values up to 1 decimal place, while for other parameters, values have been considered up to 2 decimal places. Two cases with five boxes i, five different product types a, and five secondary outlets j have been discussed here. Firstly, the base solution without considering green investment has been discussed, and secondly, the effect of green technology investment on the total cost and carbon emissions has been elaborated in case 2.

The results depicted in Table 3 well establish the impact of green technology investment on the total cost and total carbon emissions during the various stages of reverse logistics, product distribution, collection, and storage from primary markets, secondary outlet stores, and ReDC. It is evident from the results that the total cost increases by 1.71% with green investment. However, this meagre increase in cost brings a noticeable decrease in the total carbon emission amount. There is a substantial drop of 23.19% in the amount of carbon emitted during the various processes when green investment is made.

Table 3. Solution with and without green investment.

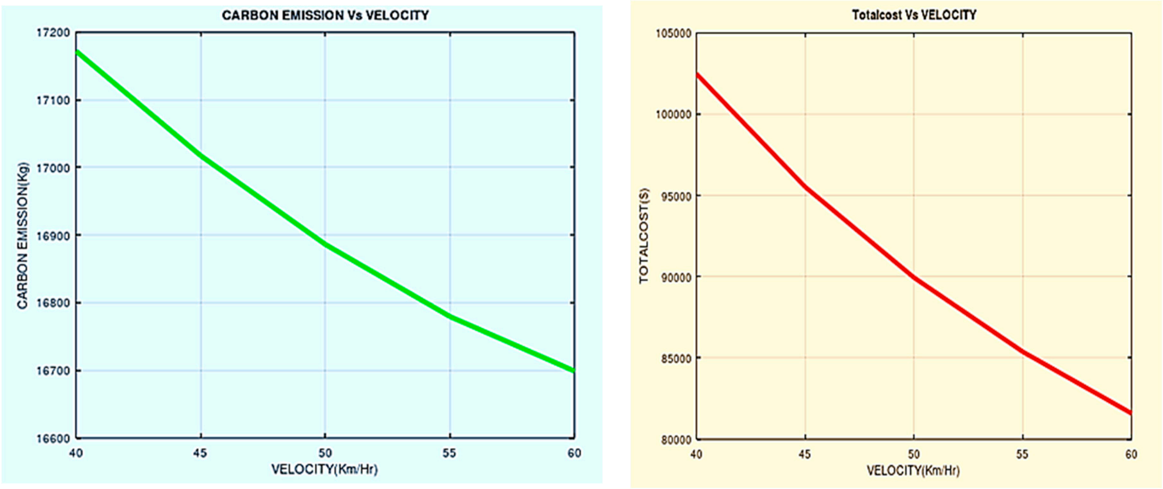
		TC ($)	CE (kg)
Case 1	without green investment	88,442.7	21,986.2
Case 2	With green investment	89,942.7	16,886.2
	% change	1.71% increase in cost	23.19% decrease in carbon emission amount

6.2. Sensitivity Analysis

In accordance with the previous section, Tables 4–6 discuss the sensitivity analysis for the various parameters connected to our elaboration in Case 2. The sensitivity analysis helped to evaluate the effect of the varying parameters on the objective function and the total emitted carbon amount. The findings are then used to offer management implications.

6.3. Theoretical Implications

1. The amount of carbon emitted due to transportation is a function of velocity. Thus, the velocity of the vehicle is an important parameter in optimizing the total cost as well as reducing carbon emissions. From the results in Table 6 and Figure 3a, as well as Figure 3b, it can be stated that the velocity has a good impact on the total cost and total carbon emission. The results depict that the change in velocity inversely affects the total cost and carbon emissions. As the velocity of the vehicles increases, the total cost and carbon emissions decrease. A 20% increase in the velocity of the vehicle drops the total cost and carbon emission amount by more than 9% and 1%, respectively. A net fall in the CE amount with increasing velocity is due to the decrease in transportation-related emissions. Further, an increase in vehicle velocity correspondingly decreases the TC and CE.



(**a**) (**b**)

Figure 3. This is a figure. (**a**) Defines the effect of V on CE; (**b**) Defines the effect of V on TC.

2. When a box is returned from the primary market, the number of articles stored in the box impacts the total cost as well as the CE. A higher number of returned articles means an increase in total cost, as the return cost is calculated per unit of returned

articles. Also, carbon is emitted during transportation of the returned articles from the primary market to the reverse distribution center, which is also affected by the number of returned articles. According to Table 4, more returned items add to the CE amount. It is seen that a 20% increase in the return articles from the primary market increases the total cost by 2.45% and the carbon emission amount by 2.96%.

Table 4. Effect of the parameters on total cost and total carbon emissions.

	20%	***paj***	**−20%**	**20%**	***GSaj***	**−20%**	**20%**	***Cai***	**−20%**
	0.48	0.4	0.32	48	40	32	120	100	80
	0.72	0.6	0.48	36	30	24	66	55	44
	0.24	0.2	0.16	30	25	20	96	80	64
	0.48	0.4	0.32	24	20	16	72	60	48
	0.48	0.4	0.32	60	50	40	60	50	40
	0.96	0.8	0.64	24	20	16	186	155	124
	0.42	0.35	0.28	36	30	24	210	175	140
	0.72	0.6	0.48	24	20	16	78	65	52
	0.24	0.2	0.16	60	50	40	96	80	64
	0.36	0.3	0.24	36	30	24	48	40	32
	0.48	0.4	0.32	30	25	20	168	140	112
	0.12	0.1	0.08	12	10	8	120	100	80
	0.6	0.5	0.4	30	25	20	96	80	64
	0.72	0.6	0.48	24	20	16	108	90	72
	0.72	0.6	0.48	36	30	24	84	70	56
	0.36	0.3	0.24	12	10	8	120	100	80
	0.18	0.15	0.12	24	20	16	84	70	56
	0.3	0.25	0.2	18	15	12	102	85	68
	0.48	0.4	0.32	36	30	24	78	65	52
	0.36	0.3	0.24	48	40	32	90	75	60
	0.24	0.2	0.16	24	20	16	108	90	72
	0.48	0.4	0.32	48	40	32	120	100	80
	0.3	0.25	0.2	36	30	24	84	70	56
	0.12	0.1	0.08	24	20	16	96	80	64
	0.24	0.2	0.16	24	20	16	72	60	48
TC ($)	**105,393.1**	**89,942.7**	**74,492.3**	**105,393.1**	**89,942.7**	**74,492.3**	**92,151**	**89,942.7**	**87,734.6**
CE (Kg)	**207,83.3**	**16,886.2**	**12,989.1**	**20,783.3**	**168,86.2**	**12,989.1**	**17,386.4**	**16,886.2**	**16,386.1**

Similarly, the number of excess articles returned from the secondary outlet given by $E[R\hat{P}_{aj}] = GS_{aj} * p_{aj}$ also escalates the total cost and CE. As the estimated number of returned articles from secondary outlets is dependent on the global surplus of articles and the returned probability of the articles from the secondary outlet, a change in any of these two parameters impacts the TC and CE, as shown in Table 4. In the model, we have considered five different types of articles that have been dispatched to five different secondary outlets. So, we recorded 25 instances of the return probability and global surplus of all the articles from the secondary outlets. It is fascinating to find from the results in Table 4 that a 20% increase in either return probability or global surplus of items brings a huge increase of 23% in CE and 17.17% in total cost, also enhancing the chances of crossing the carbon cap. Increased return probability (p_{aj}) means fewer boxes will be directed to cross-docking and more boxes to traditional warehouses, as traditional warehouse costs are higher than cross-docking costs, so it affects the total cost. More items in warehouses will increase carbon emissions.

The results in Table 5 confirm that a simultaneous increase in both the global surplus of articles and the return probability heavily enhances the total cost and carbon emissions, enhancing the possibility of crossing the carbon cap. However, a noticeable decrease in the total cost and CE is recorded when global surplus of articles and return probability of the articles are both reduced. A 20% reduction in both parameters can bring a noticeable reduction of 31% in the total cost and 40% in the CE. As the total cost is directly affected by the number of returned articles from the secondary outlet, fewer surplus items in a box and a reduced tendency of secondary outlets to return products will result in fewer returned items, which subsequently reduces the total cost and CE (Figures 4–7).

3. Distance is another important factor in transportation. The results of Table 6 show that a lesser distance of the primary market or secondary outlet from the distribution center means a reduction in the total cost and CE. Also, dumping the damaged or unwanted articles in the nearest landfill can reduce the total cost and carbon emissions. Increased distance leads to increased costs and CE. However, the increase in carbon emissions due to traveling to faraway primary markets and secondary outlets can be balanced by increasing the velocity of the vehicle. It is clear from Figure 7 that a 20% increase in the distance of primary markets, secondary outlets, and the nearest landfill from the reverse distribution center increases the carbon emission amount by an average of 0.315%, which can be balanced by increasing the velocity of the vehicle by 20%. It is observed that increasing the velocity of the vehicle against the increased distance lowers the carbon emission amount by 1.13%.
4. According to Table 6, different cost parameters heavily influence the objective function. The model is characterized by five different costs: cross-docking cost, traditional warehousing cost, return cost, rework cost, and transportation cost, apart from the carbon tax. Changes in any of these costs would affect the total cost of the model. From the results in Table 6, it is understood that a 20% increase in the return cost and rework cost of the articles increases the total cost to nearly 3% and 0.90%, respectively. However, there is a massive increase of 10.89% in the total cost due to the increase in transportation costs. As the traditional warehousing cost is higher than the cross-docking cost, when a greater number of returned boxes from the primary market are directed to secondary outlets through cross-docking, a noticeable drop of 0.33% in the total cost is observed, though CE remains unaffected. A further increase in the traditional warehousing cost adversely affects the system by escalating the total cost.
5. A certain percentage of the returned articles are defective and need to be reworked. The process of reworking the returned articles emits carbon, which affects the total cost and total amount of carbon emission. A larger percentage of discarded items in a lot implies a reduced rework percentage. When more articles are subjected to rework, the rework cost increases the total cost by nearly 7%. As rework of returned articles also emits a considerable amount of carbon so increased rework percentage of returned items increases the carbon emission amount as well by 8%.
6. More investment in green technology leads to an appreciable drop in carbon emissions (Figure 6). Though green investment increases the total cost, its effect on lowering carbon emissions is more recognizable (Table 3). Also, the results in Table 6 assert that for each 20% increase in green investment, the CE amount is lowered by 4.76%. CE reduction is a function of μ and σ. As the carbon reduction efficiency factor μ is increased, the reduction in carbon emission function is greater, leading to a reduction in total carbon emissions with the total cost remaining the same. However, it is advisable that, to ensure a further reduction in the carbon emission amount, the decrease return parameter be maintained in a lower range.
7. It is understood from Figure 4 that, though every operation emits carbon, the maximum is from the rework process of the returned articles. Also, a substantial amount of carbon is released into the environment due to the inventory held at the reverse distribution center. It is evident from Figure 5 that, though all operations contribute to the cost, the transportation cost of the returned goods contributes tremendously to the overall cost, followed by the carbon tax.

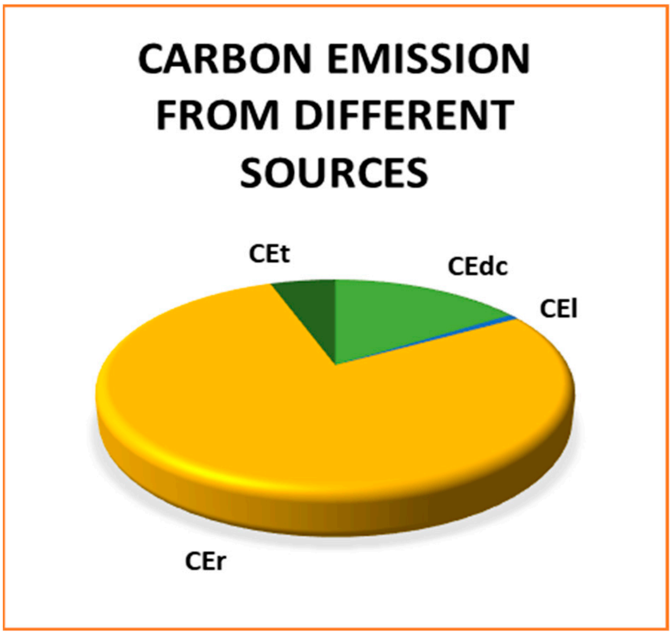


Figure 4. Carbon emission from different sources.

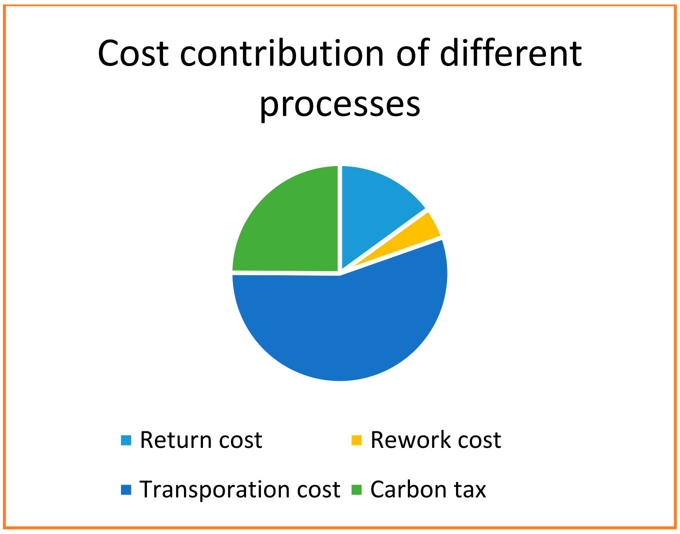


Figure 5. Cost contribution of different processes.

Table 5. Effect of the return articles from the secondary market on total cost and total carbon emissions.

	Paj			
	20%		−20%	
GSaj	**TC ($)**	**CE (Kg)**	**TC ($)**	**CE (Kg)**
20%	123,933.6	25,459.8	86,852.6	16,106.8
−20%	86,852.6	16,106.8	62,132.0	9871.5

Table 6. Sensitivity analysis of the cost and distance parameters.

Parameter		TC	CE	Parameter		TC	TE
L_{dc}	160	89,869.6	16,813.1	CDC_i	8	89,936.7	16,886.2
	200	89,942.7	16,886.2		10	89,942.7	16,886.2
	240	90,015.9	16,959.4		12	89,948.7	16,886.2

Table 6. *Cont.*

Parameter		TC	CE	Parameter		TC	TE
	240	80,055.9	16,802.2		9.8	89,920.7	16,886.2
L_r	300	89,942.7	16,886.2	TWC_i	12	89,942.7	16,886.2
	360	99,829.5	16,970.2		14.4	89,966.7	16,886.2
	200	89,927.7	16,871.2		3.2	87,301.1	16,886.2
L_l	250	89,942.7	16,886.2	RC_a	4	89,942.7	16,886.2
	300	89,957.7	16,901.2		4.8	92,584.3	16,886.2
	160	89,896.1	16,839.6		4	89,125.8	16,886.2
L_{j1}	200	89,942.7	16,886.2	C_r	5	89,942.7	16,886.2
	240	89,989.3	16,932.8		6	90,759.6	16,886.2
	200	89,896.7	16,840.2		4	80,139.9	16,886.2
L_{j2}	250	89,942.7	16,886.2	T_n	5	89,942.7	16,886.2
	300	89,988.8	16,932.3		6	99,745.5	16,886.2
	180	89,897.2	16,840.7		0.8	85,545.5	16,886.2
L_{j3}	225	89,942.7	16,886.2	C_t	1	89,942.7	16,886.2
	270	89,988.2	16,931.7		1.2	94,340.0	16,886.2
	240	89,887.7	16,831.2		48	89,642.7	17,762.2
L_{j4}	300	89,942.7	16,886.2	I	60	89,942.7	16,886.2
	360	89,997.7	16,941.2		72	90,242.7	16,082.2
	280	89,873.8	16,817.3		0.008	89,942.7	16,706.2
L_{j5}	350	89,942.7	16,886.2	σ	0.01	89,942.7	16,886.2
	420	90,011.7	16,955.2		0.012	89,942.7	17,066.2
	40	10,2482.0	17,172.0		3.2	89,942.7	18,086.2
V	50	89,942.7	16,886.2	μ	4.0	89,942.7	16,886.2
	60	81,586.3	16,698.8		4.8	89,942.7	15,686.2
	16	86,675.1	13,618.6		0.24	95,880.4	18,272.6
CE_r	20	89,942.7	16,886.2	μ_r	0.3	89,942.7	16,886.2
	24	93,210.3	20,153.8		0.36	84,005.0	15,499.8
	0.8	89,709.3	16,652.8		0.4	89,907.7	16,851.2
CE_{dc}	1	89,942.7	16,886.2	CE_l	0.5	89,942.7	16,886.2
	1.2	90,176.1	17,119.6		0.6	89,977.7	16,921.2

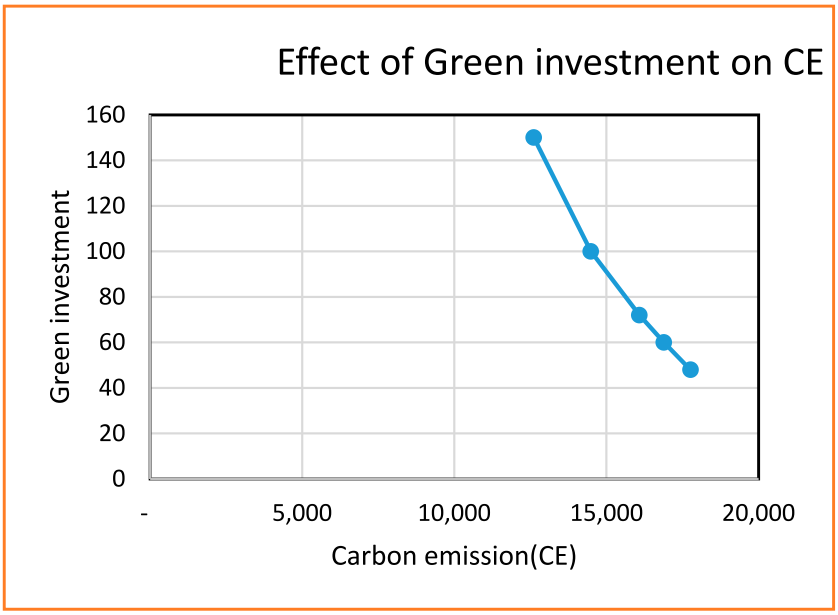


Figure 6. Effect of green technology on CE.

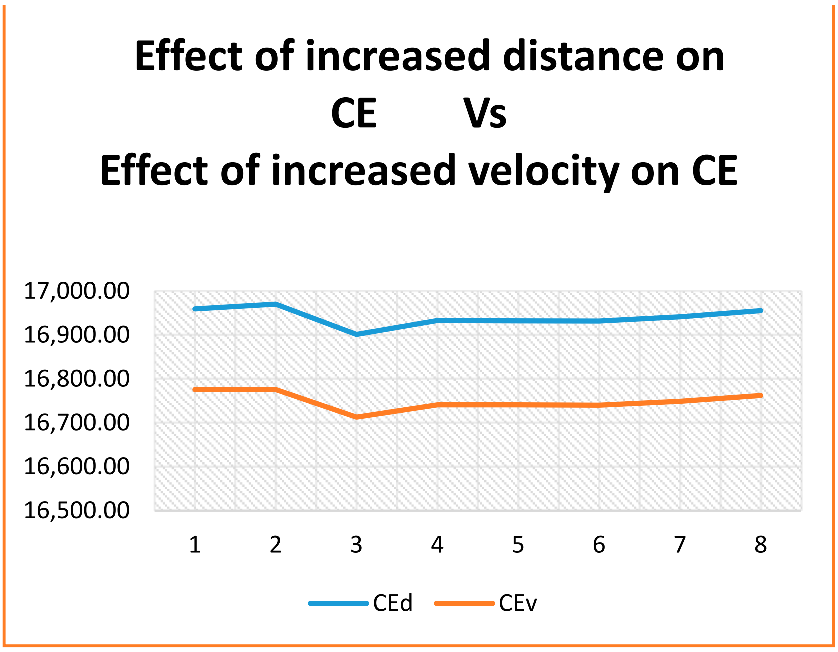


Figure 7. Effect of increased distance on CE vs. effect of increased velocity on CE.

6.4. Managerial Implications

This research aims to present a decision-making strategy in a reverse cross-docking model for returned articles. By presenting a thorough analysis of the different parameters affecting the total cost and carbon emissions, the model suggests to the decision-makers in the fashion industry that returns should be minimized to limit emissions associated with transportation. Boxes transferred to the secondary outlet should have a very high matching percentage with the product demand so that the number of return articles is reduced (Table 2). More emphasis on proper labelling of the box and on its contents should be laid. Transportation being a major contributor to cost and carbon emissions, decision makers could encourage increased use of sustainable transport, decarbonizing road freight transport, and choosing local markets and rework centers. The use of Hydrogen fuel cells for heavy-duty trucks and the switch to renewable biofuels like ethanol and biodiesel could prove to be major breakthroughs in reducing the carbon emission from transportation. The price of electric batteries being reduced by 90% will help to shift to electric vehicles powered by renewable electricity, such as wind or solar, for transportation rather than internal combustion engines. Fashion managers can improve their efficiency by shifting to less carbon-intensive fibers which may reduce carbon emissions during rework and recycling.

7. Concluding Remarks

Companies are attempting to address the problems related to carbon because of rising environmental concerns. The fashion industry, which is responsible for emitting a gigantic amount of carbon during its various processes, faces a lot of pressure to control GHG emissions. In this study, we focus on reducing carbon emissions as well as optimizing the total cost of managing the return articles from the primary market and secondary market through reverse cross-docking. In this study, two different models are explored in order to examine scenarios with and without investments in green technologies and the development of a carbon tax and strict carbon cap policy. Reworking, disposal, warehousing, and logistical operations all produce carbon emissions.

The results of the quantitative study show that Investing in green technology definitely increases the total cost by nearly 2%, but it also brings a noticeable drop of 23% in carbon emissions. More investment leads to more carbon reduction. The findings of this study suggest that total cost can be controlled when the number of returned articles from primary markets and secondary outlets is reduced. Less return articles would reduce the return cost as well as the total cost and total amount of carbon emitted. Checking the global surplus of items in the secondary outlet as well as the return probability brings a noticeable drop in TC and CE and eradicates the chances of crossing the carbon cap. Considering the defined numerical values, our model establishes that the rework process is a major contributor of greenhouse gases and that investment in green technology is truly capable of reducing carbon emissions. Transportation of the returned articles adds major amounts to TC and CE, but increasing the vehicle velocity and opting for nearby facilities play a phenomenal role in controlling carbon emissions and total cost. The study also suggests that managing the return articles through cross-docking should be more facilitated than traditional warehousing as it reduces the total cost. The study confirms that reduced emissions surely reduce the total cost by affecting the carbon tax.

It is possible to expand on some potential study directions. The first extension of the model can be allowing multiple secondary outlets or vendors with multiple product types. Other carbon caps, carbon trading, and carbon offsets can all be used to reduce carbon emissions. In addition to considering deterministic demand, it is also possible to extend the work to consider random demand. The model has been designed from the perspective of the fashion industry. It can be extended to other types of products. There are also plausible options to consider, including single- and multi-period planning horizons. The return probability of the unsold articles in this model has been determined by considering the mean of the return items in the past. The model can be extended by expressing the return probability and the rework percentage of the articles through fuzzy sets. The cross-docking cost discussed in this model is inclusive of the labor expenses, the cost related to the collection and dispatching of information about returned products, and the carbon emission cost while shifting the returned articles to the secondary outlets. The cross-docking cost and the total cost can be further investigated by considering the impact of these dimensions individually. In our discussed model, carbon emissions have been considered during the stages of transportation, rework, inventory holding at the reverse distribution center and landfilling. Cleaning fabrics while recycling or remanufacturing also contributes to carbon emissions. This could be an interesting aspect to look at to see how the cleaning of fabric during recycling contributes to the total cost and carbon emission amount. Boxes not matching the TP of the secondary outlets and the matching percentage are directed to traditional warehousing. Redesigning the fate of those boxes by processing them through other channels and its impact on total cost and CE could be a new dimension of future research.

Author Contributions: T.M.: methodology, writing—original draft, software, data curation, resources, formal analysis, visualization, writing—review and editing. I.S.: supervision, conceptualization, methodology, validation, investigation, resources, writing—review and editing, project administration, visualization. B.S.: conceptualization, resources, supervision, validation, data curation, formal analysis, resources, visualization, writing—review and editing, methodology, investigation. Q.A.: investigation, project administration, validation, writing—review and editing, fund acquisition. T.M.A.: investigation, project administration, validation, writing-review and editing, fund acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to express their gratitude to the Gulf University in Bahrain for continuing to encourage academic excellence and scientific research. All authors are very thankful to the reviewers for their valuable suggestions and comments.

Conflicts of Interest: The authors declare there are no conflict of interest.

Abbreviations

The subsection represents the notation used in the formulation of this model. Indices, decision variables, and parameters have been included in the notation.

Indices	
a	index for articles a = 1, 2, 3 . . . A
i	index for boxes i= 1, 2, 3 . . . I
j	index for oulets j= 1, 2, 3 . . . J
Parameters	
C_{ai}	Number of units of article a stored in box i
O_{aj}	Number of units of articles a ordered by outlet j
TP	Tolerance percentage of an outlet.
μ_r	Percentage of return articles a to be destroyed.
$1 - \mu_r$	Percentage of return articles a to be reworked.
L_{dc}	Distance between the primary market and the distribution center (km)
L_j	Distance between the distribution center and the secondary outlet j (km)
L_l	Distance to the nearest landfill (km)
L_r	Distance to the local repair/rework center (km)
V	Velocity of the vehicle (km/h)
p_{aj}	Return probability of unsold, excess items from outlet j to the ReDc
CE_{dc}	Carbon emission amount due to inventory holding at the distribution center (kg/unit)
CE_r	Carbon emission amount due to rework (kg/unit)
CE_t	Carbon emission amount due to transportation (kg per km)
CE_l	Carbon emission amount due to landfilling (kg per unit)
TWC_i	Traditional warehousing cost for box i
CDC_i	Crossdocking cost for box i.
RC_a	Return costs for article a. ($/unit)
C_r	Rework cost ($/unit)
T_n	Cost due to transportation of per unit item per unit time to the local repair shop ($/unit/h)
$T_{n'}$	Cost due to transportation of per unit item per unit time from the local repair shop to the ReDc ($/unit/h).
C_t	Carbon emission tax ($/kg)
I	Green investment amount
Decision Variables	
BA_{ij}	1, when a box i is assigned to outlet j and 0 otherwise.
BT_i	1, when a box i is directed to traditional warehousing and 0 otherwise.
SP_{aij}	Number of articles a in box i not ordered by outlet j, i.e., excess articles a.
LP_{aij}	Number of deficient articles a that the box i need to satisfy the ideal product assortment of outlet j. i.e., deficient articles
GS_{aj}	Global surplus: number of surplus articles a sent to outlet j.
GL_{aj}	Global deficient: number of deficient articles a required to satisfy the ideal product assortment of outlet j.
MP_{ij}	Matching percentage of the product content of box i with the requirement of outlet j

$\mathrm{E}[\widehat{RP_{aj}}]$	Estimated number of units of returned article a sent back to the ReDC from an outlet *j*. This variable is assessed from a binomial distribution that relies upon (a) the articles sent in abundance to the power source and (b) a probability *p* laid out by the ReDC. In this way, the normal number of articles returned relates to $\mathrm{E}[\widehat{RP_{aj}}] = GS_{aj} * p_{aj}$

Appendix A

Transportation is one of the major causes of carbon emissions. In this model, the amount of carbon emitted due to transportation is explained for four different scenarios.

The carbon emissions (ton/kilometer) from transportation can be represented as a function of velocity V and expressed as $CE_t = a_0 + a_1 V + a_2 V^3 + \frac{a_3}{V^2}$ (here a_0; a_1; a_2; a_3 are the coefficients depending on vehicle type and size) [50].

Carbon is emitted during the transportation of the returned articles from the primary market to the reverse distribution center.

$$CE_{t1} = (a_0 + a_1 V + a_2 V^3 + \frac{a_3}{V^2}) L_{dc} * \sum_{a=1}^{A} \sum_{i=1}^{I} C_{ai} \tag{A1}$$

Carbon is emitted during the transportation of the returned article from the secondary outlet to the reverse distribution center.

$$CE_{t2} = (a_0 + a_1 V + a_2 V^3 + \frac{a_3}{V^2}) \sum_{a=1}^{A} \sum_{j=1}^{J} (L_j * GS_{aj} * p_{aj}) \tag{A2}$$

Carbon is emitted while transporting the unsold articles to the local remanufacturing/recycling workshop and delivering the reworked article to the reverse distribution center.

$$CE_{t3} = 2[(1 - \mu_r) \sum_{j=1}^{J} \sum_{a=1}^{A} GS_{aj} * p_{aj}\} (a_0 + a_1 V + a_2 V^3 + \frac{a_3}{V^2}) L_r] \tag{A3}$$

Transporting the discarded articles to the landfill also contributes to carbon emissions.

$$CE_{t4} = (a_0 + a_1 V + a_2 V^3 + \frac{a_3}{V^2}) L_l * \mathrm{\mu}_r \sum_{j=1}^{J} \sum_{a=1}^{A} GS_{aj} * p_{aj} \tag{A4}$$

The reworking process of the defective article is another major cause of carbon emissions. Reworking the articles at a local workshop is more economical than shifting the products to their global manufacturer.

$$\text{Emission of rework} = [(1 - \mu_r) \sum_{j=1}^{J} \sum_{a=1}^{A} GS_{aj} * p_{aj}] * CE_r \tag{A5}$$

The discarded articles are dumped into landfills. Some amount of carbon is emitted due to the decomposition of the manufacturing waste.

$$[\mu_r * \sum_{j=1}^{J} (GS_{aj} * p_{aj}) * CE_l] \tag{A6}$$

The returned articles from the secondary market are stored at the reverse distribution center before being sorted and processed through other channels. Carbon emitted due to inventory holding

$$(\sum_{a=1}^{A} \sum_{i=1}^{I} C_{ai} + \sum_{j=1}^{J} \sum_{a=1}^{A} GS_{aj} * p_{aj}) * CE_{dc} \tag{A7}$$

Total carbon emission amount

$$\begin{gathered}\{(a_0+a_1V+a_2V^3+\tfrac{a_3}{V^2})[L_{dc}*\textstyle\sum_{a=1}^{A}\sum_{i=1}^{I}C_{ai}+\sum_{a=1}^{A}\sum_{j=1}^{J}(L_j*GS_{aj}*p_{aj})\\ +2(1-\mu_r)\textstyle\sum_{j=1}^{J}\sum_{a=1}^{A}GS_{aj}*p_{aj}*L_r+L_l*\mu_r\sum_{j=1}^{J}\sum_{a=1}^{A}GS_{aj}*p_{aj}]\\ +[(1-\mu_r)\textstyle\sum_{j=1}^{J}\sum_{a=1}^{A}GS_{aj}*p_{aj}*CE_r+\mu_r\sum_{j=1}^{J}\sum_{a=1}^{A}GS_{aj}*p_{aj}*CE_l+\\ \textstyle\sum_{a=1}^{A}\sum_{i=1}^{I}C_{ai}+\sum_{j=1}^{J}\sum_{a=1}^{A}GS_{aj}*p_{aj}*CE_{dc}]\}\end{gathered} \tag{A8}$$

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