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Multi-Objective Optimization for Economic and Environmental Sustainability in Apparel E-commerce Reverse Logistics

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Abstract
In the realm of supply chains, the necessity of a robust reverse logistics network is paramount. While substantial efforts have been directed towards enhancing forward logistics, the domain of reverse logistics remains underdeveloped. This article presents an approach that centers on the formulation of a reverse logistics network for an Indian e-commerce company specializing in apparel sales. Through the construction of single and multi-objective integer programs, the aim is to simultaneously mitigate economic costs and environmental repercussions. To tactfully address environmental concerns while maintaining cost efficiency, different network designs are proposed via the utilization of multi-objective Integer programs, solved using IBM ILOG CPLEX Optimization Studio an optimization software based upon simplex algorithm. The Environmental-Cost-Efficiency (ECE) framework is used to evaluate the multiple network designs. Scrutinizing the intricate equilibrium between costs and ecological implications, the study ultimately identifies an optimized reverse logistics network that yields maximal returns on investment in terms of environmental impact reduction. This comprehensive exploration of the cost-environment trade-off offers valuable guidance to similar organizations aiming to prudently minimize ecological footprints without compromising financial viability. Just as the reverse logistics network is vital within supply chains, this article underscores the potential of its strategic enhancement in driving eco-friendly and economically efficient practices.

Keywords- E-commerce, Reverse logistics, Integer programming, Multi-objective optimization.

1. Introduction

Reverse Logistics (RL) is defined as “the process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods, and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal" (Rogers and Tibben-Lembke, 1999). Reverse logistics is the utmost governing factor to the business success in the E-commerce industry; it is the cost of doing online retailing business. An online retailer cannot put a board like "no returns," unlike brick-and-mortar stores. The reverse logistics network of any customer market is the customer-faced side of E-commerce. In recent years, there has been an enormous rise in online shopping. This unprecedented rise has resulted in what many call a "commercial revolution"(Future of E-commerce: Dominance over Retail by 2024 - Generix Group, n.d). With the incredible growth in online retail, the number of returns has grown exponentially. The volume and amount handled in reverse logistics have increased to an all-time high. The RL process has a significant economic impact on the e-commerce company. Product returns account for about 8% to 10% of the product's total cost. Return rates in certain businesses, such as apparel and clothing, are much higher than in others.

Returns cause an economic burden on online retailers and damage the environment. According to data from Optoro (2020), e-commerce returns added 2.27 million tons of garbage to landfills and 15 million metric tons of CO2 emissions. Worse yet, the companies are not taking this issue seriously, dismissing it as an economic burden and immaterial to their growth (Turrisi et al., 2013). Because most firms regard RL primarily as a cost, the informal sectors handle RL activities in emerging nations. It is critical to track crucial metrics to develop and implement an effective RL strategy (Bernon et al., 2018). The firms have been focusing only on optimizing the forward logistic network. The RL network is often considered a mirror image of the forward network. However, studies have shown that the optimum RL network must not reflect the forward network.

The e-commerce industry is often left with a much-unsold inventory. The products remain unsold for several reasons, including outdated products and physical damage. For the company, holding items in the inventory is also a cost. At a specific time, holding these products becomes uneconomical; in this situation, the company discards the products. This disposal of products by e-commerce companies is seen as an industry-standard practice. This practice of disposal of products becomes much more prominent in the clothing or apparel industry as the cost of goods is lower compared to other categories, such as electronics. Discarding such items is not much of a financial burden for manufacturers and retailers. In the previous decades, there used to exist markets for such discarded clothing items in several African and Asian counties. With developments in their economies, such markets have become obsolete. The manufacturers and retailers have no option but to dispose of this extra inventory, which severely impacts the environment. This problem isn't limited to one place; it affects the whole world due to the e-commerce industry's growth. Let's focus on India, which is the eighth biggest e-commerce market globally (Global Ecommerce Forecast 2021, 2021). As e-commerce booms in India, it brings both chances and challenges. With the world pushing for eco-friendly practices, it's crucial for India and the e-commerce industry as a whole to start using more environmentally friendly methods in online retail.

The measures currently being taken include innovative packaging materials and electrification of delivery vehicles (Kumar, 2018). Sustainability in the operations should be economical and environmentally friendly so that the industry fosters in the long term. Sustainability will be achieved by optimizing both forward and reverse logistic networks. So far, the focus has been on optimizing the forward network; the reverse network must be given due attention as reverse logistics operations' environmental and economic impacts are severe.

This paper proposes an optimization model for the Reverse Logistic network of an e-commerce company selling clothing items. The proposed model aims to minimize operations costs and the associated environmental damage. Specific objectives of the paper are:

(i) To quantify the economic impact of reverse logistics operations of an online clothing retailer and associated environmental damage.

(ii) To optimize the reverse logistic network to reduce environmental damage in an economical manner.

(iii) To propose multiple RL network designs and compare them against each other.

The present research paper is organized in the following way. Section 2 deals with the literature review, which highlights the present status of reverse logistics in India and at the global level. Section 3 explains the problem and section 4 explains its mathematical formulation. Section 5 is dedicated to methodology and results and is followed by discussion and implications in Section 6. Section 7 presents the conclusion and further scope of research.

2. Literature Review

The global clothing and apparel industry is valued at $2 trillion. It contributes to over 2% of global GDP, but the industry's supply chain accounts for 4% of global total greenhouse gas (GHG) emissions (Business of Fashion & McKinsey & Company, 2021). The direct impact of these complex and global supply chains is most felt in water consumption, energy emissions, waste creation, and chemical usage (One Planet Network, 2021). In 2018, consumers worldwide spent over $2.8 trillion online, representing more than 10% of overall global retail sales. Online retail sales have been growing at around 25% Y-o-Y basis (Hjort et al., 2019). Online fashion retailing has also been growing along the same trend, and the associated environmental impact has increased manifolds.

To reduce this impact, a circular model in fashion/apparel supply chains is the need of the hour. The currently employed models are based on the "take-make-dispose" philosophy and are highly linear. These models do not appear to meet the Sustainable Development Goals (SDGs), which dominate the agenda of policy-makers at a global level (Jacometti, 2019). European Commission's Action Plan defines a Circular Economy (CE) as an economy "where the value of products, materials, and resources is maintained in the economy for as long as possible, and the generation of waste minimized" (European Commission, 2015). A number of global brands such as Zara, Levi's, and H&M are now adopting sustainable practices with initiatives such as Eco-Material preparation, green distribution, and retailing with the "Garment Take Back Program" and thus transitioning to circular models (Shen, 2014; Edvardsson and Enquist, 2011). In India, this shift is being led by groups such as Aditya Birla Fashion Retail Limited (ABFRL), the custodian of leading fashion brands in the country, including Louis Philippe, Van Heusen, Allen Solly, Peter England, and Pantaloons. They focus on the life cycle assessment of their products by shifting to green procurement strategies, which include synthesizing raw materials such as dye from "non-edible agricultural or herbal industry waste, leaving the edible part still available for food consumption"(One Planet Network, 2018). Accenture Strategy & Fashion for Good (2019) have addressed the issue of understanding the financial viability of circular models for established retailers. For this analysis, they did a financial analysis for three circular business models, namely rental, subscription-Rental, R-Ecommerce based on a "bottom-up" approach.

In existing literature and commercial practices, forward logistic routes are well optimized. However, the reverse logistics network and disposal of goods are not paid due attention to, which is a significant barrier in implementing circular models. Today, just 1% of clothing is recycled back, and 73% goes to landfill (Accenture Strategy & Fashion for Good, 2019). Typical return rates are 20–40% which go up to 70% during certain times of the year (Frei et al., 2020). Today major brands take reverse logistics as a burden and dispose of the goods (landfills or incineration) to reduce operating costs, making the currently employed models more linear.

Researchers have undertaken extensive investigations into the realms of reverse logistics and sustainable waste management, addressing various facets of this multifaceted field. Scholars have delved into these topics with the aim of optimizing processes, minimizing environmental impacts, and enhancing the efficient use of resources. For instance, Wang et al. (2021) have recognized the escalating challenge of healthcare waste management resulting from urbanization and population growth. They propose a two-stage reverse logistics network for healthcare waste that integrates a predictive model for waste quantity and a multi-objective model to optimize facility allocation and waste flow control, placing considerable emphasis on cost reduction and mitigating environmental impact.

Furthermore, the role of organized retail in sustainable municipal waste management has gained attention from researchers like Sharma et al. (2021). Their work explores the relatively uncharted territory of reverse logistics practices within organized retail. Employing the TOPSIS method, they rank retailers based on their proficiency in RL practices, highlighting the pivotal significance of key factors in elevating sustainability in the retail sector.

In parallel, several scholars, including Chang et al. (2021), concentrate on the quest for a low-carbon economy and its transformative potential in China. They center their research on optimizing the locations of reverse logistics facilities within a broader logistics network, meticulously balancing carbon emissions and economic benefits. To achieve this, they harness a hybrid multi-objective optimization algorithm and substantiate their model's efficacy with a case study focused on mobile phone recycling logistics in Jilin Province.

Hashemi (2021) addresses the fundamental objective of waste collection, with a strong emphasis on safeguarding the environment and public health. Their research navigates the complexities of waste collection and addresses the challenges associated with simultaneously balancing costs and customer demand, contributing substantially to the sustainable management of waste. Hashemi (2021) adopts a fuzzy mathematical programming approach to construct a multi-objective model for a reverse logistics network.

In the quest for more sustainable waste management and reverse logistics practices, scholars have explored various dimensions, as illustrated by Zhang et al. (2021). They grapple with the Multiple Vehicle Routing Problem with Simultaneous Pickup and Delivery with Time Windows in B2C e-commerce logistics. Zhang et al. (2021) develop a mixed-integer non-linear programming model and leverage both exact optimizations using CPLEX and metaheuristic algorithms like DE, Par-DE, GA, and BBGA to optimize transportation costs and penalties for service provider delays. Nanayakkara et al. (2022) have introduced a three-stage circular reverse logistics framework aimed at addressing various aspects of e-commerce returns while optimizing the associated network. Kannan et al. (2023) have developed a multi-objective mixed integer programming (MOMIP) model to optimize the design of a reverse logistics network, considering various factors such as multiple products, recovery facilities, processing technologies, and vehicle types, and validated their model with a real-life case study of an electronics manufacturing company in India. Their study provides a comparative analysis of the results, contributing significantly to the evolving landscape of sustainable reverse logistics in e-commerce.

Fu et al. (2021) have cast a spotlight on closed-loop supply chains (CLSC), which are recognized for their environmental benefits. Their research underscores the need for more comprehensive studies in this field, which often focuses on homogeneous CLSC products and dyadic structures involving single entities. The authors propose a novel coupled CLSC network model designed for heterogeneous products with varying market demands. This innovative approach highlights the recycling of end-of-life products to extract raw materials for the reverse supply chain, resulting in the production of different products. By examining CLSC network equilibriums, considering factors such as market size, raw material costs, and consumer environmental awareness, the research provides valuable managerial insights into optimizing CLSC networks, fostering sustainability.

In the pursuit of efficient and sustainable reverse logistics, scholars have explored a variety of methodologies, with most researchers focusing on obtaining utility from goods nearing the end of their life cycles, this has been studied in a great detail by Ding et al. (2023) for construction industry and Mu et al. (2023) for retired new energy vehicle power batteries. These endeavors extend beyond theoretical discussions, as illustrated by Guo et al. (2017), who have meticulously planned two-stage forward and reverse logistics networks. They strategically address the challenge of minimizing costs in the context of Shanghai's fresh food E-commerce enterprises by employing genetic algorithms and Particle Swarm Optimization techniques. In a similar vein, Bal and Satoglu (2018) have developed a decision-making framework for the recovery of Waste Electric and Electronic Equipment (WEEE) by utilizing a goal programming model and validating their results through a case study.

In conclusion, the research conducted by these scholars has notably advanced sustainable waste management and reverse logistics. However, there remains a critical gap in quantifiable studies, particularly in understanding why many goods are discarded before realizing their utility. The e-commerce industry, in particular, grapples with the challenges of handling returns driven by factors like inaccurate sizes and shifting consumer preferences, which is an area underexplored in existing literature. These findings underscore the growing importance of sustainable waste management and the need for more comprehensive research to address these challenges effectively.

The literature review uncovered four notable gaps in the field of reverse logistics. Firstly, while extensive research has been conducted on the reverse logistics of items like electronics and automobiles, there has been a relative dearth of studies focusing on the reverse logistics of apparel items, despite their substantial environmental impact. Additionally, the majority of existing research in reverse logistics primarily centers on products at the end of their life cycles, with limited attention directed towards products that are returned before they even commence their life cycles. Furthermore, in the context of e-commerce, studies have predominantly emphasized forward logistics networks and packaging, often leaving return handling processes understudied. Finally, the reverse logistics network is frequently overlooked, typically regarded as a mere reflection of the forward network, resulting in inefficiencies that deserve further analysis and improvement. This paper attempts to overcome the above-stated gaps in the literature by proposing a model based on multi-objective linear integer programming to optimize the reverse logistic network of an online clothing retailer based in India. The paper also focuses on the economic feasibility of the sustainable approach adaption.

3. Problem Statement

The present study is based on an Indian e-commerce retailer dealing only with cotton clothing items. The required datasets are taken from the work of Dutta et al. (2020). These data sets were generated through surveys and meetings (both formal and informal), and some essential data were taken from a Maharashtra-based e-commerce company.

3.1 Network Formulation
The retailer services four different markets (namely P, Q, R and S). The forward logistic network of the company is assumed to be well established and fully functional. A reverse logistics network needs to be set up. For setting up the reverse logistic network, facilities to handle returns need to be installed at existing locations: Delivery Hubs (DH) and Fulfillment Centers (FC). Four delivery hubs are present for each customer market (W, X, Y, and Z). And two Fulfillment Centers (parent warehouses, A and B) are also present. Each of the four customer markets has waste disposal facilities in a giant landfill (L1, L2, L3, and L4) or a network of recycling centers (R1, R2, R3, and R4). The flow of material in the RL network is shown in Figure 1. The facilities set up can be either labor-intensive (referred to as Technology 1) or significantly automated (referred to as Technology 2). There is a trade-off between the two technology options: fixed costs against operating costs.

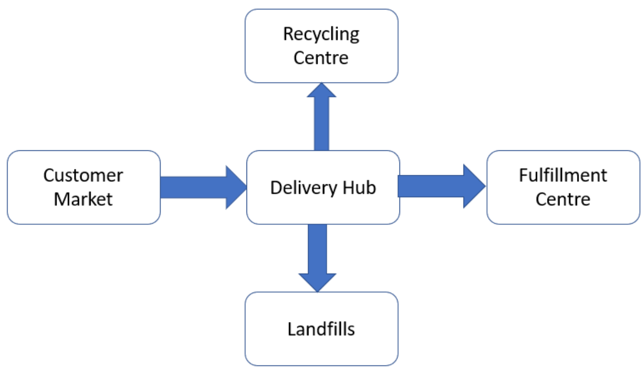


Figure 1. Material flow in the reverse logistics network.

The important details and features of the volume of sales and returns are as follows:
Period: Single period (1 month).
Total demand: 10 million units in single period.
Percentage returns: 10% (Industry average).
The volume of return: 1 million units.
Composition of returns: 60% fit for resale and 40% discarded.

3.2 Data Sets
In order to completely state the problem, a number of datasets are needed. These were generated through surveys and meetings (both formal and informal). Some essential data were taken from a Maharashtra-based online retailing company. The data about distances between various nodes of the RL network is shown below in Table 1. There are two levels of transportation involved in the RL network. Level 1 transportation is for shorter ranges; this includes transportation from the customer market to a delivery hub, delivery hub to landfills and recycling centers. Level 2 transportation is for longer ranges; this includes transportation from delivery hubs to fulfillment centers. The distance in kilometers between the nodes involved in level 1 transportation is shown in Tables 1a, 1b and 1c. Table 1d shows the distance between nodes involved in level 2 transportation. The cost of transportation is assumed to be Rs. 0.1 per kilometer, was determined through data collection from three major courier service providers, averaging the charges for half-kilogram parcels across various source and destination combinations. This figure is considered conservative, as it is based on retail rates rather than the discounted rates businesses receive due to high volume (Gupta et al., 2018).

After the transportation cost has been accounted for, operating costs must be considered. Operating the RL network includes the fixed cost of establishing facilities and processing costs. The processing cost includes the wages paid to the workers and the cost of electricity. The costs associated with the delivery hubs: fixed costs and wages are shown in the table, and the costs associated with fulfillment centers are shown in Table 2. Electricity consumption depends on the level of automation at the facility. For delivery hubs with a lower level of automation (Technology 1), 0.55 units of electricity (KWh) are needed to process one order for the hubs with significant automation (Technology 2) 0.85 units are needed. The cost of electricity is taken to be Indian Rupees (INR) 10 per unit, which is approximately equal to the commercial cost of electricity in India.

Table 1. Distances between various nodes of the reverse logistics network.

(a) Distances between customer markets and delivery hubs

		Delivery Hubs (Km)			
Customer Markets		**W**	**X**	**Y**	**Z**
	P	1	1400	1450	2200
	Q	1400	1	2000	1300
	R	1450	2000	1	1650
	S	2200	1300	1650	1

(b) Distances between delivery hubs and recycling centers

		Recycling Centers (Km)			
Delivery Hubs		**R1**	**R2**	**R3**	**R4**
	P	50	1400	1450	2200
	Q	1400	50	2000	1300
	R	1450	2000	50	1650
	S	2200	1300	1650	50

(c) Distances between delivery hubs and landfills

		Landfill (Km)			
Delivery Hubs		**L1**	**L2**	**L3**	**L4**
	W	10	1400	1450	2200
	X	1400	10	2000	1300
	Y	1450	2000	10	1650
	Z	2200	1300	1650	10

(d) Distances between delivery hubs and fulfillment centers

		Delivery Hubs (Km)	
Delivery Hubs		**A**	**B**
	W	20	2100
	X	1400	1000
	Y	1450	1850
	Z	2200	350

Table 2. Fixed cost of establishing facility to handle returns at delivery hubs.

Delivery Hub	Fixed Cost with Technology 1 (INR)	Fixed Cost with Technology 2 (INR)
W	1,73,40,000	2,23,40,000
X	1,71,00,000	2,21,00,000
Y	1,63,00,000	2,13,00,000
Z	1,69,00,000	2,19,00,000
Delivery Hub	**Labor Cost with Technology 1 (INR)**	**Labor Cost with Technology 2 (INR)**
W	18,00,000	11,25,000
X	18,00,000	11,25,000
Y	12,50,000	7,81,250
Z	12,50,000	7,81,250
Fulfillment Center	**Fixed Cost (INR)**	
A	4,33,50,000	
B	3,63,75,000	

To quantify the environmental impacts, Eco-Indicator 99 is used. Eco-Indicator works by assigning a numerical penalty commonly measured in Eco Indicator points to different activities, procedures, energy production, disposal, and usage of material (Eco-indicator 99 | Manuals, 2014); milli points (mPt) is a more practical unit and this has been used here. The values are usually for one ton of material. Hence it is essential to assume the average weight of an item so that penalty can be calculated for each item. Each item’s weight is assumed to be 500 grams; using this, the penalty has been converted from per ton of items to per unit. The environmental penalty in mPt is shown above in Table 3. The table shows that the penalty for short-range (Level 1) transportation is significantly higher than for long-range transportation. Recycling has a negative penalty implying a positive impact on the environment; all the other activities have a positive penalty and thus a negative impact on the environment. The penalty associated with the manufacturing of each unit is also considered as its life cycle ends abruptly once discarded.

Table 3. Fixed cost of establishing facility to handle returns at delivery hubs

Environmental Impact due to	Eco indicator value(mPt)
Level 1 transportation per item	0.07
Level 2 transportation per item	0.017
Disposal of one item at the Landfill	2.1
Recycling of one item at the Recycling Center	-4.1
Generation and consumption of one KWh of electricity in India	160
Manufacturing of one clothing item(Unbleached and Un-dyed)	0.6

4. Problem Formulation

The formulated model aims to reflect the actual Indian major e-commerce companies. The usefulness of using this model grows when we consider the massive impacts of such businesses.

4.1 Indices, Parameters and Variables

Indices:
Four Customer markets, m = P, Q, R, S
Four Delivery hubs, h = W, X, Y, Z
Two fulfillment centers, f = A, B
Four recycling centers, r = R1, R2, R3, R4
Four landfills, l = L1, L2, L3, L4

Parameters:
$\boldsymbol{d}_{i,j}$= distance in kilometres between i and j.
$\boldsymbol{C}_T$ = cost of transportation per unit per km.
$\boldsymbol{C}_E$= cost of electricity per unit (KWh).
$\boldsymbol{F}_h^1$= fixed cost of opening delivery hub 'h' with technology 1.
$\boldsymbol{F}_h^2$= fixed cost of opening delivery hub 'h' with technology 2.
$\boldsymbol{F}_f$= fixed cost of opening fulfillment centre 'f'.
$\boldsymbol{E}^1$= electricity unit consumed in processing one unit at a delivery hub with technology 1.
$\boldsymbol{E}^2$= electricity units consumed in processing one unit at a delivery hub with technology 2.
$\boldsymbol{W}_h^1$= wages paid to workers at delivery hub 'h' with technology 1.
$\boldsymbol{W}_h^2$= wages paid to workers at delivery hub 'h' with technology 2.
$\boldsymbol{O}_h$= capacity of delivery hub 'h'.
$\boldsymbol{O}_f$= capacity of fulfillment centre 'f'.
$\boldsymbol{\beta}_m$= returns originating from customer market 'm'.
$\boldsymbol{e}_{T1}$= environmental impact associated with transport of one unit per km at level 1 transportation.
$\boldsymbol{e}_{T2}$= environmental impact associated with transport of one unit per km at level 2 transportation.
$\boldsymbol{e}_R$= environmental impact associated with recycling of one unit.
$\boldsymbol{e}_L$= environmental impact associated with dumping of one unit in landfill.
$\boldsymbol{e}_E$= environmental impact associated with generation and utilization of one KWh of electricity.
$\boldsymbol{e}_P$= environmental impact associated with production of one unit.

Binary Decision Variables:
$\boldsymbol{\alpha}_h^1$= 0 or 1 indicating opening or closing of delivery hub ’h’ with technology 1.
$\boldsymbol{\alpha}_h^2$= 0 or 1 indicating opening or closing of delivery hub ’h’ with technology 2.
$\boldsymbol{\alpha}_f$= 0 or 1 indicating opening or closing of fulfillment centre ’f’.
Total number of binary decision variables = 10.

Integer Decision variables:
$\boldsymbol{\beta}_{m,h}$= returns coming from market’m’ going to delivery hub’h’
$\boldsymbol{\beta}_{h,f}$= returns coming from delivery hub ’h’ going to fulfillment centre ’f’.
$\boldsymbol{\beta}_{h,r}$= returns coming from delivery hub ’h’ going to recycling centre ’r’.
$\boldsymbol{\beta}_{h,l}$= returns coming from delivery hub ’h’ going to landfill ’l’.
Total number of integer decision variables = 56.

4.2 Objective Functions

Economic Objective Function

This function simply adds all of the costs associated with the reverse logistics supply chain. The economic objective function (Z1) is the sum of costs incurred in the following:

Fixed Cost of opening delivery hub ($\boldsymbol{a_1}$)

$$\boldsymbol{a_1} = \Sigma\boldsymbol{\alpha}_h^1 * \boldsymbol{F}_h^1 + \Sigma\,\boldsymbol{\alpha}_h^2 * \boldsymbol{F}_h^2 \forall h \tag{1}$$

Cost of transportation from market to a delivery hub ($\boldsymbol{a_2}$)

$$\boldsymbol{a_2} = \boldsymbol{C}_T * \Sigma\boldsymbol{\beta}_{m,h} * \boldsymbol{d}_{m,h} \forall h, m \tag{2}$$

Fixed cost of opening fulfilment center ($\boldsymbol{a}_3$)

$$\boldsymbol{a}_3 = \Sigma\boldsymbol{\alpha}_f * \boldsymbol{F}_f \qquad \forall f \tag{3}$$

Cost of transportation from delivery hub to fulfilment center ($\boldsymbol{a}_4$)

$$\boldsymbol{a}_4 = \boldsymbol{C}_T * \Sigma\boldsymbol{\beta}_{h,f} * \boldsymbol{d}_{h,f} \qquad \forall h, f \tag{4}$$

Cost of transportation from delivery hub to a recycling center ($\boldsymbol{a}_5$)

$$\boldsymbol{a}_5 = \boldsymbol{C}_T * \Sigma\boldsymbol{\beta}_{h,r} * \boldsymbol{d}_{h,r} \qquad \forall h, r \tag{5}$$

Cost of transportation from delivery hub to landfill ($\boldsymbol{a}_6$)

$$\boldsymbol{a}_6 = \boldsymbol{C}_T * \Sigma\boldsymbol{\beta}_{h,l} * \boldsymbol{d}_{h,l} \qquad \forall h, l \tag{6}$$

Cost of electricity consumed ($\boldsymbol{a}_7$)

$$\boldsymbol{a}_7 = \boldsymbol{C}_E * \Sigma\boldsymbol{\alpha}_h^1 * \boldsymbol{E}^1 + \boldsymbol{C}_E * \Sigma\boldsymbol{\alpha}_h^2 * \boldsymbol{E}^2 \forall h \tag{7}$$

Wages paid to workers at delivery hubs ($\boldsymbol{a}_8$)

$$\boldsymbol{a}_8 = \Sigma\boldsymbol{\alpha}_h^1 * \boldsymbol{W}_h^1 + \Sigma\boldsymbol{\alpha}_h^2 * \boldsymbol{W}_h^2 \forall h \tag{8}$$

The goal is to do reduce the cost of reverse logistics operations. Hence, the economic objective function is:

$$Min\ Z1 = \boldsymbol{a_1} + \boldsymbol{a_2} + \boldsymbol{a}_3 + \boldsymbol{a}_4 + \boldsymbol{a}_5 + \boldsymbol{a}_6 + \boldsymbol{a}_7 + \boldsymbol{a}_8 \tag{9}$$

Environmental Objective Function

The Eco-Indicator 99 methodology (Eco-indicator 99 | Manuals, 2014) is used to quantify the environmental damage. The damage is measured in eco-indicator points, this technique is far more concise than the original LCA methodology. The environmental objective function (Z2) is the sum of eco-indicator points incurred in the following:

Transportation from customer markets to Delivery Hubs ($\boldsymbol{b}_1$)

$$\boldsymbol{b}_1 = \boldsymbol{e}_{T1} * \Sigma\boldsymbol{\beta}_{m,h} * \boldsymbol{d}_{m,h} \qquad \forall m, h \tag{10}$$

Transportation from Delivery Hubs to either disposal center or fulfilment center ($\boldsymbol{b}_2$)

$$\boldsymbol{b}_2 = \boldsymbol{e}_{T2} * \Sigma\boldsymbol{\beta}_{h,f} * \boldsymbol{d}_{h,f} + \boldsymbol{e}_{T1} * \Sigma\boldsymbol{\beta}_{h,r} * \boldsymbol{d}_{h,r} + \boldsymbol{e}_{T1} * \Sigma\boldsymbol{\beta}_{h,l} * \boldsymbol{d}_{h,l} \forall h, f, r, l \tag{11}$$

Dumping of items in a landfill ($\boldsymbol{b}_3$)

$$\boldsymbol{b}_3 = \boldsymbol{e}_L * \Sigma\boldsymbol{\beta}_{h,l} \qquad \forall h, l \tag{12}$$

Recycling the items ($\boldsymbol{b}_4$)

$$\boldsymbol{b}_4 = \boldsymbol{e}_R * \Sigma\boldsymbol{\beta}_{h,r} \qquad \forall h, r \tag{13}$$

Generation and utilization of electricity ($\boldsymbol{b}_5$)

$$\boldsymbol{b}_5 = \boldsymbol{e}_E * \boldsymbol{\alpha}_h^1 * \boldsymbol{E}^1 + \boldsymbol{e}_E * \Sigma\boldsymbol{\alpha}_h^2 * \boldsymbol{E}^2 \forall h \tag{14}$$

Manufacturing of clothing items ($\boldsymbol{b}_6$)

$$\boldsymbol{b}_6 = \boldsymbol{e}_P * \Sigma(\boldsymbol{\beta}_{h,l} + \boldsymbol{\beta}_{h,r}) \qquad \forall h, l, r \tag{15}$$

The goal is to do reduce the environmental damage caused due to reverse logistics operations.

Hence, the economic objective function is:

$$Min\ Z2 = \boldsymbol{b}_1 + \boldsymbol{b}_2 + \boldsymbol{b}_3 + \boldsymbol{b}_4 + \boldsymbol{b}_5 + \boldsymbol{b}_6 \tag{16}$$

4.3 Constraints

The objective functions described above in equations 9 and 16 are subject to the following constraints:

Equation (17) below ensures that a delivery hub has only of the two available technologies, either manual or automated.

$$\boldsymbol{\alpha}_h^1 + \boldsymbol{\alpha}_h^2 \leq 1 \qquad \forall h \tag{17}$$

Equation (18) below ensures that all the return orders originating from different customer markets are picked up.

$$\Sigma_h \boldsymbol{\beta}_{m,h} - \boldsymbol{\beta}_m = 0 \qquad \forall m \tag{18}$$

Equation (19) below ensures that allocation is not done at delivery hubs which are closed.

$$\boldsymbol{\alpha}_h * \boldsymbol{O}_h - \Sigma_m \boldsymbol{\beta}_{m,h} \geq 0 \qquad \forall h \tag{19}$$

Equation (20) below ensures that 60% of all returns arrived at a particular delivery hub 'h' must be sent to either of the two fulfilment centers.

$$\Sigma_f \boldsymbol{\beta}_{h,f} - 0.6 * \left(\Sigma_m \boldsymbol{\beta}_{m,h}\right) = 0 \quad \forall h \tag{20}$$

Equation (21) below ensures that allocation is not done at fulfilment centers which are closed.

$$\boldsymbol{\alpha}_f * \boldsymbol{O}_f - \Sigma_h \boldsymbol{\beta}_{h,f} \geq 0 \qquad \forall h \tag{21}$$

Equation (22) below ensures that 40% of all returns arrived at a particular delivery hub 'h' are being sent to either a recycling center or landfill.

$$\Sigma_r \boldsymbol{\beta}_{h,r} + \Sigma_l \boldsymbol{\beta}_{h,l} - 0.4 * \Sigma_m \boldsymbol{\beta}_{m,h} = 0 \quad \forall h \tag{22}$$

5. Methodology and Results

Since the problem is linear in nature, Integer Linear Programming (ILP) is used to solve it. The proposed model is similar to the one developed by Chopra (2012). ILP is employed in single and multi-objective optimization because of its simplicity and robustness. IBM® ILOG® CPLEX® Optimization Studio is employed to solve the mathematical model.

5.1 Single Objective Optimization

Single objective optimization of Pure Economic (Z1) and Pure Environmental (Z2) objective functions will be done separately first. Single objective optimization will give us the most economical and most eco-friendly solutions. The results of single objective optimization are shown below in Table 4.

Table 4. Results of single objective optimization

Min. Z1(Pure Economic objective)	
Minimum economic cost (Indian Rupees)	18,74,35,149
Corresponding environmental cost (mPt)	11,83,96,635
Min. Z2(Pure Environmental objective)	
Minimum environmental cost (mPt)	9,50,79,989
Corresponding economic cost (Indian Rupees)	20,23,01,181

From the above table, a clear trade-off between economic and environmental costs is observed, implying that the environmental cost associated with the most economical solution is the highest and vice-versa. This gives the maximum and minimum values of the economic and environmental costs, which are used to normalize the objective functions on a linear scale, as explained in equation 23 where Z is normalized objective function and Z is actual objective function.

$$Z' = \frac{Z - Z_{min}}{Z_{max} - Z_{min}} \tag{23}$$

5.2 Multi Objective Optimization

The objective function for multi-objective optimization is the linear combination of the two normalized pure objective functions (Z1' and Z2'). The objective function (Z') is explained in equation 24, where α is the weightage given to economic objective.

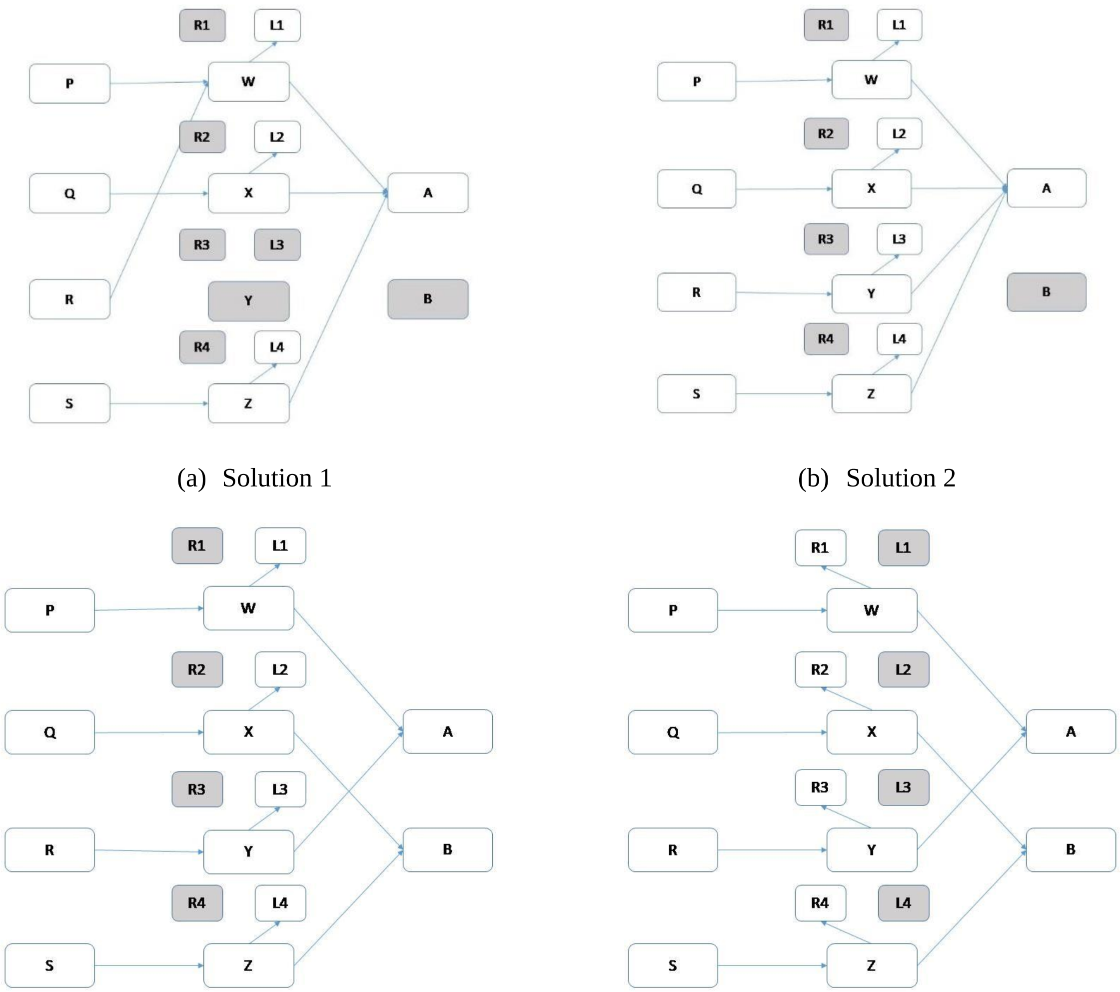
$$Min\ Z' = \boldsymbol{\alpha} * \boldsymbol{Z1}' + (1 - \boldsymbol{\alpha}) * \boldsymbol{Z2}' \tag{24}$$

A single optimum solution is usually not obtained in a multi-objective optimization problem. Instead, a set of "non-inferior" solutions having trade-offs is obtained (Wang and Rangaiah, 2017). The objective function (Z) for the multi-objective optimization problem was changed by varying the weights given to the pure economic and environmental objectives. The solutions were obtained by varying the value of α from 1 to 0 at intervals of 0.1. The solutions obtained are shown below in Table 5; from the table four unique solutions are identified.

Table 5. Results of multi objective optimization.

Value of α	Environmental cost(mPt)	Economic cost(|Rupees)	
1.0	11,83,96,635	18,74,35,149	**Solution 1**
0.9	11,83,96,635	18,74,35,149	
0.8	11,83,96,635	18,74,35,149	
0.7	11,83,96,635	18,74,35,149	
0.6	10,18,41,336	19,60,98,792	**Solution 2**
0.5	10,18,41,336	19,60,98,792	
0.4	10,18,41,336	19,60,98,792	
0.3	9,64,39,987	20,07,01,197	**Solution 3**
0.2	9,50,79,989	20,23,01,181	**Solution 4**
0.1	9,50,79,989	20,23,01,181	
0.0	9,50,79,989	20,23,01,181	

The RL networks corresponding to the four unique solutions are shown in Figure 2. The nodes which are closed are shaded in grey.



(a) Solution 1

(b) Solution 2

(c) Solution 3

(d) Solution 4

Figure 2. Different RL networks for various values of α.

In Solution 1 (Figure 2(a)); Recyclingcenters are not used, all the disposal is done at landfills. The delivery hub "Y" and fulfillment center "B" is closed. In Solution 2 (Figure 2(b)); Recycling centers are not used, all the disposal is done at landfills. All the delivery hubs are being used and fulfillment center "B" is closed. In Solution 3 (Figure 2(c)); Recycling centers are not used, all the disposal is done at landfills. All the delivery hubs and fulfillment centers are being used to save the environmental cost. In Solution 3 (Figure 2(d)); Landfills are not used, all the disposal is done at recycling centers. All the delivery hubs and fulfillment centers are being used to reduce environmental penalty.

It is also important to analyze different components of the cost and environmental damage so that the areas of improvement can be diagnosed. The significant cost components are transportation, fixed expenses, labor, and electricity, shown in Table 6. The major components of environmental damage are damage due to transportation, disposal, generation, and consumption of electricity and apparel manufacturing, which is shown in Table 7.

Table 6. Different components of economic cost.

	Solution 1	**Solution 2**	**Solution 3**	**Solution 4**
Transportation Cost (INR)	82 Million	74 Million	42 Million	43 Million
Fixed Cost (INR)	95 Million	111 Million	147 Million	147 Million
Labor Cost (INR)	5 Million	6 Million	6 Million	6 Million
Electricity Cost (INR)	5 Million	5 Million	5 Million	5 Million

Table 7. Different components of environmental penalty.

	Solution 1	**Solution 2**	**Solution 3**	**Solution 4**
Penalty due to Transportation (mPt)	29 Million	12 Million	7 Million	8 Million
Penalty due to Disposal (mPt)	0.84 Million	0.84 Million	0.84 Million	-1.64 Million
Penalty due to Electricity (mPt)	88 Million	88 Million	88 Million	88 Million
Penalty due to Manufacturing (mPt)	0.24 Million	0.24 Million	0.24 Million	0.24 Million

5.2 Trade-off Analysis

The previous results show that the RL network’s cost cannot be decreased without increasing the environmental damage and vice versa. Therefore, a straightforward trade-off between cost and environmental damage exists. The set of solutions forms a Pareto front, as shown below in Figure 3.

Assuming the most economic network (Solution 1) to be the current strategy, the following important observations can be made about the multiple solutions:
Solution 2 proposes to reduce environmental costs by 13.98% with 4.62% additional expense.
Solution 3 proposes to reduce environmental costs by 18.54% with 7.08% additional expense.
Solution 4 proposes to reduce environmental costs by 19.69% with 7.93% additional expense.

The different solutions will be evaluated against each other using the Environmental Cost Efficiency framework. This works by comparing the environmental benefits and difference in costs by calculating the Environmental Cost Efficiency (ECE) index. The ECE index is defined as the" ratio between value-added and environmental impact added" (Scholz and Wiek, 2005). The standard methods of measuring trade-offs do not apply to the present case as this has an analogy with the end-of-pipe emissions. It is challenging for a reverse logistic network to be financially and environmentally viable. The e-commerce retailer must build the network and reduce the impact on the environment on account of some economic costs. Generally, any solution to reduce end-of-pipe emissions is targeted to have a reduced environmental impact and there is no monetary gain expected.

ECE index is calculated for solutions selected pairwise: for solution 1 & 2 ECE index is 1.91, for solution 2 & 3 ECE index is 1.17 and for solution 2 & 3 it is 0.85. Maximum cost efficiency is obtained when moving to solution two from solution one. The ECE index value decreases as we move towards solution four implying diminishing marginal environmental benefits. The high value of the ECE index implies a higher reduction in environmental damage per extra rupee spent or a better Return on Investment (ROI).

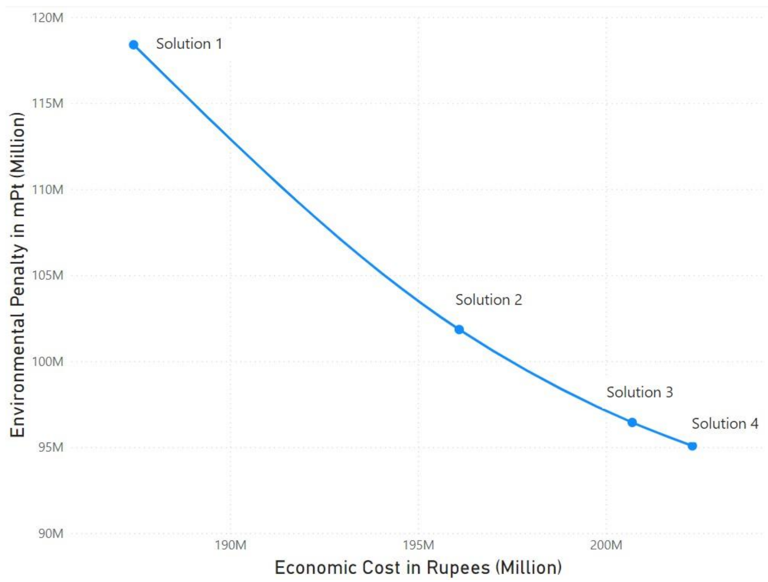


Figure 3. Pareto Optimal front of the different solutions obtained.

6. Discussion and Implications

The results of our study present multiple solutions for optimizing the reverse logistics network, each with varying environmental and cost implications. We begin with the baseline solution, Solution 1, which represents the current strategy and serves as our point of reference. Our analysis delves into the environmental and economic consequences of transitioning to alternative network configurations, namely Solutions 2, 3, and 4.

Solution 2, although incurring an additional expense of 4.62%, demonstrates a noteworthy reduction in environmental costs, amounting to 13.98%. This configuration prioritizes environmental sustainability by utilizing all delivery hubs while closing the fulfillment center "B." In a similar vein, Solution 3 goes a step further by achieving an 18.54% reduction in environmental costs, albeit with a 7.08% increase in expenses. Here, we observe a commitment to environmental responsibility as all delivery hubs and fulfillment centers are engaged to minimize the network's environmental footprint. Finally, Solution 4 emerges as the most promising in terms of environmental sustainability, reducing costs by 19.69%, though with a 7.93% added expense. This alternative optimally balances both environmental and economic considerations, favoring the utilization of recycling centers over landfills.

Our findings emphasize the significance of striking a balance between environmental sustainability and economic considerations in optimizing reverse logistics networks. Each solution represents a trade-off between environmental benefits and additional costs, and the choice of the most suitable network configuration should align with the organization's specific goals and priorities in achieving a sustainable and efficient reverse logistics system.

6.1 Managerial Implications
Managers who design reverse supply chains and formulate "operation strategies" could use the proposed model as a key criterion. The paper employed mathematical optimization techniques to provide decision-makers with a solution space. The final decision may be made based on the availability of funds, damage control legislation, or the availability of carbon credits. Trade-off analysis provides insights into the most effective utilization of their funds and indicates to the firm what maximum utility can be achieved. Different components of the economic and environmental costs provide a diagnostic view into the areas whose contribution to damage is high; this diagnostic view into the problem can be very well used to establish financially sustainable and greener reverse supply chains.

6.2 Theoretical Implications
The present study quantified the impacts of reverse logistic operations and proposed multiple supply chain network designs. Integer programming was used to optimize the network designs. The present study proposed reverse supply chains with a lesser environmental footprint. This work contributes to the literature on the sustainability of reverse supply chains of online retailers. The present research gathered information from Indian academic institutions and businesses. Future research can examine these concerns on a worldwide basis. Future research can be conducted employing advanced and powerful techniques that reduce the time required for solution. The present study was mostly concerned with a specific category of commodities; future research may examine this approach for a broader range of products.

7. Conclusions
The present study has made significant contributions to the field of reverse logistics and supply chain network design. By quantifying the impacts of reverse logistics operations and proposing multiple supply chain network designs, our research aims to enhance the sustainability of reverse supply chains. We employed integer programming to optimize these network designs, with a particular focus on reducing the environmental footprint of reverse logistics operations. This study highlights a critical trade-off between economic and environmental costs within reverse logistics operations. The findings underscore the challenges of optimizing reverse supply chains to minimize environmental impact while managing costs.

However, it is important to acknowledge the shortcomings of our study. The research primarily focuses on Indian retail businesses and a specific category of commodities, namely apparel. This limited scope restricts the generalizability of our findings to a global scale and other product categories. Additionally, our study is confined to a single period, and further research can explore the dynamics of reverse logistics networks over multiple periods. Looking ahead, future research endeavors can expand the scope of investigation to encompass a wider range of products and examine the challenges and opportunities presented by reverse logistics on a global basis. Moreover, the use of advanced and efficient techniques can expedite the solution process, enabling quicker decision-making for organizations seeking to enhance the sustainability of their reverse logistics networks.

In conclusion, our study offers multiple solutions for optimizing reverse logistics networks, each with distinct environmental and cost implications. These solutions provide organizations with the flexibility to align their network configuration with their specific sustainability goals and economic priorities. By striking a balance between environmental responsibility and cost efficiency, organizations can work towards establishing a more sustainable and efficient reverse logistics system that benefits both their operations and the environment.

Conflict of Interest
The authors confirm that there is no conflict of interest to declare for this publication.

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