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# Modelling and optimisation of sustainable production model with screening and carbon awareness for manufacturing industry

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**Abstract:** The awareness of environmental issues has resulted in remanufacturing and repurposing rules in the industrial sector. An ecological concern is carbon emission and the implementation of an appropriate carbon policy on manufacturing might assist to reduce emissions. Another significant factor is screening for industry is to improve the quality of the product, this work achieves various targets of sustainable development goals (SDG9 and SDG11). Over a finite time horizon, the manufacturing-remanufacturing framework with carbon emission costs and screening costs for a single product, like electronic gadgets is consider and some defective units produced during the manufacturing and continually moving into the remanufacturing. Also, this study provides the sustainable production model with screening cost and a carbon policy to decrease carbon emissions and resulting an optimal total profit of the system. To ensure the model's stability, an illustration and sensitivity analysis for significant factors of the model have been presented.

**Keywords:** optimisation; reverse logistics; sustainable production; defective items; carbon emission; screening.

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## 1 Introduction

In a world, where the population is growing and eco-friendly assets high demand, firms confront the problem of satisfying customer demands while also exploring innovative techniques for making things effective and secure. Green manufacturing may increase the market economy, boost customer favourability and subsequently improve the market share by encouraging the sustainable improvement of businesses. As a result, several firms have started to spend on environment friendly goods. To improve sustainable growth and achieve economic benefits over the long run, firms have developed sustainable supply chain strategies in response to the public interest in sustainable products and growing consumer knowledge of environmental issues. Long term viability of any industry depends on effective systems for collecting, recycling and disposing of waste. To remain successful in today's globalised, highly competitive world, firms must be able to recognise and target different market possibilities.

Numerous organisations and countries are making tremendous efforts to enhance their environmental management abilities and resource usage efficiency because of the rising scarcity of natural resources and the degradation of their human living conditions. As the result of global concern over environmental damage, depletion of resources ecological disparity, these concerns have attracted worldwide attention. When it comes to sustainable social development, the traditional supply chain for manufacturing is no longer able to keep up with economic growth with consumer awareness of environmental safety. Therefore, sustainable supply chain management, which reflects environmental conservation and sustainability of resources, appears because of the need for time.

For many sectors, waste clean-up in a manufacturing process under sustainable supply chain management is a major concern. To keep up with customer awareness of environmental sustainability and their preferences for low-carbon commodities, industries are required to mitigate their carbon emissions. Because of this, several industries are increasingly focusing on reducing carbon emissions and attempting to develop strategies to do it. For any sustainable management, maintaining the carbon emission while improving product quality in manufacturing is very essential. Now manufacturers consider carbon emission as one of the most significant factors affecting manufacturing decisions as a result of a better understanding of the necessity to protect the natural ecosystem and laws pertaining to carbon emission.

Businesses are beginning to offer this purposeful choice much more consideration in light of the advantages of reverse logistics for sustainable growth. Alnoor et al. (2019) gave a detailed analysis of the literature to determine how successfully the reverse logistics operation was carried out using three pillars of sustainable growth of the environment, trade and industry and social factors. Srivastava and Srivastava (2006) developed a methodology for managing returned items for reverse logistics, with a focus on the Indian perspective's forecast of returns for commodities categories. They contributed to the study in which they identified several significant issues and weaknesses, as well as challenges and opportunities, in the field of Reverse Logistics Network Design (RLND), notably concerning assessing and monitoring returned goods. To make this a reality, they create a model of procedures for a successful and effective RLND. They conduct informal interviews with several partners in order to assess and confirm genuine trends and requests. Additionally, they calculate various costs, operational characteristics and the broadest range of collection facility locations from long-term term return suppliers. Remanufacturing performs a gradually more important character in the financial system, the environment and society as it grows as a manufacturing mode. Remanufacturing is the primary driver of sustainability, which contributes to environmental issues such as climate change, water contamination, soil contamination and air pollution. Manufacturers have developed green supply chain strategies because of the growing social interest in green products and the increasing environmental consciousness of consumers to promote sustainable development and obtain competitive benefits in the long term. Facing the necessary needs of government laws and regulations as well as public perception, manufacturing industries are pursuing more eco-friendly economic industries of manufacturing in order to achieve sustainability in aspects of the nature and economy. As a key approach for sustainability, remanufacturing is recognised as one of the most effective means of achieving environment-friendly and emission reduction. Remanufacturing process entails gathering main components such as cleaning, repairing, and then screening and the repairing process entails re-assembling, refurbishing and again screening.

Furthermore, government regulations and increased public awareness of environmental issues and laws have all contributed to the growth of reverse logistics operations. Reverse logistics is becoming a vital competitive supply chain strategy for many innovative manufacturing enterprises as the emphasis on sustainability design continues. To build an ideal sustainable supply chain via which they can introduce refurbished or remanufactured variations of their goods back into the markets, several manufacturers and remanufacturing industries are improving their reverse logistics strategies. In addition to helping to reduce environmental effects, refurbished or remanufactured product strategies are restricted to existing business markets or at least a portion of those markets and do commercialise or aim new markets. In any industry, the screening process is essential to sustain the industry's reputation as well as maximise the total profit of the system. A product's quality can have a negative impact on a company's image and reputation in the marketplace. A checking process of an item in a manufacturing framework is necessary to boost profits, maintain a good reputation and enhance brand image. To achieve consumer expectations, screening is essential at various stages of manufacturing. Every day, the world's intellect increases. Each company strives to produce goods that are of high quality and free from flaws in order to enhance earnings while spending the lowest costs possible. It is natural for a manufacturing system to generate faulty or defective products when it's been functioning for a long period owing to various difficulties. If such items are delivered to users, the company's reputation will progressively diminish which has a direct impact on the company's profit. Therefore, the screening process is necessary to detect defective items and then withdraw them from the process for remanufacturing or landfill.

Screening technologies and processes are vital in both supply chain and production management as they ensure the quality, safety and efficiency of operations. By identifying defects and inconsistencies early, these technologies help maintain high standards of product quality, thereby enhancing customer satisfaction and brand reputation. They contribute to cost efficiency by reducing waste and minimising the need for rework. Additionally, screening technologies are crucial for regulatory compliance, ensuring that products meet industry standards and avoiding legal repercussions. They also play a key role in safeguarding supply chain integrity by preventing counterfeit or substandard materials from entering the production process. Overall, the implementation of effective screening processes leads to safer, more reliable products, streamlined operations and improved risk management, ultimately driving operational success and customer trust.

The rest of this study is designed as follows. Now next part will look over the relevant literature. Section 3 discusses the assumptions and notations for the developed model. The mathematical model is provided in Section 4. Sections 5 and Section 6 present the optimality computational criteria and numerical example respectively. In Section 7, the sensitivity analysis is shown by concluding the managerial insights. Furthermore, the conclusion and direction for future work are presented in Section 8 and Section 9, respectively.

## 2 Review literature

This research concentrated on two essential aspects of sustainable management: environmental contamination and economic. The concept of industrial sustainable development has taken a lot of interest in the last couple of decades due to the excellent work done by many researchers. Sustainability can be described as the desire of any company to achieve economic objectives while also controlling trash that manifests in society. The primary purpose of the sustainable distribution network is to decrease expenses and maintain the total profit of the system. Net waste has steadily increased as the number of industries has grown. Remanufacturing is distinct from mending, renewing and recycling. Zadjafar and Gholamian (2018) presented a sustainable inventory model. Shu et al. (2017) believed that Remanufacturing is the finest representation of material recycling as it raises the worthwhile keeping of the actual worth of the product. Generally, remanufacturing serves to extend the life cycle of a commodity and improve its durability. Economic growth technological advancements have substantially reduced the life cycle of the product. A growing number of old items that still are operationally viable are being disposed. Remanufacturing is now becoming a successful business by retrieving the resale value of such end-of-life goods. In this study, stock control schemes with cap-and-trade law have been considered. In this manner, Sinha and Modak (2019); Tao (2019); Liao and Deng (2018) and Chauhan and Singh (2015) proposed an economic order quantity (EOQ) framework with fuzzy demand and carbon tax. Furthermore, the use of green technology in manufacturing companies typically decreases emissions as technology develops and matures. A carbon tax and cap concept for sustainable growth production quantity (Mishra et al., 2020) has been suggested for a controlled carbon emission amount by promoting green technology initiates in various including and not including scarcity conditions. Pant et al., 2023) discussed channel financing policy for fast moving consumer goods. The major challenge for many organisations is waste reduction in a manufacturing system with green procurement. As a reason, the dual benefits of enhanced product quality and carbon emission reduction are critical for any sustainability practices. A three-tiered sustainable procurement architecture is being proposed Sarkar et al. (2021), with a single supplier, one manufacturer and numerous retailers. Adak and Mahapatra (2021) presented a two-distribution network for imperfect and non-defective products manufactured by manufacturers and merchants. The producer manufactures products with the expectation that defective items would be returned to the manufacturer after examination, with no financial responsibility to the retailer. The factory detects and repairs faulty items when the entire inspection operation is completed. As a result, the business sells the client non-defective items. A multi-objective optimisation model Kang et al. (2018) is formed to identify the optimal number of inspectors at each level of expertise to satisfy the criteria of a screening centre. This technique included three skill levels (poor, average and outstanding) and evaluation time to evaluate assessment cost, assessment error and assessment quantity.

## 2.1 Carbon emission

Any firm seeking to be sustainable must manage both the diminution of carbon emission and the improvement of service quality. Carbon emission must be maintained to a minimum, but product quality must be improved on a regular basis. Paul and Giri (2022) investigated the government's participation in a three-tier distribution network that comprised one manufacturer and one retailer Given the amount of carbon generated during production, the government is the most involved in seeking to ameliorate environmental repercussions. The government supervises the chain by subsidising or fining the manufacturer and increasing income from the retailer, which is ultimately supported by the customer. Remanufacturing can be seen (Konstantaras and Skouri (2010) as a way to reduce carbon emissions while also increasing the number of materials recycled. For companies and academicians, sustainable stock management and carbon emission reduction have become a worldwide problem. The consequence of air contamination on human health, as well as the expenses associated with loss of life and sickness, is increasingly acknowledged as a serious policy concern. In light of this, environmental laws governing the quantities of carbon emissions and other pollutants that are permissible have become increasingly severe. Absi et al. (2013) presented a concept of some major constraints of carbon emission in lot sizing. Kannan et al. (2012) and Aljuneidi and Bulgak (2020) represented a sustainable network design model for the carbon footprint. A case study of second-generation biofuel has been provided (Ahmed and Sarkar, 2018) with the impression of carbon emission in a green environment. In addition, Tiwari et al. (2019) demonstrated a green inventory framework with degrading items that aids companies in maximising overall profit under various trade credit rules while also decreasing carbon emissions for a cleaner environment. Xu et al. (2020) introduced a mathematical framework for decaying products to examine the effects of carbon emissions on logistics systems with time-varying demand, wherein shortage is permitted. An EOQ model for controlling carbon emissions through carbon tax scheme was presented by Aliabadi et al. (2019). A sustainable EOQ framework with two categories of price-based demands for controlled carbon emissions and rates of degradation was suggested by Mishra et al., 2021). In a manufacturing system (Allah et al., 2018) proposed four different long-term economic production quantity models that incorporate the effects of different types of inventory shortages. A two-layer green distribution network for imperfect production has been proposed by Manna et al. (2017) under the trade credit scheme. In which the rate of defectiveness has been taken as the function of manufacturing rate and time. Arora et al. (2022) described remanufacturing inventory model using cap and trade regulation. Taylor et al. (2013) developed an inventory model for calculating the economic production amount and the extent of backorders in a single-phase production process that produces poor quality items. Thereafter (Tiwari et al., 2018) provided a green production system of multi-items, in which random defective products are generated and then recycled. Taleizadeh et al. (2020) investigated the production model of different demand rates with carbon consideration. Pant et al. (2022) presented a sustainable frozen product model for price-stock-dependent demand with preserve strategy. Sharma et al. (2023) described impact of carbon emission with trade credit scheme, Cheng and Wang (2009) provided a trapezoidal consumption rate inventory system for degrading products. Rajput et al. (2022) described fuzzy optimisation production model with credit scheme. Ullah and Sarkar (2020) proposed a hybrid manufacturing-remanufacturing process model that procures used items of varying quality from both the old business retrieval channel and the innovative Radio Frequency Identification (RFID)-based channel. Jain et al., 2018) formulated a manufacturing and remanufacturing model under the time-based demand in which both the processes produced the defective items which are gathered by screening process. Zhao et al. (2018) established a framework which was based on the EOQ framework of the growing goods, and the carbon restriction technique is considered, before analysing the effects of the carbon tax mechanism on carbon emission, total expenses, mealtime and quantity required. Furthermore, it is commonly acknowledged that the advancement of remanufacturing has massive positive effects on society because it minimises carbon pollution and resource usage, distracts components from wastes and provides skilled employment in local areas.

## *2.2 Reverse logistics*

In recent years, environmental concerns have grown significantly. The term 'reverse logistics' is used and explained in a variety of ways, depending on the perspective of scholars and researchers. The importance of reverse logistics has risen dramatically in recent years. Firms are now becoming familiar with the benefits that reverse logistics management may provide. For some firms, reverse distribution network may be extremely risky; nevertheless, maintaining a fair management of reverse logistics chain can make a large difference in revenues. It is essential to realise that the back flow logistics processes are environmentally friendly because recycling, repair and refurbishment, are viable alternatives, with dumping as the last resort. Reverse logistics has developed as a vital competence in the current distribution network for managing end-of-life goods and attaining sustainability for all enterprises, public and private. Developing assessment criteria is a key step in creating a comprehensive and well-coordinated plan for reverse logistics performance. The combination of upward and downward supply chains is a major issue in reverse logistics. Returns and upward distribution network information should be combined to achieve the most effective management and save money. As a result, it is possible to efficiently help both forward and backward logistical actions by organising the full support system. This relates to the idea of a closed-loop distribution network. Several scholars have highlighted the issues with closed-loop supply chains in distinct case studies. A producer can benefit from a strategic collaboration with an eco-non-profit corporation in a closed-loop distribution network collecting process, according to a mathematical model established by Kumar and Malegeant (2006). This is more advantageous to the corporation than setting up its gathering system. The business should highlight its core initiatives, reduce travel costs and improve its sustainability standards. According to the literature reviewed in the study, adopting the life cycle of the goods and closed-loop supply network system approaches strengthens a competitive edge in the industry. The case study used Nike's reuse-a-shoe initiative and the concept of Throwplace.com to highlight the profits of collaborations between eco-non-profit corporations and producers. A framework of the research and functional system based on sustainable supply chain management have been created by Sheu (2008) to manage cross-functional products transportation activities and induced-waste reverse supply chain activities for local nuclear power generation. By specifying the model's essential roles and related operational requirements, a combined multi-objective function and pertinent system considerations are created. First off, by including the costs and risks of nuclear waste generation in model development, the concept of a sustainable supply distribution network integrated into a national nuclear power producing system arises. Additionally, the allocation of national electrical resources and ecological protection plans are considered in their system, which is based on execution of key administrative regulations. In response to the growing global ecological consequence concerns, the right outcomes and solutions from these factors may assist evaluate and update the present national power plan and energy production ways. Two mathematical models (Chauhan et al., 2022) has been suggested as a foundation for sustainable development looked at disposal issues. Most of the time, manufacturing involves the creation of occasionally damaged products, which is a kind of disposal for a business. The business deals with this waste by selling products at a discount on the secondary market. The firm also collects used items from clients to manage waste in keeping with the company's sustainability approach. These previously used goods were collected, recycled, and used as raw materials for further production. By collecting market discards and repurposing them as raw materials, significant efforts have been made to reduce trash. Because advertising enables companies to sell more items in the extremely competitive business climate of today, each industry invests more in marketing to increase its profits. As the emphasis on sustainable design grows, reverse logistics is becoming an essential effective logistics strategy for many progressive production firms. The idea of reverse logistics is used and described in a variety of ways, depending on the perspective of practitioners and scholars. Xia et al. (2011) defined closed-loop distribution network and recycle distribution network. Karmakar et al. (2018) and the idea of e-waste recycling process Nikabadi and Hajihoseinali (2018) proposed for the betterment of the reverse logistics strategies. Design (2018) addressed a network design of reverse logistics with carbon emission policies. Zou et al. (2019) developed a game theory technique to examine a manufacturer's strategy for a downward logistics distribution network with the combination of supplier, manufacturer and remanufacturer, while taking consumer awareness of environmental issues into consideration. Zadjafar and Gholamian (2018) dealt with the case study of pulp and paper mills. They presented a long-term economic quantity model that would aid businesses in lowering total costs, decreasing pollution and avoiding irreversible consequences of neglecting environmental scientific management principles. Hence, they initially offered the basic framework, which included income from garbage sales in addition to the traditional Economic quantity model. After that, a green economic quantity framework is designed. Basiri et al. (2011) proposed a closed loop distribution network model thereafter (Mishra et al., 2020) investigated a closed-loop logistics involving a single manufacturing company, a retailer and another gateway that is third party, in which the manufacturing company first reproduces new manufactured product and afterwards delivers some of the finalised products to the retailer using a single-arrangement multi distribution scheme. Many firms are having a difficult time returning used items since government regulations and the aim to reduce overall logistical costs have put the firm under a lot of pressure to accept used items of electronic waste. The contribution of authors is as follows:

The goal of sustainable framework is to maximise the overall profit with carbon emission and screening costs. This study focuses on the environmental aspects of a reverse logistic framework. Manufacturers now see carbon emission as one of the very essential factors influencing production decisions, because of rising recognition of the necessity to protect the natural ecosystem and schemes pertaining to carbon emission. This study deals with manufacturing and remanufacturing system with the impact of carbon emission cost and screening cost in overall profit of the system. Linear demand of the product has been considered in this framework. This is the best way to understand such manufacturing process of the electronic gadgets. Electronic gadgets waste is very harmful for the environment. Hence, recycle and reusing used items is the ideal plan for strengthening the greener future and sustainable practises.

**Table 1** Contribution of authors

| *Author* | *Objective type* | *Remanufacturing* | *Demand type* | *Screening investment* | *Carbon emission* |
|---|---|---|---|---|---|
| Roy et al. (2009) | Profit maximisation | Yes | Constant | No | No |
| Konstantaras and Skouri (2010) | Cost minimisation | Yes | Constant | No | No |
| Shu et al. (2017) | Cost minimisation | Yes | Constant | No | Yes |
| Design (2018) | Cost minimisation | Yes | Constant | No | Yes |
| Ahmed and Sarkar (2018) | Cost minimisation | No | Uncertain | No | Yes |
| Taleizadeh et al. (2020) | Profit maximisation | No | Variable-price-based demand | No | Yes |
| Jain et al. (2018) | Cost minimisation | Yes | Constant | Yes | No |
| Aliabadi et al. (2019) | Profit maximisation | No | Price-credit-carbon emission | No | Yes |
| Tiwari et al. (2019) | Profit maximisation | No | Price dependent | No | Yes |
| Ullah and Sarkar (2020) | Cost minimisation | Yes | Constant | Yes | No |
| Mishra et al. (2020a) | Cost minimisation | Yes | Constant | Yes | Yes |
| Mishra et al. (2020b) | Profit maximisation | No | Constant | No | Yes |
| Mishra et al. (2021) | Profit maximisation | No | Price-based demand | No | Yes |
| This study | Profit maximisation | Yes | Linear demand | Yes | Yes |

In the existing literature, there was a necessity for the techniques for waste reduction, a sustainable manufacturing / remanufacturing model with a screening process, trade credit and carbon emission consideration. Also, a mathematical model can be explored with the integration of linear demand with screening and carbon emission consideration. No study was reported by simultaneously integrating the profit maximization problem with the screening process, remanufacturing and carbon emission perspectives. Keeping in view the above facts, developing a Mathematical model for manufacturing and remanufacturing system with the impact of carbon emission cost and screening cost in overall profit of the system. Shortages are not allowed and linear demand has been considered in this framework.

## 3 Assumption and notations

Throughout the developed model, the following assumptions and notations are implemented.

- The time horizon $T$ is supposed to be known and finite and lead time is zero.
- Generally, demand is assumed to remain constant in most cases. However, the demand is linear as $(a + bt)$ in this model to make it more realistic.
- It is considered that shortage is not permitted.
- Sustainable inventory system contains a single type of product.
- To maintain the reputation of industry, the idea of screening process is considered to assure excellent product-quality.

$y_u(t) =$ Ready to use stock of the usable items at time $t$

$y_{nu}(t) =$ Ready to use stock of the non-usable items at time $t$

$K =$ The total number of cycles in $T$

$J =$ The number of cycles in which useful goods can be purchased

$q_f =$ other cycle's time duration in days.

$M_1 =$ Manufacturing rate of the first cycle (Constant) in \$

$M_3 =$ Remanufacturing rate in \$

$M_4 =$ Other cycles manufacturing rate in \$

$H_1 =$ Carrying cost of usable items in \$/unit time

$H_2 =$ Carrying expense of non-usable products in \$/unit time

$H_3 =$ Set up expense in \$

$H_4 =$ Usable item's purchasing cost in \$ /unit from market

$H_5 =$ Manufacturing cost in \$ / unit

$H_6 =$ Carbon emission tax in \$

$H_7 =$ Remanufacturing cost in \$

$H_8 =$ Screening cost in \$

$d =$ Time duration of first cycle

$e_p =$ Manufacturing time duration of first cycle

$v_p =$ Manufacturing time duration of other cycles

$S$ = Selling price in \$

$X$ = Disposal rate is constant

$\rho$ = Defective units produced during manufacturing

$t_1$ = The time period in the *k*-th cycle when useable goods are gathered for remanufacturing.

## 4 Mathematical formulation

The mathematical formulation was established with the purpose of maximising the total profit of the system while considering the cost of carbon emissions and the screening process. In this research, considering an imperfect production system including recycling and remanufacturing of defective items and used items. While developing this model it is assumed that there are *K* manufacturing loops throughout the finite period horizon *T*. Remanufacturing begins in the second loop and it stays until the end loop. The demand of first loop is fulfilled only by high quality items from manufacturing and other cycle consumption is addressed by high-quality items from both manufacturing and remanufacturing. Remanufactured products include non-serviceable commodities retrieved from the market as well as defective manufacturing. However, certain acquired non-serviceable goods that are not eligible for remanufacturing are removed from the circulation before remanufacturing may take place. Some acquired non-serviceable products that are not suitable for remanufacturing are disposed before remanufacturing. The level of serviceable and non-serviceable commodities is represented in Figures 1 and 2.

**Figure 1** Stock level for serviceable goods

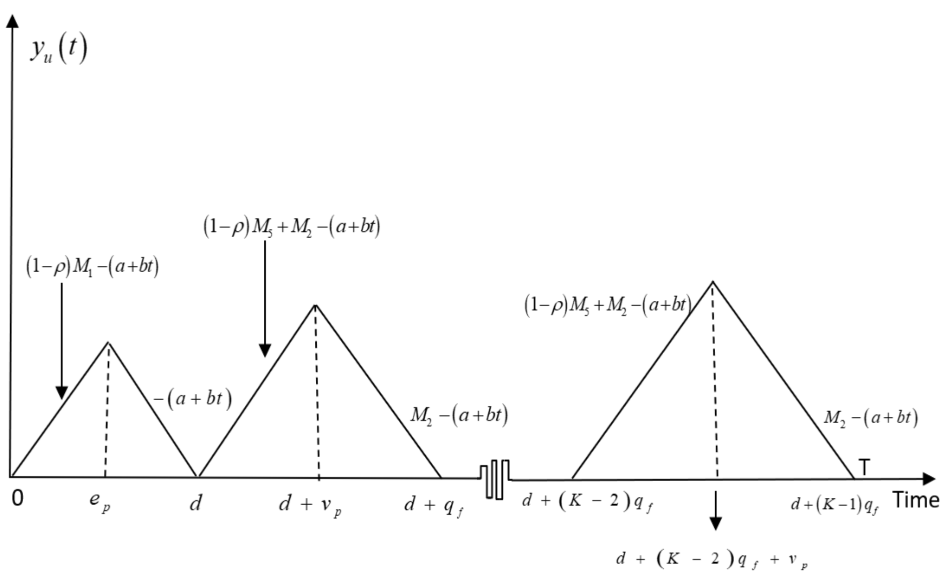
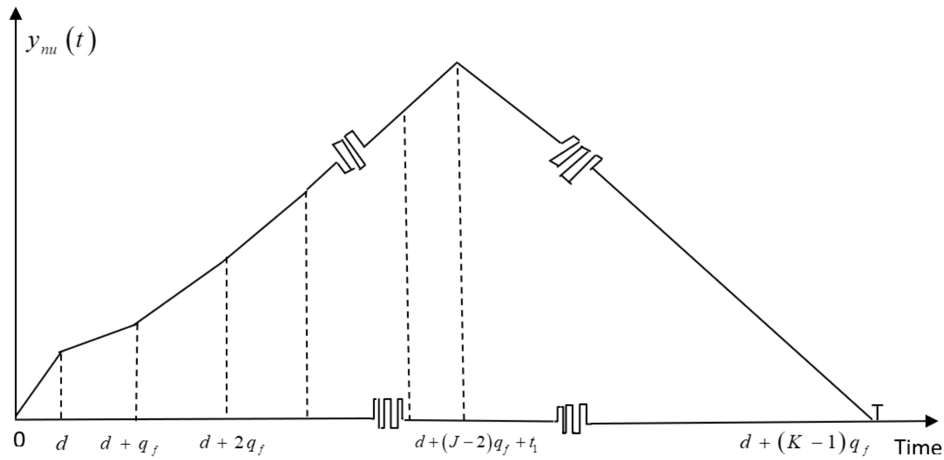
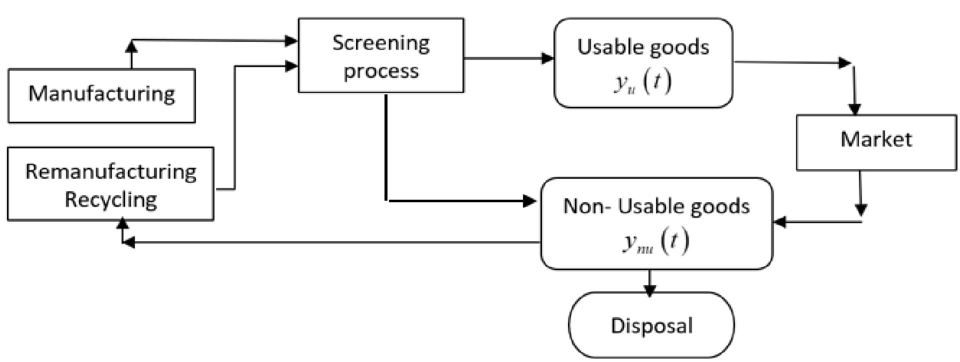


**Figure 2** Stock-level for non-serviceable goods




Let us consider the production–recycling material flow model. In this model, in the first cycle, $M_1$ represents the constant manufacturing rate. In other cycles, $M_5$ denotes the manufacturing rate, which is dependent on the remanufacturing rate. $y_u(t)$ represents the operable (serviceable) item's on-hand stock at time *t*. non-serviceable products $y_{nu}(t)$, which have been used products retrieved from the market and faulty manufacturing, are remanufactured. A certain amount of gathered non-serviceable goods that cannot recycled are disposed at the rate *X* before remanufacturing. The material flowchart is depicted in the Figure 3.

**Figure 3** The material flowchart of inventories




## 4.1 Formulation for the first cycle

The mathematical expression explaining the usable stock level $y_u(t)$ in the period $0 < t < d$ is provided below:

$$\frac{dy_u(t)}{dt} = (1-\rho)M_1 - (a+bt),\ 0 \le \text{t} \le \text{e}_p \tag{1}$$

$$\frac{dy_u(t)}{dt} = -(a+bt), \text{e}_p \le \text{t} \le d \tag{2}$$

With the boundary situations $y_u(t) = 0$ at $t = 0$ and $t = d$, where $\rho > 0$.

The mathematical expression describing the non-serviceable stock level $y_{nu}(t)$ in the period $0 < t < d$ is provided below:

$$\frac{dy_{nu}(t)}{dt} = \gamma_{11}(a+bt) + \rho M_1 - X,\ (0 < \gamma_{11} < 1)0 \le \text{t} \le d \tag{3}$$

The outcome of the equations (1) and (2) is given by

$$y_u(t) = \begin{cases} \left\{(1-\rho)M_1 t - \left(a + \frac{bt}{2}\right)t\right\}, & 0 \le t \le e_p \\ \left(a + \frac{bd}{2}\right)d - \left(a + \frac{be_p}{2}\right)e_p, & e_p \le t \le d \end{cases} \tag{4}$$

The outcome of the equation (3) is as follows:

$$y_{nu}(t) = \left(\gamma_{11}\left(a + \frac{bd}{2}\right) + \rho M_1 - X\right)d,\ 0 \le t \le d \tag{5}$$

From equation (4)

$$e_p = \frac{\left(a + \frac{bd}{2}\right)}{(1-\rho)M_1}d \tag{6}$$

### *4.1.1 Carrying cost for the serviceable goods*

Carrying expense is incurred when the stock is carried by the system for an extended period. Therefore, the carrying cost for the serviceable products is as follows:

$$\begin{aligned} HU_1 &= H_1\int_0^{e_p} y_u(t)dt + H_1\int_{e_p}^{d} y_u(t)dt \\ &= H_1\left[\left\{(1-\rho)M_1 - \left(a + \frac{be_p}{3}\right)\right\}\frac{(e_p)^2}{2}\right] \\ &\quad + H_1\left[\frac{b(d)^3}{2} + \frac{b(e_p)^3}{2} - \frac{b(e_p)^2 d}{2} - \frac{b(d)^2 e_p}{2}\right] \end{aligned}$$

### *4.1.2 Carrying cost for the non-serviceable goods*

The carrying expense for the non-serviceable goods is as follows:

$$HN_1 = H_2\int_0^{d_f} y_{nu}(t)dt = H_2\left\{\gamma_{11}\left(a + \frac{bd_f}{2}\right)(d_f)^2 + (\rho M_1 - X)d_f\right\}$$

$$\text{Selling price} = S\left[a\left(d-e_p\right)+\frac{b}{2}\left(\left(d\right)^2-\left(e_p\right)^2\right)\right]$$

### 4.1.3 Manufacturing cost

Some manufacturing or material expenditures are also required to make the product. To do so, a manufacturing cost is estimated, which is as follows: $= H_5 M_1 e_p$

### 4.1.4 Ordering cost

The ordering cost can be estimated as follows: $= H_3$

### 4.1.5 Purchasing cost

To purchase the material for manufacturing, a cost is utilised, which is known as purchasing cost. Purchasing cost can be evaluated as follows:

$$= H_4\left[\gamma_{11}\left\{a\left(d-e_p\right)+\frac{b}{2}\left(\left(d\right)^2-\left(e_p\right)^2\right)\right\}\right]$$

### 4.1.6 The overall profit in the first cycle

The overall profit in the first cycle is as follows:

$$\begin{aligned} \text{TPC}_1 = {} & S\left[a\left(d-e_p\right)+\frac{b}{2}\left(\left(d\right)^2-\left(e_p\right)^2\right)\right]-H_1\left[\left\{\left(1-\rho\right)M_1-\left(a+\frac{be_p}{3}\right)\right\}\frac{\left(e_p\right)^2}{2}\right] \\ & -H_1\left[\frac{b\left(d\right)^3}{2}+\frac{b\left(e_p\right)^3}{2}-\frac{b\left(e_p\right)^2 d}{2}-\frac{b\left(d\right)^2 e_p}{2}\right]-H_2\left\{\begin{array}{l}\gamma_{11}\left(a+\frac{bd}{2}\right)\left(d\right)^2 \\ +\left(\rho M_1-X\right)d\end{array}\right\} \\ & -H_4\left[\gamma_{11}\left\{a\left(d-e_p\right)+\frac{b}{2}\left(\left(d\right)^2-\left(e_p\right)^2\right)\right\}\right]-H_5 M_1 e_p \end{aligned} \tag{7}$$

## 4.2 Mathematical expression for i-th cycle $\left(2 \le i \le K\right)$

The differential equation defining the serviceable stock levels $y_u\left(t\right)$ in the period $\left(d+\left(i-2\right)q_f \le t \le d+\left(i-1\right)q_f\right)$ is defined as follows:

$$\frac{dy_u\left(t\right)}{dt} = \left(1-\rho\right)M_5+M_2-\left(a+bt\right),\ d+\left(i-2\right)q_f \le \text{t} \le d+\left(i-2\right)q_f+v_p \tag{8}$$

$$\frac{dy_u\left(t\right)}{dt} = M_2-\left(a+bt\right),\ d+\left(i-2\right)q_f+v_p \le \text{t} \le d+\left(i-1\right)q_f \tag{9}$$

With the boundary situations

$y_u\left(t\right)=0$ at $t = d+\left(i-2\right)q_f$ and $t = d+\left(i-1\right)q_f$, where $M_2 < \left(a+bt\right)$.

Now, the differential equation defining the non-serviceable stock levels $y_{nu}(t)$ in the period $\left(d+(i-2)q_f \le t \le d+(i-1)q_f\right)$ is defined as

$$\frac{y_{nu}(t)}{dt}=\sum_{f=1}^{i}\gamma_{if}(a+bt)+\rho M_5-M_2-X,\quad d+(i-2)q_f\le t\le d+(i-1)q_f \qquad (10)$$
$$i\ge f,\quad i=2,3,\ldots,J-1,$$

$$\frac{y_{nu}(t)}{dt}=\sum_{f=1}^{J}\gamma_{if}(a+bt)+\rho M_5-M_2-X,\ d+(J-2)q_f\le t\le d+(J-2)q_f+t_1 \qquad (11)$$

$$\frac{y_{nu}(t)}{dt}=\rho M_5-M_2,\quad d+(J-2)q_f+t_1\le t\le d+(K-1)q_f \qquad (12)$$

With the boundary situations

$y_{nu}(t)=0$ at $t=d+(K-1)q_f$, where $\sum_{f=1}^{i}\gamma_{if}=i\gamma_{11}+\frac{i(i-1)}{2}g\le 1$, for every $i=2,3,\ldots,J-1.$

By equations (11) and (12)

$$t_1=\frac{(X-a)+\sqrt{(a-X)^2+2b}}{b}\left[\begin{array}{l}\left\{(M_2-\rho M_5)(K-J)q_f-(\rho M_5-M_2)q_f\right\}\\ -\left(\gamma_{11}\left(a+\frac{bd}{2}\right)+\rho M_1-X\right)\mathrm{d}\\ -\sum_{p=1}^{J-2}\left\{p\gamma_{11}+\frac{p(p-1)}{2}g\right\}\left(a+\frac{bq_f}{2}\right)q_f\\ +J-3(M_2-\rho M_5)q_f+Xq_f\\ -\left\{\begin{array}{l}\left((J-1)\gamma_{11}+\frac{(J-1)(J-2)}{2}g\right)\left(a+\frac{bq_f}{2}\right)\\ -X-(M_2-\rho M_5)\end{array}\right\}q_f\end{array}\right] \qquad (13)$$

The outcome of the equations (8) and (9) as follows:

$$y_u(t)=\left\{\left((1-\rho)M_5+M_2-\left(a+\frac{bq_f}{2}\right)\right)v_pM_2(v_p-q_f)-\left\{a(v_p-q_f)+\frac{b\left((v_p)^2-(q_f)^2\right)}{2}\right\}\right\} \qquad (14)$$

$$v_p=-\frac{\left(M_2-\left(a+\frac{bq_f}{2}\right)\right)}{(1-\rho)M_5}q_f \qquad (15)$$

where $q_f = \dfrac{T-d}{K-1}$

Thus, the entire cost's worth is made up of the following components.

Carrying cost for the usable products is defined as

$$\begin{aligned} CU_i &= H_1 \int_{d+(i-2)q_f}^{d+(i-2)q_f+v_p} y_u(t)dt + H_1 \int_{d+(i-2)q_f+v_p}^{d+(i-1)q_f} y_u(t)dt \\ &= H_1 \left[ \left\{ (1-\rho) M_5 + M_2 - \left( a + \frac{bv_p}{2} \right) \right\} (v_p)^2 \right. \\ &\quad \left. + \left\{ M_2 - \left( a + \frac{b(v_p - q_f)}{2} \right) \right\} \left( 2v_p q_f - (v_p)^2 - (q_f)^2 \right) \right] \end{aligned} \tag{16}$$

Carrying cost for the non-usable products is defined as

$$\begin{aligned} CN_{u2} &= \int_d^{d+q_f} y_{nu}(t)\,dt = H_2 \left[ \left\{ (2\gamma_{11} + g) \left( a + \frac{bq_f}{2} \right) - X - (M_2 - \rho M_5) \right\} q_f \right. \\ &\quad \left. + \left\{ \gamma_{11} \left( a + \frac{bq_f}{2} \right) + \rho M_1 - X \right\} dq_f \right] \end{aligned} \tag{17}$$

Carrying cost for non-usable products for *i*-th cycle $(3 \le i \le K-1)$ is as follows:

$$\begin{aligned} CN_i &= H_2 \int_{d+(i-2)q_f}^{d+(i-1)q_f} y_{nu}(t)\,dt \\ &= H_2 \left[ \begin{aligned} &\left( \gamma_{11} \left( a + \frac{bd}{2} \right) + \rho M_1 - X \right) dq_f + \sum_{p=2}^{i-1} \left\{ p\gamma_{11} + \frac{p(p-1)}{2} g \right\} \left( a + \frac{bq_f}{2} \right) (q_f)^2 \\ &-(i-2)(M_2 - \rho M_5)(q_f)^2 - X(q_f)^2 \\ &+ \left\{ \left( i\gamma_{11} + \frac{i(i-1)}{2} g \right) \left( a + \frac{bq_f}{2} \right) - X - (M_2 - \rho M_5) \right\} q_f \end{aligned} \right] \end{aligned} \tag{18}$$

Carrying cost for non-usable products for *J*-th cycle is as follows:

$$\begin{aligned} CN_J &= H_2 \int_{d+(J-2)q_f}^{d+(J-2)q_f+t_1} y_{nu}(t)dt + H_2 \int_{d+(J-2)q_f+t_1}^{d+(J-1)q_f} y_{nu}(t)\,dt \\ &= H_2 \left[ \begin{aligned} &\left( \gamma_{11} \left( a + \frac{bd}{2} \right) + \rho M_1 - X \right) dt_1 + \sum_{p=2}^{J-2} \left\{ p\gamma_{11} + \frac{p(p-1)}{2} g \right\} \left( a + \frac{bd}{2} \right) q_f t_1 \\ &-(J-3)(M_2 - \rho M_5) q_f t_1 - X q_f t_1 \\ &+ \left\{ \left( (J-1)\gamma_{11} + \frac{(J-1)(J-2)}{2} g \right) \left( a + \frac{bq_f}{2} \right) - X - (M_2 - \rho M_5) \right\} q_f t_1 \\ &+ \left\{ \left( J\gamma_{11} + \frac{J(J-1)}{2} g \right) \left( a + \frac{bt_1}{2} \right) - X - (M_2 - \rho M_5) \right\} (t_1)^2 \\ &+(M_2 - \rho M_5)(K-J)(q_f - t_1) q_f \end{aligned} \right] \end{aligned} \tag{19}$$

Carrying cost for non-usable products for *i*-th cycle $\left( \left( K+1 \right) \le i \le n \right)$ is as follows:

$$\mathrm{CN}_i = \int_{d+(J-1)q_f}^{d+(K-1)q_f} y_{nu}\left(t\right)dt = \mathrm{H}_2\left\{ \frac{\left(M_2 - \rho M_5\right)}{2}\left(K-J\right)^2\left(q_f\right)^2 \right\} \tag{20}$$

### 4.2.1 Overall purchasing cost for used products

The expense of purchasing the used products is given by

$$PC = H_4\left[ \sum_{i=2}^{J-1}\left\{ i\gamma_{11} + \frac{i\left(i-1\right)}{2}g \right\}\left(a + bq_f\right) + \left\{ J\gamma_{11} + \frac{J\left(J-1\right)}{2}g \right\}\left(a + bt_1\right) \right] \tag{21}$$

### 4.2.2 Overall manufacturing cost with carbon emission tax for $\left(K-1\right)$ cycle

Maintaining carbon emissions while enhancing the quality of the product in manufacturing is critical for any sustainable management strategy. Because of increased understanding of the demand to protect the natural world and legislation governing carbon emissions, manufacturers now consider carbon emissions to be one of the most important variables influencing production decisions. The overall manufacturing expense with carbon emission tax is provided by

$$MC = \left(K-1\right)H_5M_5v_p + \left(K-1\right)H_6M_5v_p + H_6M_1e_p \tag{22}$$

### 4.2.3 Overall re-manufacturing cost with carbon emission tax

The overall re-manufacturing cost with carbon emission tax is as follows:

$$RC = H_7M_2\left(T-d\right) + H_6M_2\left(T-d\right) \tag{23}$$

### 4.2.4 Overall screening cost for the whole system

The screening procedure is critical to maintaining the industry's reputation while also optimising the system's economic income. Hence, the screening process is required to discover faulty goods, which must then be removed from the process for remanufacturing or disposal. The screening cost for the whole system is estimated by

$$SC = \left(K-1\right)H_8M_5v_p + H_8M_1e_p \tag{24}$$

Overall profit of the system is as follows:

$$\mathrm{OP}\left(J, q_f\right) = \left\{ \begin{array}{l} \text{Sales revenue} - \text{Overall manufacturing cost with carbon emission cost} \\ - \text{Overall remanufacturing cost with carbon emission cost} \\ - \text{Overall purchasing cost} - \text{ Overall carrying cost} \\ - \text{Overall ordering cost} - \text{ Overall screening cost} \end{array} \right\} \tag{25}$$

## 5 Optimality computational criteria

To achieve the optimum profit value per unit of $P(J, q_f)$ with respect to $J$ and $q_f$.

The following steps are used:

*Step 1*: The 1st order derivative of $P(J, q_f)$ is took w.r.t. continuous variable $J$ and $q_f$.

$$\frac{\partial P(J, q_f)}{\partial J} = 0 \; \& \; \frac{\partial P(J, q_f)}{\partial q_f} = 0$$

*Step 2*: The equation from step 1 must be solved simultaneously in order to reach an optimal solution.

*Step 3*: Take 2nd order of $P(J, q_f)$ satisfying the condition

$$A_H = \begin{bmatrix} \frac{\partial^2 P(J, q_f)}{\partial J^2} & \frac{\partial^2 P(J, q_f)}{\partial q_f \partial J} \\ \frac{\partial^2 P(J, q_f)}{\partial J \partial q_f} & \frac{\partial^2 P(J, q_f)}{\partial (q_f)^2} \end{bmatrix}$$

$$\frac{\partial^2 P(J, q_f)}{\partial J^2} \frac{\partial^2 P(J, q_f)}{\partial (q_f)^2} - \left( \frac{\partial^2 P(J, q_f)}{\partial J \partial q_f} \right)^2 > 0$$

## 6 Numerical illustration

To validate the model, in this study, the manufacturer acquires used items from the market, and proceeds to recover and remanufacture after that some of the components and parts which cannot recycle led are disposed of. Numerical data has been taken from (Roy et al., 2009). To demonstrate the developed model, the numerical values have been considered as follows: $M_1 = 50$, $M_3 = 5$, $M_4 = 50$, $H_1 = 2$, $H_2 = 0.5$, $H_3 = 10$, $H_4 = 5$, $H_5 = 15$, $H_6 = 1$, $H_7 = 8$, $H_7 = 2$, $d = 10$, $e_p = 0.4$, $\gamma_{11} = 0.125$, $S = 30$, $X = 3.5$, $\rho = 0.05$, $T = 8$, $K = 4$, $a = 12$, $b = 0.3$, $g = 0.02$, $J_1 = 0.1$, $J_2 = 10$.

The optimum results for *J and* $q_f$ as well as the overall profit from equation (25) have been evaluated. The results are presented in Table 2. The complexity of the overall profit of the model can be found in the Figure 4.

**Figure 4** Convexity of the overall profit w.r.t. *J and* $q_f$ (see online version for colours)

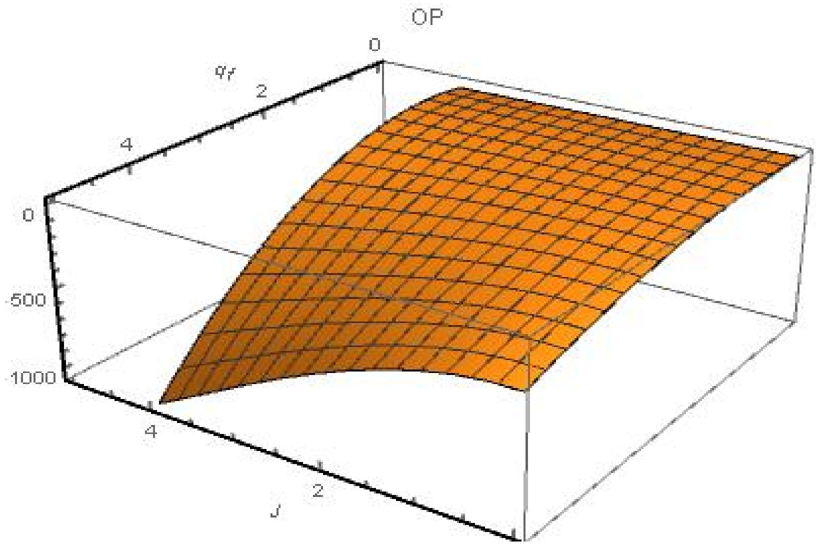



**Table 2** Optimum results of overall profit, *J and* $q_f$ .

| *Overall profit* | *J* | $q_f$ *(Days)* |
|---|---|---|
| 14.8594 | 1.8599 | 0.64514 |

## 7 Sensitivity analysis

This analysis is needed to understand the behaviour of the parameter throughout the model acquiring the right sustainable manufacturing management solutions.

- When the amount of carbon emission tax raises, then the total profit of the system reduces and *J*, i.e., the number of cycles in which serviceable goods have purchased, are decreases.
- If the value of Screening cost increases, then the total profit of the system decreases and *J*, i.e., the number of cycles in which serviceable goods have purchased, are decrease.
- When both, carbon emission tax and Screening cost are increase, then $q_f$ , i.e., the duration of other cycles increases. Table 3 shows that the carbon emission and screening costs are both highly effective in terms of the system's total profit. The behaviour of carbon emission and screening costs on overall profit is also shown in Figures 5 and 6.

**Table 3** Sensitivity analysis w.r.t. the parameters of the mentioned example

| *Parameters* | *Change in %* | *OP* | *J* | $q_f$ |
|---|---|---|---|---|
| | –50% | 15.3164 | 1.86008 | 0.64496 |
| | –25% | 15.0879 | 1.85999 | 0.64505 |
| $H_6$ | 0 | 14.8594 | 1.85991 | 0.64514 |
| | 25% | 14.6309 | 1.85982 | 0.64522 |
| | 50% | 14.4024 | 1.85973 | 0.64531 |
| | –50% | 17.3282 | 1.86015 | 0.64489 |
| | –25% | 16.0938 | 1.86003 | 0.64501 |
| $H_8$ | 0 | 14.8594 | 1.85991 | 0.64514 |
| | 25% | 13.625 | 1.85979 | 0.64526 |
| | 50% | 12.3906 | 1.85966 | 0.64538 |

**Figure 5** Effect of carbon emission cost on optimal profit

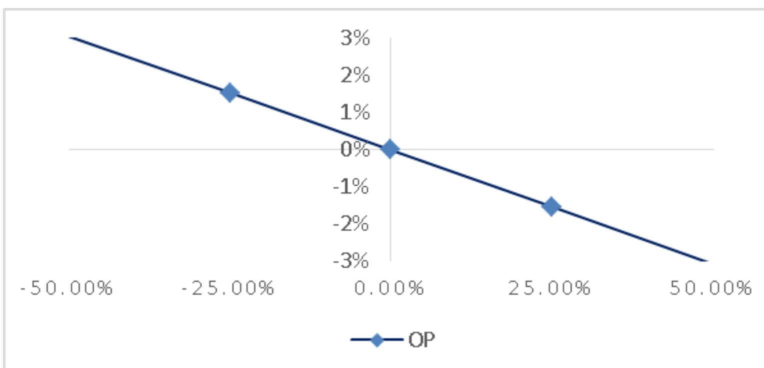
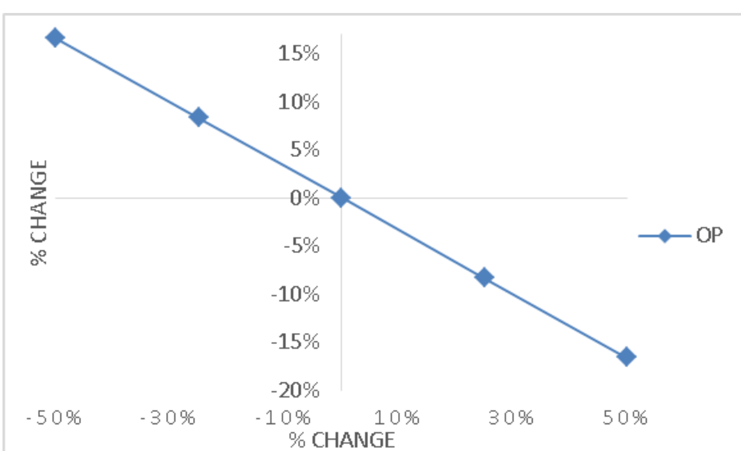



**Figure 6** Effect of screening cost on optimal profit



The screening process plays a crucial role in reducing carbon emissions and ultimately maximising profits. By identifying and eliminating inefficiencies and defects early in the production cycle, the process minimises waste and optimises resource use, leading to lower carbon footprints. Additionally, efficient screening ensures that only high-quality materials and products proceed through the supply chain, further reducing the need for rework and disposal, which are both carbon-intensive activities. This paper's focus on the integration of screening processes in sustainable frameworks draws attention to its significant contributions to both environmental and economic performance. By highlighting how effective screening can align profitability with sustainability goals, this paper underscores its relevance and importance in the context of modern manufacturing and supply chain management.

### *7.1 Managerial insights*

This research has significant and relevant implications for several organisations in the remanufacturing industry. Based on the findings, the following appropriate management ideas for this area may be described:

- It is essential for the firm to consider sustainability since, according to the optimal solution, there are significant changes in the overall profit by adopting the strategy of screening cost carbon emission cost when environmental aspect is considered.
- Carbon emission is the most significant pollution that has an impact on the world, humans and revenue. In the manufacturing context, this is something we can't ignore.
- Both the processes of production and remanufacturing emit the carbon emission in electronic gadgets production, which is harmful for the society and the environment as well. Therefore, the manufacturing industry should adopt the recycling strategies for used items.
- As a result, disposal rate decreases by applying such strategies.
- Screening process is highly effective for the manufacturing and remanufacturing because it is the major concern for the brand's image.
- Screening process saves the expenses of the different holding stages which clearly impacts the total profit of the system.

## 8 Conclusion

The worth of resources in a sustainable society can be reused, refurbished, recycled and remanufactured again without diminishing their characteristics. Furthermore, this study showed that recycling is among the most important ways to sustainable manufacturing that emphasises contamination and the conservation of the world's resources. A mathematical framework for sustainable inventory has been developed in which the linear demand is satisfied by manufactured and remanufactured items. The optimal result demonstrates that if the value of carbon emission and screening costs decreases, then the system's overall profit improves, which is an apparent reason. This represents a departure from traditional reverse logistics systems, which primarily focused on reusing materials to protect the environment. By promoting remanufacturing, this approach not only supports environmental sustainability but also offers significant benefits for industrial applications. It enhances both ecological and economic performance, providing a more comprehensive and advantageous strategy for modern industry practices. This dual focus on profitability and environmental responsibility presents a compelling case for integrating sustainable practices into industrial operations. In the real world, electronic gadgets are reconditioned and considered as viable things on the market. The manufacturing/remanufacturing idea may be used in the business scheme of electronic devices on the marketplace for any such items. Therefore, corporate managers, academics and social organisers simply indicated as electronic parts manufacturers to take advantage of remanufacturing. We recommend that companies employ the screening-level evaluation discussed here, ensuring that they do not neglect significant sources of environmental consequences throughout their supply chains. Such data can assist businesses in pursuing carbon and ecological emission reduction efforts not only inside their operations, but also throughout their supply chain.

## 9 Future work

This work aims to develop the manufacturing-remanufacturing framework with carbon emission costs and screening costs for a single product, such as electronic gadgets. This model was established with the assumption of linear demand being met by manufactured/remanufactured products. It is preferable to assume that demand is probabilistic, as demand cannot be predicted in advance in real-world circumstances. Addressing the uncertainty in demand and the presence of defective items from manufacturing could significantly enhance the model's applicability and accuracy. Furthermore, the current assumption that produced and remanufactured goods are of equal quality opens up another avenue for refinement. By examining quality differences between new and remanufactured products, future extensions of the model can provide deeper insights and more practical solutions for optimising manufacturing and remanufacturing processes. These advancements will help researchers and practitioners develop more effective strategies for sustainability and operational efficiency in industrial applications.

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