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Extended Producer Responsibility in the Apparel Industry: An Agent-Based Simulation Incorporating Physical and Emotional Product Durability

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ABSTRACT

Objective: This study examines the impacts of Extended Producer Responsibility (EPR) on product life extension and market dynamics. It investigates the relationship between the physical and emotional durability of products in the apparel supply chain, highlighting the importance of the secondary market in prolonging product life and value. By understanding the connections among producers, consumers, and the secondhand market, the study aims to develop a practical approach that helps planners derive optimal synergistic solutions, considering the needs of consumers, ecological considerations, and the economic factors within the apparel market.

Methods: The interactions among consumers, producers, and the government are demonstrated through agent-based simulations across five scenarios. The market includes various groups of consumers to represent its heterogeneous nature. The simulation, conducted in NetLogo, models the behavior of both producers and buyers in the context of government intervention.

Results: Simulation results indicate that EPR policies, combined with government interventions such as incentives, penalties, and regulations, can effectively promote the management of products at the end of their life cycle. In scenarios that utilized incentives, producers were more likely to buy and sell secondhand products, reducing the production of new items and increasing recycling rates. These results underscore the critical importance of collaboration among the government, the public, and producers to implement EPR policies successfully.

Conclusion: Effective implementation of EPR policies requires government market intervention calibration. When the government applies a reward-and-penalty system to enforce EPR, product waste is reduced, and producer profitability surpasses other scenarios.

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Introduction

The apparel industry faces significant environmental challenges stemming from excessive consumption of natural resources, pollution generated at various stages of the supply chain, and the creation of a vast volume of textile waste, with more than 92 million tons of clothing discarded annually. This figure is estimated to exceed 134 million tons annually by the end of 2030 (Singh et al., 2025). This waste is often buried or incinerated, which can have devastating environmental effects (Moazzem et al., 2021). High water consumption—20,000 liters to produce one kilogram of cotton—industrial wastewater from dyeing and finishing processes, greenhouse gas emissions, and industrial pollution are among the industry's environmental challenges (Moazzem et al., 2021; Vitale et al., 2025). So far, numerous studies have been conducted in the field of designing green and sustainable supply chain networks, using various techniques such as game theory (e.g., Allameh et al., 2014), mathematical programming (e.g., (Fallah Lajimi et al., 2010)), and robust optimization (e.g., (Hosseini Dehshiri et al., 2012)). Extended producer responsibility (EPR) requires manufacturers to manage their products' waste at the end of their useful life (Anh et al., 2025). As a result of these policies, manufacturers are driven to design and produce more durable and recyclable products, establish more efficient collection and recycling systems, and foster a market for secondhand goods. Due to the importance of EPR in balancing economic profitability and environmental sustainability, numerous studies have been conducted in this field (Huang et al., 2019; Gui et al., 2018, 2016; Tian & Debo, 2019; Aleve et al., 2020, 2022; Lifset et al., 2023).

This study explores how to implement EPR in the apparel industry, considering the product's physical and emotional durability from the consumer's point of view. It aims to develop a detailed model to help governments apply EPR effectively. Using simulations, the study examines how economic and environmental policies influence each other. Such models can guide policymakers to create better strategies for sustainable business and economic growth (Anderson & Cavendish, 2001). The research uses agent-based simulation to study interactions among buyers, governments, and producers. Different scenarios test how government incentives and penalties affect producer behavior and supply chain performance. Agent-based simulation captures complex stakeholder relationships, especially in economic and environmental areas (Arnejo et al., 2025). The study's results may help find effective ways to encourage producers to manage end-of-life products properly and reduce waste.

This research, using agent-based simulation, sought to answer the following questions:

1. How does the implementation of EPR affect the producer's profit?
2. What is the appropriate government tool for implementing EPR, whether a reward or a penalty, based on reducing end-of-life products?
3. How can producers remain profitable if EPR is implemented?

4. Can the dependence of production volume on profit guarantee profitability in the presence of EPR policies?

The research continues with a review of the literature and theoretical background, followed by the research innovations, research methodology, and findings, including an analysis of the five scenarios under study. It then presents the results obtained from implementing agent-based simulation in the research findings section and concludes with recommendations and suggestions.

Literature Background

This study explores the multifaceted impacts of EPR on product longevity and market dynamics, with a particular focus on the apparel sector. It investigates how EPR shapes the interplay between physical and emotional product endurance, the secondary market, and supply chain mechanisms. The research aims to conceptualize a framework that guides strategic decision-making, balancing consumer satisfaction, environmental sustainability, and economic viability within the fashion industry by examining the interrelations among producers, consumers, and secondhand markets. Several studies have been conducted on EPR modeling in the apparel industry, examining the effectiveness of EPR in reducing environmental impacts, increasing recycling, and encouraging manufacturers to design more sustainable products. Qui et al. (2025) showed that EPR schemes incentivize producers to invest in recycling technology, with collective producer responsibility systems providing higher economic benefits when brand differentiation or investment effectiveness is substantial.

Chapman (2008) argues that the importance of design for durability goes beyond its traditional concept of solely relating to the physical lifespan of the product. The research argues that consumer preferences are constantly evolving. In contrast, consumer electronics products designed to meet these preferences are stagnant over time, and this inability to reciprocate prevents the formation and maintenance of lasting relationships with users. This incompatibility leads to the production of a significant volume of waste, which, in addition to causing economic losses for manufacturers under the pressure of the European Union WEEE Directive, also harms the environment. Emotional durability fosters lasting connections between consumers and products, promoting long-term use and reducing waste. By designing products that maintain relevance, aesthetic appeal, and personal attachment, manufacturers can discourage throwaway culture and contribute to sustainability goals. This aligns with the producer-consumer sustainability continuum, emphasizing mutual understanding for implementing practical Extended Producer Responsibility (EPR). Some research emphasizes the importance of stakeholder engagement throughout the product life cycle to ensure the success of EPR (Faybil et al., 2022; Lifset et al., 2023). Malik et al. (2024) examined producer-consumer interactions and revealed gaps in public awareness and neutral consumer attitudes towards EPR. Flygansvær and Dahlstrom (2024) study the factors influencing companies' adoption

of ecologically designed packaging in producer responsibility networks. The study, based on data from 188 companies, shows that financial resources, recycling capabilities, regulations, internal integration, and customer demand significantly affect the ecological design of plastic packaging. Additionally, competitive intensity moderates the effect of customer demand.

Table 1. Summary of literature review

Source	Product	Durability	Solution approach
(Gui et al., 2016)	Electronic Products	Durable good	Game theory
(Gui et al., 2018)	Electronic Waste	Durable good	Game theory
(Huang et al., 2019)	Photovoltaic Panels (PVP)	Durable good	Game theory
(Alev et al., 2020)	Durable Electronic Products	Durable good	Game theory
(Alev et al., 2022)	Medicine	Durable good	Game theory
(Flygansvær & Dahlstrom, 2024)	Plastic Packaging	Semi-durable goods	Structural Equation Modeling (PLS-SEM)
(Qui et al., 2025)	Electric Vehicle Batteries	Durable good	Game theory

Table 1 presents important studies related to the implementation of EPR. These studies primarily focus on physically durable products or consumer goods, most commonly electronics. However, there is little research on the emotional durability of products.

Since EPR is a subset of the broader circular economy (CE) concept (OECD, 2024), Table 2 provides an overview of research on the circular economy and its findings to illustrate the impact of this concept on supply chain management.

Table 2. Summary of the literature review on circular economy for waste management

Source	Area of research	Methodology	Findings
(Kirchherr et al., 2017)	CE	Review	CE promotes resource efficiency and waste reduction in the long term.
(Wysokińska, 2016)	CE	Analytical and descriptive	CE reduces waste through production and consumption management.
(EU Commission, 2015)	CE action plan	Analytical	CE maximises the value of products and reduces waste.
(Ghisellini, 2016)	Waste management	Review	CE can improve current production and consumption models
(Stahel, 2016)	CE and resource efficiency	Conceptual and analytical	CE improves production efficiency through effective product and material design.
(Davies, 2013)	Sustainability	Conceptual and analytical	Sustainability can balance environmental protection with human development.
(Maitre-Ekern & Dalhammar, 2019)	Consumer behaviour in CE	Conceptual and analytical	A hierarchy of consumption behaviors can effectively support CE policies.
(Atasu, 2018)	EPR	Game theory	Designing effective EPR requires considering product durability and market dynamics for better environmental impact.

Source	Area of research	Methodology	Findings
(Faibil et al., 2022)	EPR	Grey decision making and DEMATEL	Operational factors outweigh strategic ones, driving EPR adoption for sustainable e-waste management in developing economies.
(Brown & Börkey, 2024)	EPR	Review	EPR boosts garment collection and sorting while cutting environmental impact by shifting responsibility to producers.

Table 2 provides a brief review of research related to this area. According to this table, it can be concluded that the concept of the circular economy is fundamental for the proper management of production waste. EPR is a policy that can control and ensure its implementation. However, emotional and physical durability is important for EPR implementation in the clothing sector.

Since this research examines market stability, emotional durability, and physical durability, the corresponding mathematical models are complex and cannot be solved analytically. Agent-based simulation is a tool capable of modeling complex conditions, dynamics, interrelationships, and the effects of policy changes on manufacturer behavior.

Research contribution

This study introduces the following contributions compared to existing EPR literature:

- Application: This research presents the EPR model specifically for the apparel industry, as shown in Tables 1 and 2, where little research has addressed this topic.
- Emotional Durability: Unlike previous studies focusing only on physical durability and recycling, this work integrates the concept of emotional durability (Chapman, 2008) to examine how consumers' emotional connection affects product lifecycle and EPR implementation.
- Methodology: Agent-based simulation analyzes complex scenarios and dynamic interactions between multiple factors influencing EPR outcomes.

Materials and Methods

This research uses quantitative methods and agent-based simulation to assess the scenarios. The research stages are shown in Figure 1.

Model

This research employs agent-based simulation. The agents modeled are buyers, goods, producers, and the government, each described below:

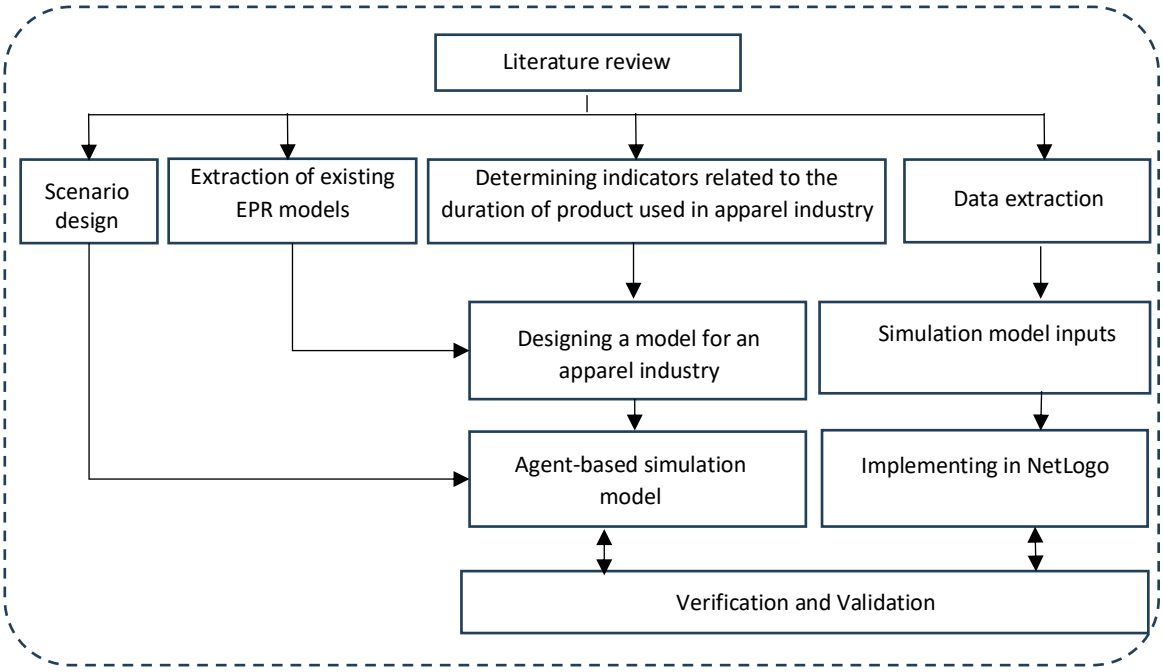

Figure 1. Research steps

1- Buyers (customers): Agents who purchase goods and belong to a fixed-size set during each period. Each buyer can make either one purchase at a time or no purchase at all. Buyers decide to buy new or second-hand goods based on assessed desirability. These agents are categorized as follows:

A. The model represents Agents who buy new goods as type 1 customers.

B. Agents who buy second-hand goods are represented as type 2 customers.

C. Agents who do not make a purchase are represented as type 3.

2- Products: In this model, products are divided into four categories:

A. New products that have been produced and marketed.

B. Collected products used only once and collected for sorting based on remaining physical durability and improvement processes (e.g., sanitizing, appearance enhancement, packaging).

C. Improved second-hand products are collected items marketed as second-hand after improvement.

D. End-of-life products, which have been used twice or whose physical durability has ended and cannot be improved.

3- Producer: In this model, the producer is responsible for producing, collecting, sorting, and improving the collected items.

4- Government: The government intervenes in the supply chain to implement EPR policies by applying incentives or penalties to the producer.

In this article, the SC consists of one seller and three types of buyers with varying sensitivity to products in the presence of government intervention.

The main assumptions of the model are:

- The price of second-hand items is less than that of new ones and decreases over the item's life.
- Physical durability decreases over the life of the item.
- Each customer can decide to purchase only one new item, or one second-hand item, or not purchase at all at any time.
- The manufacturer collects used items from consumers at a given price and resells improved second-hand items in the second-hand market.
- Each product can be consumed a maximum of two times.
- Customers consider two product characteristics, price and acceptability, when buying.
- The government can influence the supply chain through incentives or penalties.
- Customers can sell their product to the manufacturer if used only once.
- The item cannot be sold second-hand after being used twice.

Figure 2 illustrates the flow of goods in the model.

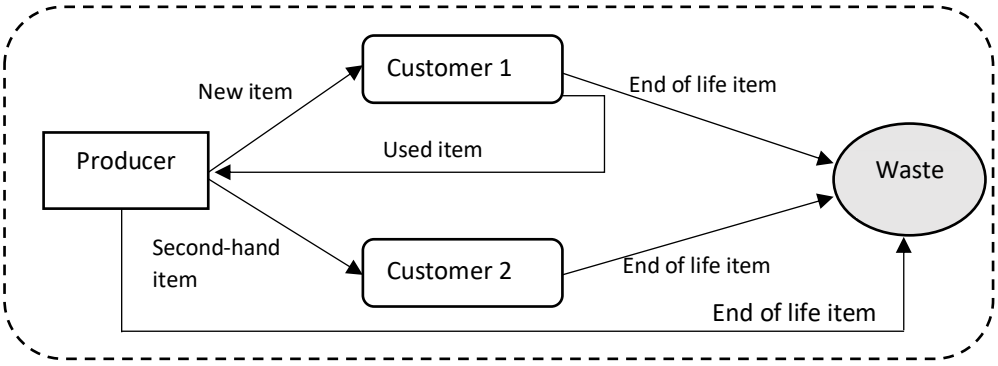

Figure 2. Product flow diagram

Table 3 lists all the notations used in the model.

Table 3. Notations

Parameter	Default values	Description
C	30	Production cost
r_d	0.1	Rate of obsolescence
k	0.005	Coefficient of production rate
Un	$Uniform\,(40,70)$	Buyer's utility threshold for new product purchase
Ur	$Uniform\,(20,40)$	Buyer's utility threshold for second-hand item purchase
W_f	$Uniform\,(0.5)$	Coefficient of newness in utility
W_p	$Uniform\,(0.5)$	Coefficient of price in utility
P	$Uniform\,(62,67)$	Initial price
F	$Uniform\,(50,45)$	newness
p_n		Price of new item
p_u		Price of a second-hand item
p_{us}		Price of improved item
q_n		Quantity of new items
q_u		Quantity of second-hand items
q_{us}		Quantity of sold second-hand items
q_{eol}		Quantity of end-of-life items
s		Subsidy for collected items
Gp		penalty

There are n buyers and m items with different prices (P_j) and freshness (F_j) for purchase in the model. Each buyer, at each time (t), selects one of the items to purchase according to their utility function (U_i), which depends on price and freshness (Relation 1).

$$U_i = \left(w_f * F_j\right) - (w_p * P_j) \tag{1}$$

Here, as mentioned earlier, items are divided into four categories: new items, which have the highest novelty and price; second-hand items, whose utility and price have decreased over time; improved second-hand items, whose utility and price are higher than non-improved ones but lower than new items; and finally, items with expired life that are no longer usable. The producer's decisions about production volume in this model depend on the conditions of the previous period, such as the profit level. There is a probability of not producing in a period. This probability depends on the profit from the previous period and is calculated using Relation 2.

$$p - produce = 1 - \ e^{-k*profit(t-1)} \tag{2}$$

At the beginning, the producer will produce a certain number m of new items. Then, the producer's profit is defined according to the model's assumptions, as shown in Relation 3.

$$profit = (p_n - C)q_n + (s - \ p_u)q_u + p_{us}.q_{us} - Gp.q_{eol} \tag{3}$$

The model parameters were extracted from data provided in official reports of the Organization for Economic Cooperation and Development and the research literature (Brown & Börkey, 2024;

Cooper & Claxton, 2022; Zhang et al., 2020; Mellal, 2020). The NetLogo software implemented the research model to determine producer profit, the number of discarded items, and the number of improved items. Five scenarios were designed and simulated to demonstrate and examine the EPR model's impact. The outputs of each scenario were compared with those from previous research models. Additionally, following standard practices in simulation literature (Windrum, Fagiolo, & Moneta, 2007), the outputs were presented to three experts for validation. These experts had backgrounds in waste management and agent-based simulation and more than three years of work experience in waste management.

Scenarios

Considering the primary purpose of this research, five scenarios were designed. All cases of government intervention in the market have been included in the designed scenarios. These scenarios were developed by examining the proper design of EPR by the government in the market. All scenarios and their assumptions are presented in Table 4.

Table 4. Proposed scenarios

Scenario	Reference	Production decision	Government's role
1	(Zhang et al., 2020)	There is a 50% chance that a new product will be produced unrelated to the profit or loss from previous periods.	The government intervenes by imposing rewards and penalties.
2	(Zhang et al., 2020)	The probability of producing a new product is related to the profit in the previous period.	The government intervenes by imposing rewards and penalties.
3	(Zhang et al., 2020)	The probability of producing a new product is related to the profit in the previous period.	The government intervention is limited to providing rewards.
4	(Aleve et al., 2020)	The probability of producing a new product is related to the profit in the previous period.	The government does not interfere.
5	(Aleve et al., 2020)	The probability of producing a new product is related to the profit in the previous period.	The government intervenes by imposing penalties.

Also, the input values that vary between scenarios are shown in Table 5, while the fixed inputs standard to all scenarios are presented in Table 6.

Table 5. Parameter values of scenarios

Scenario	1	2	3	4	5
Gp	25	25	0	0	10
s	25	25	10	0	0
$p-produce$	0.5	$1-e^{(-0.005 * profit(t))}$	$1-e^{(-0.005 * profit(t))}$	$1-e^{(-0.005 * profit(t))}$	$1-e^{(-0.005 * profit(t))}$

Table 6. Fixed parameters

Number of customers	Price of the new product	New product acceptance
50	$Normal\ [62, 67]$	$Normal\ [50, 45]$

Results

Here, the research findings and answers to the research questions were presented. First, the results obtained from each scenario are illustrated and discussed.

Scenario 1

Figure 3 shows the cumulative profit, the profit, and the number of products represented as the cumulative number of total new products, the cumulative number of end-of-life items, and the number of second-hand items. The implemented EPR policy causes fluctuations in profit. However, this policy has successfully controlled the rate of second-hand and end-of-life items. The cumulative number of end-of-life items has increased gradually and in a controlled manner, indicating the effectiveness of the EPR policy. The number of second-hand items has remained relatively constant and stable due to a fixed policy for the provision and resupply of used items. Government intervention appears to have been effective, particularly regarding rewards.

Scenario 2

Here, the production rate depends on the profit level in the period. On the other hand, the period's intervention in the form of an EPR penalty reduces profitability. As a result, the manufacturer does not produce new products but instead seeks second-hand market activity. The total profit of the manufacturer is much lower than in scenario 1 (Figure 4). Unlike scenario 1, in which the manufacturer's behavior was planned regardless of the profit level in the previous period, in this scenario, the profit level affects the production decision. Consequently, the manufacturer's behavior in producing new products is more controlled, and the growth rate of end-of-life products is slower than in the previous case. Therefore, the EPR policy has been more effective in this case. The situation of second-hand products in this scenario is similar to the previous scenario.

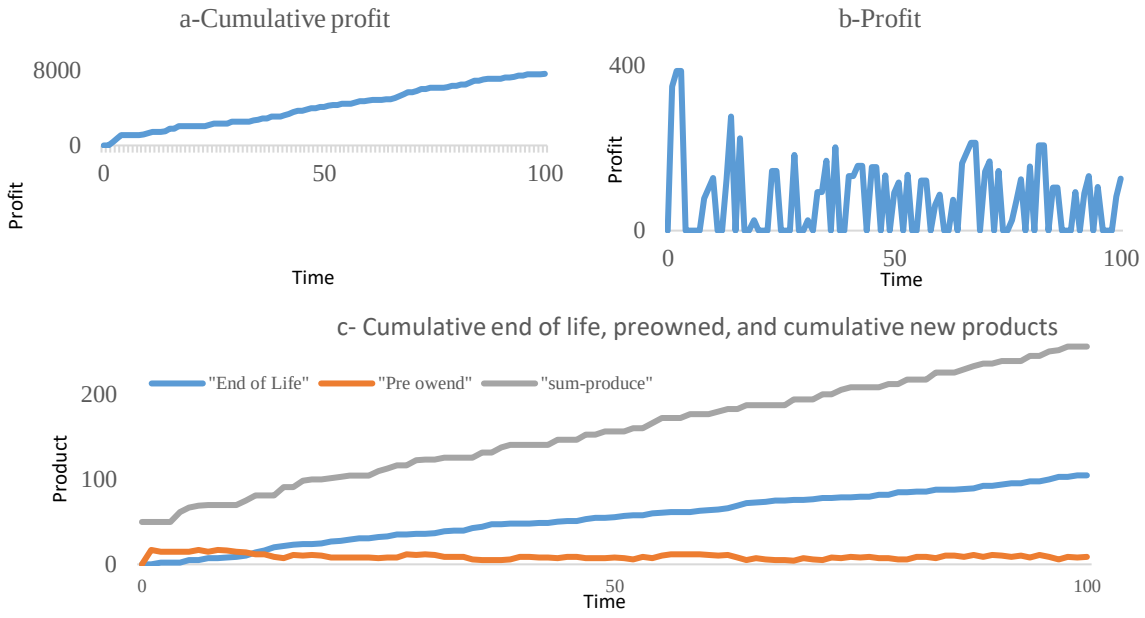

Figure 3. Results obtained from Scenario 1

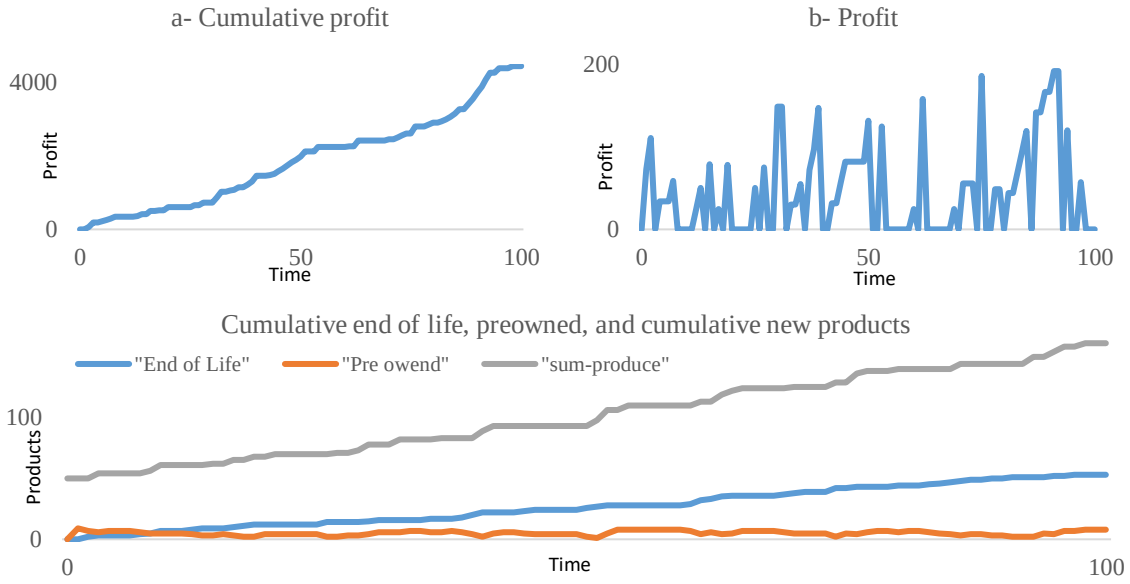

Figure 4. Results obtained from Scenario 2

Scenario 3

The government does not impose a penalty but rewards the producer for each second-hand product purchased from the market. The cumulative profit of the producer in this case is higher than in Scenario 2, due to the absence of a penalty and only the provision of a reward to the producer (Figure 5). It is also observed that the production of new products in the initial periods increased with an upward trend due to the lack of second-hand items in the market, and ultimately to the producer's disadvantage. However, this loss is quickly compensated for in subsequent periods. Additionally, the effect of implementing the EPR policy on increasing the production of new products and the high creation rate of discarded items is evident. This indicates that the objectives of the EPR policy were not fully compatible with this scenario. It is observed that the producer has purchased and sold all the second-hand items available in the market.

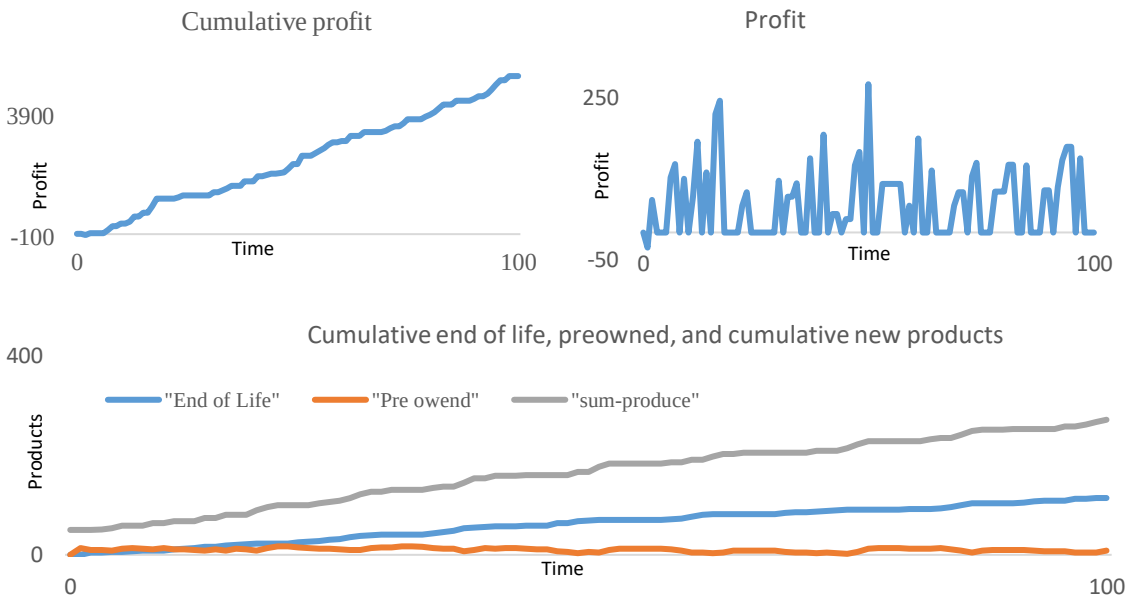

Figure 5. Results obtained from Scenario 3

Scenario 4

Here, the government does not intervene in the second-hand product sector, but the manufacturer can buy and sell second-hand products in the second-hand market. Figure 6 shows that the manufacturer's profit increases to a limited extent and stabilizes after a while due to the absence of government incentives. The manufacturer's presence in the second-hand market continues until it reaches the profitability ceiling, after which it no longer participates in the second-hand market.

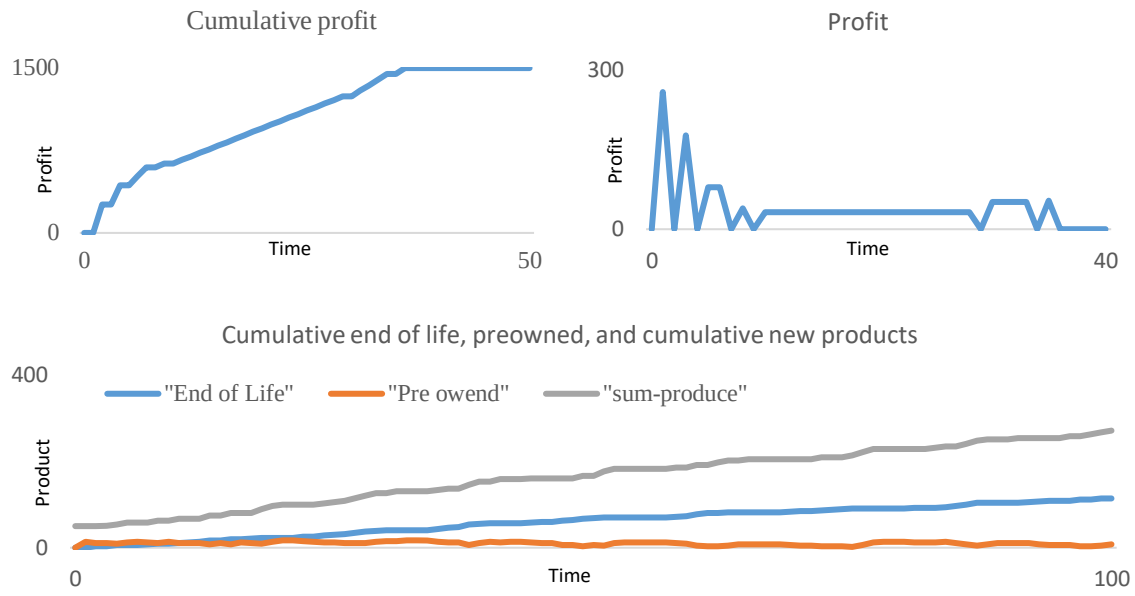

Figure 6. Results obtained from Scenario 4

Scenario 5

Figure 7 shows that the manufacturer has maintained profitability despite the government's punitive policies. Profit fluctuations indicate the direct impact of government fines on profits during specific periods. Compared to scenario 4, profitability is higher, which indicates that the manufacturer's performance complies with the rules and employs effective solutions to manage financial pressures caused by penalties. However, profits are lower than in the first, second, and third scenarios, where government incentives were provided. Figure 7 shows a decrease in the number of end-of-life products. The collection of second-hand products is carried out by the manufacturer with a time delay, indicating that the manufacturer waits until the government reaches the acceptable limit. The table provides a summary of the results of the five scenarios.

Table 7. Results from the scenarios

Scenario	Cumulative profit	Cumulative end of life	Cumulative new products	Ratio of end-of-life items to total production
1	8000	105	257	0.4
2	4500	53	161	0.32
3	5260	114	271	0.42
4	1500	36	70	0.51
5	2680	24	67	0.35

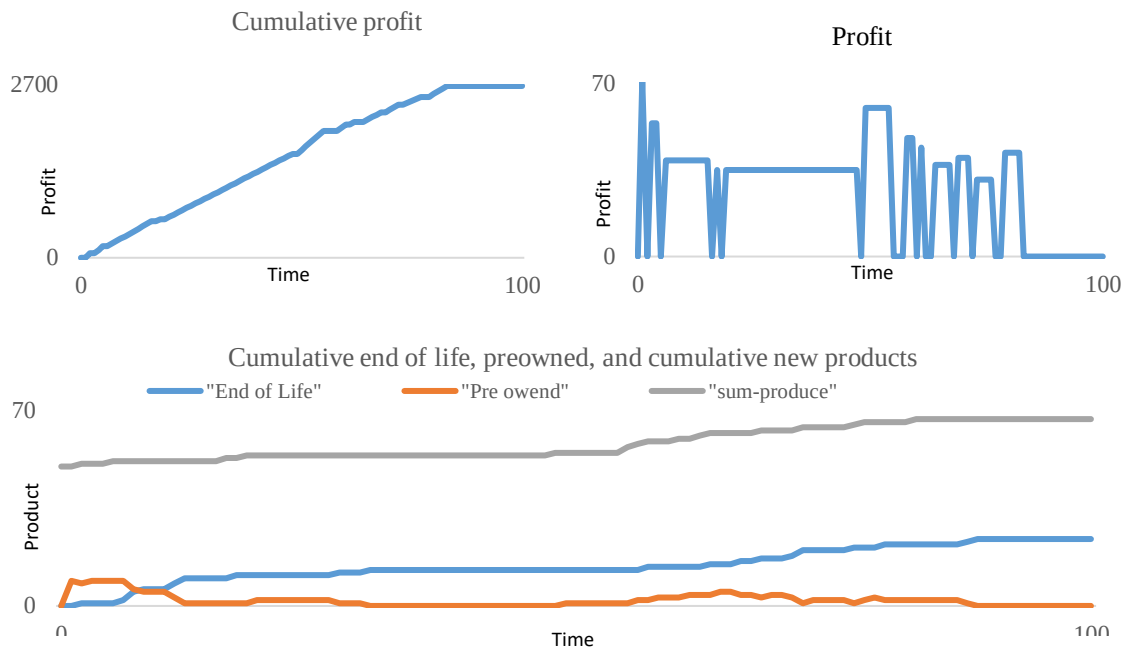

Figure 7. Results obtained from Scenario 5

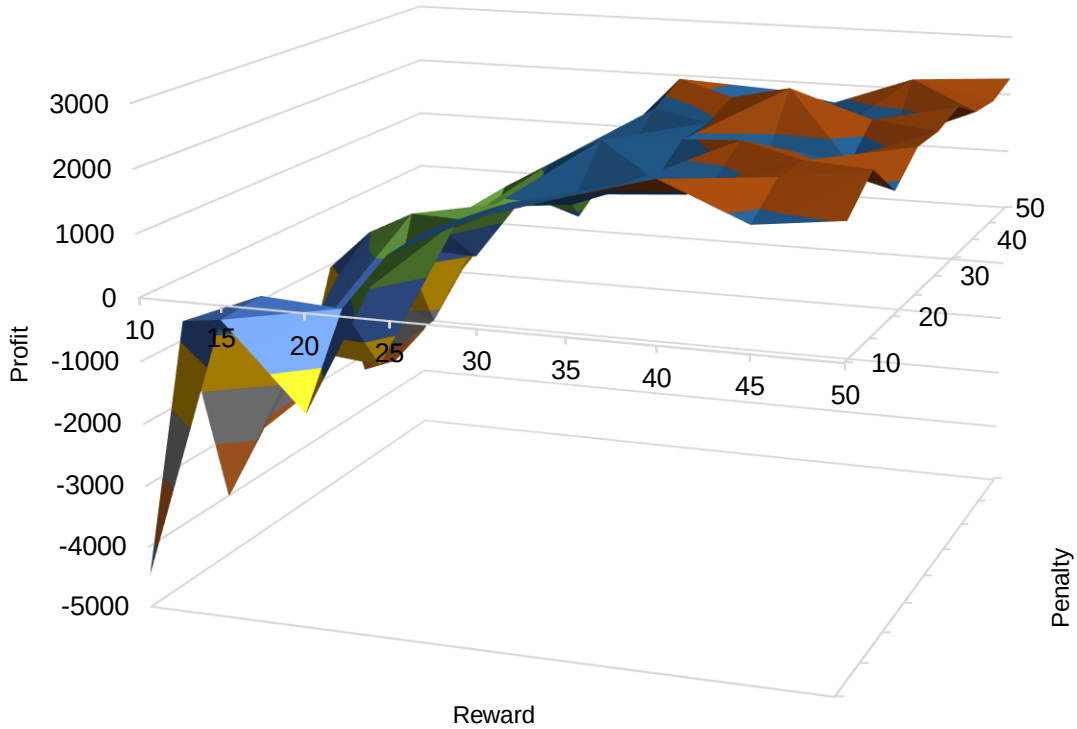

Figure 8. Profit with respect to reward and penalty

Figure 8 shows the sensitivity analysis of the reward and penalty rates applied by the government as EPR incentives. Results show that the imposition of penalties has a greater impact on profits, such that an appropriate combination of reward and penalty rates can enhance industry profitability. In response to the first and third research questions, Table 7 shows that implementing EPR in all scenarios has reduced the volume and proportion of end-of-life products in the market. At the same time, manufacturers have maintained and even increased their profitability by participating in the second-hand product market. Regarding the second research question, the results indicate that considering both the manufacturer's profitability and the reduction in the proportion of end-of-life products relative to total products, government intervention through the simultaneous application of rewards and penalties yields better outcomes. However, imposing penalties is more effective if only reducing the volume of end-of-life products is considered

Conclusion

One of the main tools for environmental sustainability and improving recycling processes is EPR, which helps governments require producers to collect end-of-life products and facilitate recycling and reuse processes. Through legislation, governments can play a key role in guiding second-hand markets and encouraging manufacturers to accept and manage end-of-life products (Wysokińska, 2016). Granting the necessary licenses to manufacturers to participate in the second-hand market can help increase the sale of second-hand products, and governments can facilitate the purchase and sale of second-hand items, allowing manufacturers to exploit this market (European Commission, 2015).

Given the high pollution level and waste generation in the apparel industry, this study examined the feasibility and modeling of implementing an EPR policy in this sector. The strong influence of fashion and the emotional connection consumers have with clothing make the implementation of EPR in this industry different from others. Based on this unique feature, this study integrated the concept of "emotional durability" alongside physical durability. It used agent-based simulation to evaluate EPR policies in the apparel industry by assessing five scenarios.

In the first and second scenarios, balanced penalties and rewards for manufacturers led to increased sustainable production and reduced waste. The cumulative profit of manufacturers in these scenarios increased steadily, indicating the positive effect of the EPR policy in guiding the market towards the collection and reuse of second-hand products. In all scenarios, including the second where production depended on the manufacturer's profit in previous periods, it is observed that the EPR policy reduces the production of new products and instead encourages manufacturers to increase profits through the second-hand market. This ultimately improves environmental

aspects and increases the efficiency of recycling systems, resulting in reduced environmental pressures (Ghisellini et al., 2016).

In the third scenario, the government does not impose penalties. It only uses rewards to incentivize the purchase of second-hand products, which increases manufacturers' profitability and improves the performance of the second-hand market. In the fourth scenario, there is no government intervention. Consequently, manufacturers participate in the second-hand market to a limited extent, demonstrating that without government intervention, manufacturers only recycle and return second-hand products when there is a substantial financial incentive.

Considering the model assumptions, this research has limitations such as the producer's monopoly, the model's two-level nature, and the absence of retailers and other intermediaries in the market. Given these limitations and the importance of further examining the effects of the EPR policy on market improvement, it is suggested that future research consider budget constraints for the government, the role of intermediary institutions in collecting and cleaning second-hand clothing, the effect of multiple manufacturers in the market, and the impact of consumer culture and advertising on buyers' longevity functions.

Data Availability Statement

The data supporting this study's findings are derived from previously published studies cited and discussed in the manuscript. No new primary data were generated in this study.

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Ethical considerations

This article does not involve any studies conducted by the authors on human participants or animals.

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Conflict of interest

The authors have no conflicts of interest to disclose.

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