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Impact of Circular Economy on Waste Elimination Within the Sustainable Supply Chain Framework

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Abstract

In a system of production and consumption, sustainable supply chain management plays a crucial role in overseeing and curbing excessive waste. This research introduces two interconnected supply chains dedicated to waste elimination within the production and consumption processes. The study integrates the tenets of the circular economy (CE) explicitly emphasizing the 3R concepts, which are Reduce, Restore and Recycle. Within this framework, the initial product in the primary chain follows degradation and transforms into raw material for the production system of the secondary chain (secondary production facilities). When transporting used products to recycling facilities, losses may occur due to leakage from the containers during transportation. The unique contribution of this study is determination of the optimal values for price discounts and container leakage costs, emphasizing a key aspect of the CE: the reduction and recovery of discarded items in successive stages. Mixed-integer nonlinear programming is employed for the dual supply chain to optimize the joint cost function using classical methods. A noteworthy numerical outcome is established to validate this concept: with an increase in the leakage cost per container from \$5 to \$10, the overall supply chain costs are immediately reduced by approximately 90%.

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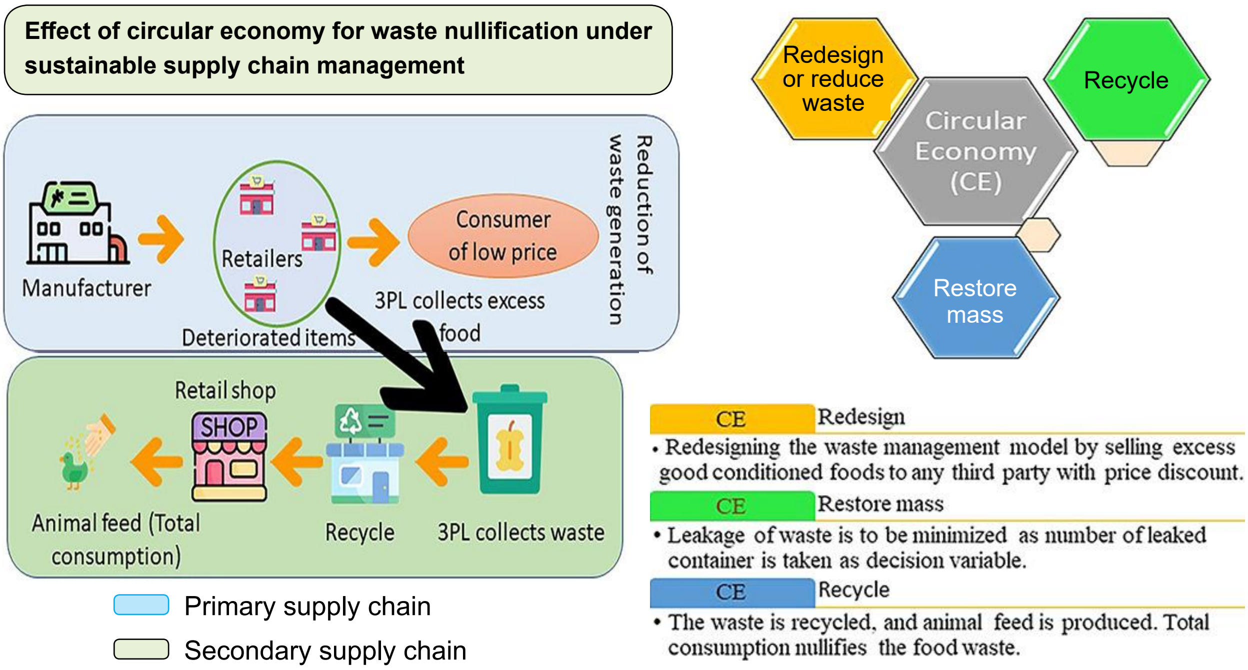
Graphical abstract



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JEL Classification: Q53, L60, Q01, M11, C61

1. Introduction

The global state of food waste, along with its environmental, social and economic impacts, is a significant concern. In this context, adopting the circular economy (CE) concept has become imperative for waste prevention, securing raw material supplies, creating jobs, providing ecological relief and stimulating the economy (Walker *et al.*, 2021). The environmental benefits of CE include reduced greenhouse gas emissions, replenishment of soil nutrients and decreased waste disposal (Hens *et al.*, 2018). Economically, CE is expected to conserve up to 70% of raw materials while fostering the development of complementary semi-skilled and local employment opportunities. By incorporating innovative concepts into the supply chain framework, we can minimize waste disposal (Hou *et al.*, 2023). The CE principle of rerouting items to alternative channels for utilization enhances this approach, illustrating the evolution of food donations and their consequences (Ghoreishi *et al.*, 2023). Additionally, a study examining Italy's food policy proposed a strategy that promotes donations of food items after their best-before dates to reduce waste (Singh *et al.*, 2023).

Recycling plays a crucial role in reducing waste within the supply chain. Anaerobic digestion and incineration processes are important considerations regarding greenhouse gas emissions and electricity generation. Efficiently recycling food waste from various sources, such as restaurants, homes, cafes and supermarkets to produce chicken feed and liquefied fertilizers is essential for achieving a sustainable future. Addressing material loss, particularly due to container leakage during transportation or loading, is a significant concern (Erdiaw-Kwasie *et al.*, 2023). Investigations into capacitance-based rapid container closure testing have been conducted as a preventive measure to mitigate beverage container leakage. When waste is transported in containers for recycling, leakage can lead to material losses, resulting in additional costs for the supply chain (Irshad *et al.*, 2019).

Addressing these research gaps can enhance our understanding of the practical implications and effectiveness of the circular economy concept in waste reduction. Waste elimination and the CE share the overarching goal of achieving sustainable development (Alola and Adebayo, 2023). In relation to UN Sustainable Development Goals (SDGs), our study explicitly states which SDGs are affected, such as Responsible Consumption and Production (SDG 12). Waste elimination concentrates solely on procedures to remove waste from society, whereas the CE operates on a broader scale. The CE involves the design and management of waste within the supply chain, aiming to maintain a functional form of products throughout their life cycles and protect natural systems (Khokhar *et al.*, 2022). Moreover, ensuring full consumption of the final product contributes to waste elimination. Waste elimination is related to CE concepts as it addresses large-scale recovery issues during waste transportation, particularly concerning container leakage maintenance (Burke *et al.*, 2023). The main contributions of this study can be summarized as follows:

- We introduce the concept of price discounts to minimize waste production at the retailer level, making food more affordable and accessible to diverse demographics, thereby reducing overall waste.
- We propose a strategy to optimize waste utilization for recycling purposes, ensuring mass restoration. It includes an assessment of the influence of leakage costs on the entire supply chain within the CE framework.
- We advocate for utilizing recycled items as feed for livestock, fisheries or poultry, effectively eliminating waste and reinforcing the principles of the CE concept.

The research questions of the study are based on the above contributions.

RQ1: How can the CE principles be effectively integrated into food waste management?

RQ2: How can the CE principles minimize environmental impact, improve economic efficiency and promote social equity, especially in the context of the United Nations Sustainable Development Goals (SDG 12)?

To answer the research questions, the study has the following research objectives.

1. Examine the global state of food waste, identify key sources, trends and statistics and assess the environmental, social and economic impacts associated with food waste.
2. Study the principles and practices of the CE, with a focus on how it can be applied to food waste management to promote sustainability and resource efficiency.
3. Quantitatively and qualitatively assess the environmental benefits of adopting CE practices in food waste management, including greenhouse gas emission reduction, soil nutrient replenishment and waste treatment.
4. Analyze the economic advantages of implementing a CE strategy, such as cost savings through material savings, job creation in the recycling and waste management sectors and the potential for increased profitability through efficient use of resources.
5. Examine how CE practices can improve food accessibility and affordability, especially for marginalized communities, while promoting responsible consumption and production patterns (SDG 12).
6. Develop strategies and recommendations for optimizing waste utilization, including introducing price discounts at the retail level, strengthening recycling processes and utilizing recycled materials in animal feed and fertilizers.
7. Assess the role of technological innovations, such as capacitance-based rapid container closure testing, in minimizing material losses due to container leakage during transportation and recycling.
8. Explore how incorporating CE practices into food waste management can contribute to achieving the United Nations Sustainable Development Goals, with a particular focus on responsible consumption and production (SDG 12), as well as broader environmental sustainability goals.

This study aims to bridge the knowledge gap on the practical implications of CE in food waste management and provide insights for sustainable practices that can reduce waste generation, enhance economic viability and improve social outcomes in line with the United Nations Sustainable Development Goals. The present study comprehensively addresses and elucidates previously identified research gaps. Notably, this study introduces unique elements such as leakage reduction to prevent waste recycling losses and price optimization to minimize waste generation.

The rest of the paper is organized as follows: Section 2 summarizes the existing literature on CE, waste management, promising technologies, supply chain management and associated topics. Section 3 outlines the problem formulation, lists the mathematical expressions representing the model and details the solution. Section 5 delves into the sensitivity analysis of the limitations, offering insights into managerial considerations that serve as the conclusion of the study.

2. Literature Review

In this section, we delve into previous research studies within the field, identifying key findings and emphasizing existing literature gaps that provide the rationale for the present study (Giannetti *et al*., 2023). Previous research has explored waste management, CE, optimization technologies and supply chain management. Key themes and results of relevant studies are summarized below:

Circular economy (CE): Several studies have investigated the principles and applications of the CE, emphasizing its role in sustainability, waste reduction and resource efficiency (Hailiang *et al*., 2023). The CE concept has been explored in diverse sectors, including manufacturing, agriculture and service industries.

Waste management: A considerable body of literature has addressed waste management strategies, encompassing waste reduction, recycling and the environmental impacts of different disposal methods (Kliestik *et al*., 2023). Studies have focused on municipal and industrial waste streams, examining technological advancements and policy interventions (Khan *et al*., 2012).

Optimization techniques: Optimization techniques in supply chain management have been a subject of interest. Research has explored mathematical models and algorithms to enhance supply chain efficiency, cost-effectiveness and sustainability (Schätter *et al*., 2019).

Supply chain management: Previous research has examined various aspects of supply chain management, including inventory control, transportation logistics and overall operational efficiency (Liao *et al*., 2023). Supply chain management research aims to improve processes, reduce costs and enhance supply chain sustainability (Vishwakarma *et al*., 2023).

Despite the wealth of existing research, certain gaps persist in the literature, paving the way for the present study.

Integrated approach: Limited research has taken an integrated approach that combines CE principles with optimization techniques in the context of waste management within supply chains (Romagnoli *et al*., 2023).

Price discount strategies: Exploring price discount strategies to reduce waste and simultaneously optimize supply chain costs remains unexplored in the existing literature.

Container leakage impact: Previous studies have lacked a comprehensive exploration of its impact on the entire supply chain, especially within the framework of the CE concept.

Given the gaps identified in the literature, the present study aims to contribute by addressing these limitations (Khokhar, Hou *et al*., 2020). The research integrates CE principles, optimization techniques and novel strategies such as price discounting and management to develop a holistic approach to waste reduction within the supply chain (Nguyen *et al*., 2023). The study aims to fill gaps and provide valuable insights to academic and industry practitioners from this interdisciplinary perspective (Yontar, 2023).

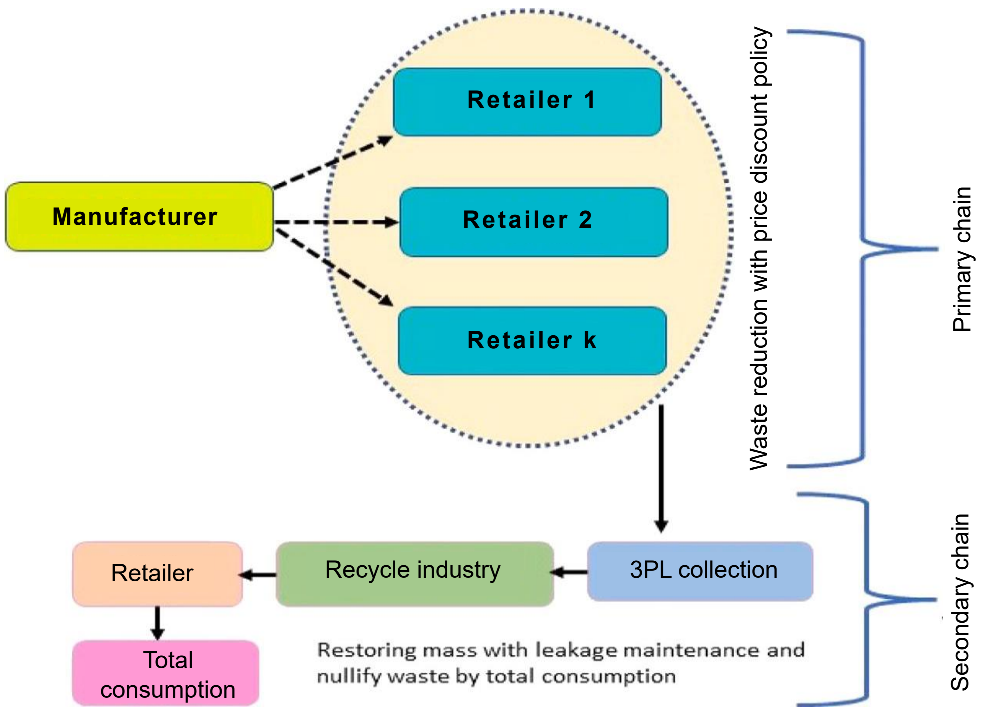
2.1 Circular economy concept and waste elimination in sustainable supply chains

The CE represents a sustainable model that focuses on redesigning or re-converting waste into valuable by-products, ultimately transforming the supply chain into a zero-waste environment. On the flip side, zero waste functions as a public policy to achieve an environment free of waste (Chen *et al*., 2023). Recent studies have observed the development of interconnected ideas, particularly the elimination of waste and the concept of CE (Chavez *et al*., 2022). The incorporation of terms such as “reuse” or “recycle” in describing the benefits of CE underscores its positive environmental impact. The collaboration between a sustainable supply chain and a CE is highlighted, outlining a roadmap for a circular bio-economy, especially concerning waste valorization (Ishaya *et al*., 2024). Ongoing research focuses on the shift from linear to CE models, aiming to strike a balance between sustainability and commensurate profitability (Hossain *et al*., 2023). The adoption of the zero-waste concept, coupled with intra-organizational learning, contributes to achieving the sustainable model of the CE, including a strategic decision-making approach for addressing issues related to perishable food goods.

2.2 Price discounts and container leakage reduction towards sustainability

Numerous supply chain management models utilize price reductions or quantity discount strategies for diverse objectives. In tackling the challenge of reducing food waste, Findik *et al*. (2023) suggested amalgamating dynamic shelf life (DSL) with a discounted pricing scheme. DeBerge (2024) focused on optimizing a meat seller's discounting policy and replenishment strategies. Ahmad *et al*. (2024) considered cash-flow discounts for perishable food products, acknowledging that demand diminishes over time, and the authors integrated the time value of money into perishable food supply chain management. Wendt and Sigurjonsson (2024) investigated sorting subsidies within solid waste management, achieving sustainable optimization. They calculated algorithm efficiencies using the relative percentage deviation process to address real-life situations. Khokhar, Iqbal *et al*. (2020) delved into an energy supply chain that integrated credit sales and accounts for stochastic demand. They formulated a study to recover mass and fortify environmental integrity within the domain of transportation and leakage.

Figure 1: CE model, highlighting components of redesign (reuse), restrictiveness and recycling



Source: Authors' own elaboration

In this supply chain model (Figure 1), the primary chain comprises two participants: the distribution process encompasses the manufacturer and multiple retailers. Given the perishable nature of the finished product, retailers implement a price discount strategy to expedite the sale of items nearing expiry (Abdallah *et al.*, 2024). This approach not only diminishes waste generation but also facilitates the reuse of products. The secondary chain manages the waste generated in the primary chain. Third-party logistics (3PL) are crucial in channeling waste from retailers within the primary network. The collected waste is then transported via containers to the recycling industry (Bai *et al.*, 2024). However, these containers can suffer damage during transportation, loading or adverse weather conditions, resulting in potential waste leakage losses. In the recycling industry, waste is eliminated by utilizing it to create specific products (Henriques and Catarino, 2017).

3. Methodology

The primary chain comprises a manufacturer and multiple retailers, whereas the secondary chain includes third-party logistics (3PL), recycling facilities and additional retailers. The direct chain is structured to minimize waste by reimagining sustainability within the CE framework. It requires redistributing the remaining quantities of viable food at discounted prices to reduce waste generation. Third-party logistics (3PL) collect low-quality items in the secondary chain and transport them to the recycling industry.

3.1 Primary chain composition

Manufacturers specialize in producing a single product type in the primary chain, which is then dispatched to retailers under a single-setup-multiple-delivery (SSMD) plan. Both supply chains adhere to the order policy. This product has scrap characteristics and its rate of deterioration is time-related, expressed by the following function: $= \frac{1}{1+\zeta-t}$, where ζ represents the maximum lifespan of a single product. It is worth noting that similar deterioration rates were considered in a recent study examining the effect of conservatism on unlimited demand. Figure 2 illustrates the inventory model of participants within the primary chain.

Table 1: Symbols representing decision variables and parameters

Index	
α	**Retailer index**
Decision	**Variable**
γ	Waste shipping (integer)
a	Multiple of major retailer time (integer)
a_1	Multiple of seller time on the primary chain (integer)
b	Multiple of 3PL time in the secondary supply chain (integer)
c	Multiple of secondary supply chain recycling industry time (integer)
β	Quantity of finished goods shipped to retailer (integer)
n_1	Quantity of items shipped to reprocessing industry (integer)
n_2	Number of animal feed shipments sent to seller (integer)
T	Time (year)
Random	**Variable**
ρ	Remaining high-quality food recovery rate; $0 \leq \rho \leq 1$
δ	Container leakage ratio; $0 \leq \delta \leq 1$
Player parameters	
Primary supply chain	**Manufacturer**
o_{m1}	Ordering costs (USD per order)
d	Unit time condition (per year) T_{unit}
b_2	Development costs (cost per time unit) $C_{development}$
h_{cm}	Finished goods holding costs (cost per time unit) $H_{finished\_goods}$
b_3	Material costs (cost per unit) $C_{material}$
p	Productivity (unit per time)
S_{e1}	Set-up costs (cost per set-up) C_{setup}
b_1	Tool costs (proportional to productivity) $C_{tool/die}$
Primary supply chain	**Retailer**
d_c	Deterioration costs ($/unit)
d_α	Retailer α demand (unit/year)

Table 1: Symbols representing decision variables and parameters (continuation)

C_{rh}	Holding costs ($ / unit / unit time)
$I_{max\alpha}$	Retailer α initial maximum inventory (units)
ζ	Maximum life of food (years)
$I_{\alpha r}$	Retailer α existing inventory, $0 \leq t \leq T$ (unit)
o_{α}	Retailer α ordering costs (cost/order)
C_{pd}	Excess product price discount (USD/item)
θ	Product deterioration rate (%)
Secondary supply chain	**3PL**
C_c	3PL collection costs ($/unit)
F_c	Fixed shipping costs (USD/ticket)
Recycling	Industry
Q_{recy}	Quantity of waste received from third party (in units)
C_l	Costs of leakage per container (cost per container unit)
k_2	Coefficient of proportionality
C_{vt}	Flexible shipping costs (cost per quantity)
d_{m2}	Recycling industry demand (units/year)
h_{cm2}	Waste holding (cost per unit)
Q_{mat}	Additional material purchase quantity (units)
h_{crecy}	Recovery holding costs (cost per unit per time)
C_{nwm}	New material procurement costs (cost per piece)
o_{m2}	Ordering costs (USD/order)
S_{erc}	Establishment costs of the recycling industry (USD/establishment)
C_{wt}	Waste procurement costs (USD/unit)
Secondary supply chain	**Retailer**
d_{r2}	Retailer demand (pieces/year)
C_{h2}	Holding costs of recycled products (cost per unit per trip)
o_{r2}	Ordering costs ($/order)

Source: Authors' own elaboration

3.2 Retailer's cost structure

The current model comprises υ sellers at the initial stage of the supply chain. The retailer α has demand for the product represented by $d\alpha$, and the overall product demand is represented by $d = \sum_{\alpha=1}^{\upsilon} d_\alpha$. The formula governing retailers is articulated as follows:

$$\frac{dI_{\alpha r}}{dt} = -d_\alpha - \theta I_{\alpha r}; 0 \leq t \leq T, I_{\alpha r}(0) = I_{max\alpha} \tag{1}$$

By solving Equation (1), combined with the boundary conditions, the retailer α's existing inventory is articulated as follows:

$$I_{\alpha r} = (1 + \zeta - t)d_\alpha \ln\left(\frac{1+\zeta-t}{1+\zeta-T}\right) \tag{2}$$

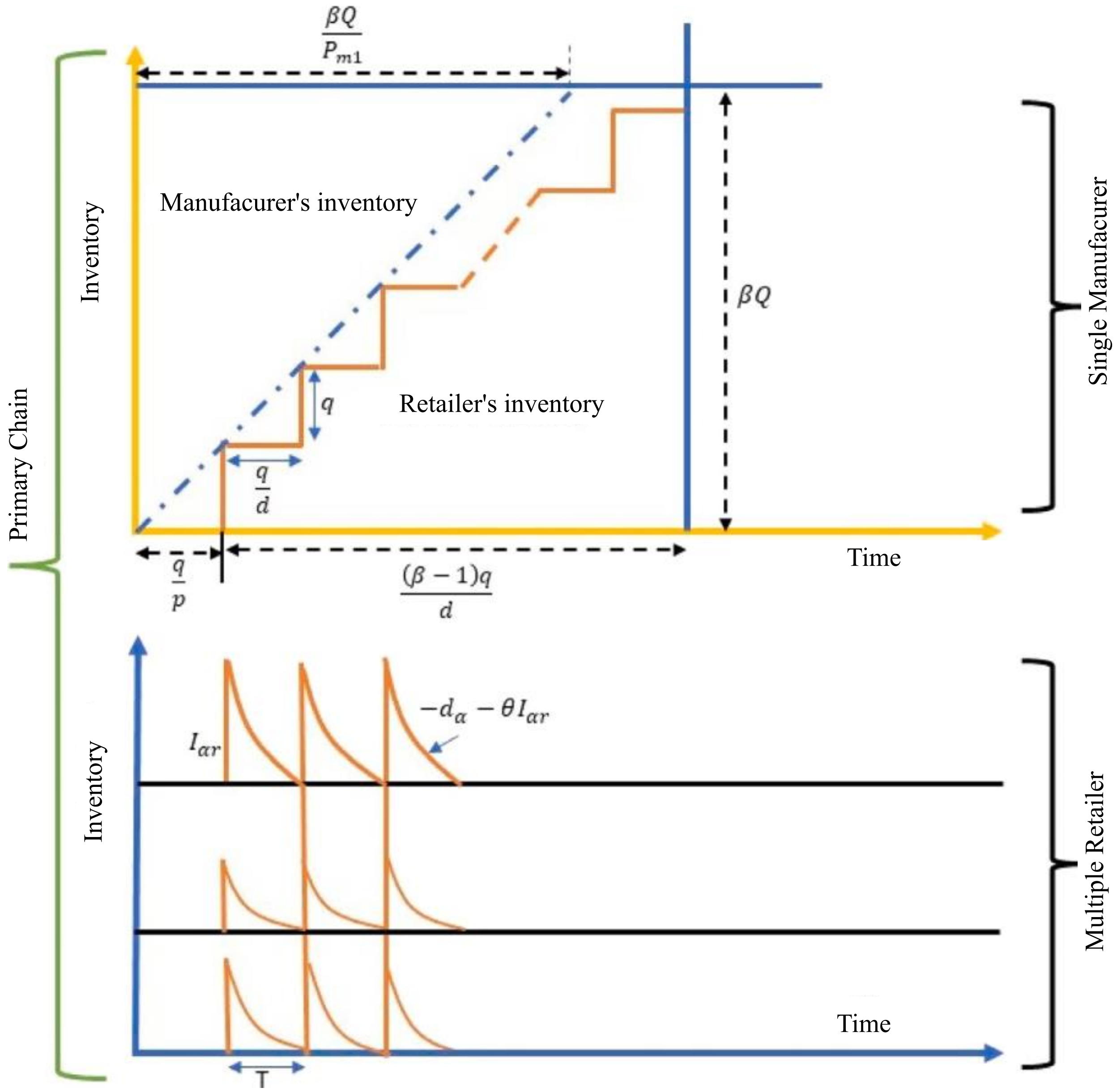
The initial maximum inventory for the retailer α is specified as follows:

$$I_{max\alpha} = (1 + \zeta)d_\alpha \ln\left(\frac{1+\zeta}{1+\zeta-T}\right) \tag{3}$$

The retailer α's finished goods inventory changes over time as follows:

$$\begin{aligned} I_\alpha^{inv} &= \int_0^T (1 + \zeta - t)d_\alpha \ln\left(\frac{1+\zeta-t}{1+\zeta-T}\right) \\ &= d_\alpha \left[\frac{(1+\zeta)^2}{2} \ln\left\{\frac{(1+\zeta)}{(1+\zeta-T)}\right\} - \frac{T\{2(1+\zeta)-T\}}{4}\right] \end{aligned} \tag{4}$$

Figure 2: Comprehensive inventory model for primary chain participants taking into account product degradation in retailer facilities



Source: Authors' own elaboration

The inventory carrying costs for retailers in each cycle are expressed as follows:

$$HC_{r1} = \sum_{\alpha=1}^{v} \frac{C_{rh} d_\alpha}{T} \left[\frac{(1+\zeta)^2}{2} \ln \left\{ \frac{(1+\zeta)}{(1+\zeta-T)} \right\} - \frac{T\{2(1+\zeta)-T\}}{4} \right] \tag{5}$$

The retailer places an order for goods with the manufacturer, incurring associated ordering costs. The ordering process requires the retailer to receive the order in batches, with each batch incurring a fee. The ordering costs are articulated as follows:

$$OC_{r1} = \sum_{\alpha=1}^{v} \frac{o_\alpha \beta}{T} \tag{6}$$

Deteriorated items generated by the retailers are transferred to a third-party logistics (3PL) entity within the secondary supply chain. The costs linked to deterioration per cycle are stated as follows:

$$DC_{r1} = \sum_{\alpha=1}^{v} \frac{d_\alpha d_c}{T} \left[\frac{(1+\zeta)^2}{2} \ln \left\{ \frac{(1+\zeta)}{(1+\zeta-T)} \right\} - \frac{T\{2(1+\zeta)-T\}}{4} - T \right] \tag{7}$$

The retailer sells excess, undamaged merchandise at a discount to the original third-party logistics (3PL) as a strategy to minimize waste generation. The 3PL, in turn, collects these remaining items at a variable rate denoted by ρ, which represents the random variable. The costs incurred by the retailer per cycle are articulated as follows:

$$PD_{r1} = \sum_{\alpha=1}^{v} \frac{E[\rho] d_\alpha C_{pd}}{T} \tag{8}$$

The total costs for the retailer in each cycle are given by:

$$\begin{aligned} TCR_1 &= HC_{r1} + OC_{r1} + DC_{r1} + PD_{r1} \\ &= \sum_{\alpha=1}^{v} \frac{C_{rh} d_\alpha}{T} \left[\frac{(1+\zeta)^2}{2} \ln \left\{ \frac{(1+\zeta)}{(1+\zeta-T)} \right\} - \frac{T\{2(1+\zeta)-T\}}{4} \right] + \sum_{\alpha=1}^{v} \frac{o_\alpha \beta}{T} \\ &\quad + \sum_{\alpha=1}^{v} \frac{E[\rho] d_\alpha C_{pd}}{T} + \sum_{\alpha=1}^{v} \frac{d_\alpha d_c}{T} \\ &\quad \times \left[\frac{(1+\zeta)^2}{2} \ln \left\{ \frac{(1+\zeta)}{(1+\zeta-T)} \right\} - \frac{T\{2(1+\zeta)-T\}}{4} - T \right] \end{aligned} \tag{9}$$

In the primary chain, manufacturers are responsible for producing perishable items and then sending them to retailers. The manufacturer's time is expressed as an integer of the retailer's period, expressed as $a_1 T$. The costs associated with this process are affected by the following:

Manufacturers procure raw materials from diverse suppliers to facilitate product production. The costs incurred for each cycle order are articulated as follows:

$$OC_m = \frac{o_{m1}}{a_1 T} \tag{10}$$

The costs incurred by the manufacturer for each unit set-up are expressed as follows:

$$SC_{m1} = \frac{Se_1}{a_1 T} \tag{11}$$

The production βq of a single item by the manufacturer is established upon the placement of an order by the buyer α for the quantity $q\alpha$ to meet its specific demand. The overall quantity resulting from the orders placed by all buyers is expressed as $q = \sum_{\alpha=1}^{v} q_\alpha$..

It ensures that $q_\alpha = \frac{d_\alpha q}{d}.d_\alpha$ represents buyers' demand α per cycle. The inventory gathered by the supplier is represented as follows:

$$Inv_v = \left[\left(\beta q\left(\frac{q}{p} + (\beta - 1)\frac{q}{d}\right) - \frac{\beta^2 q^2}{2p}\right) - \sum_{\alpha=1}^{v}\left\{\frac{q_\alpha^2}{d_\alpha}(1 + 2 + 3 + \cdots + (\beta - 1))\right\}\right]\frac{d}{\beta q} = \frac{da_1 T}{2}\left[\beta\left(1 - \frac{d}{p}\right) - 1 + \frac{2d}{p}\right] \tag{12}$$

The following expression represents the manufacturer's carrying costs per period:

$$HC_{m1} = \frac{h_{cm} da_1 T}{2}\left[\beta\left(1 - \frac{d}{p}\right) - 1 + \frac{2d}{p}\right] \tag{13}$$

A manufacturer's production costs depend on and are directly affected by the production rate of individual products.

The production costs are articulated as follows:

$$C_p = b_1 p + \frac{b_2}{p} + b_3 \tag{14}$$

where b_1, b_2 and b_3 represent tool, enlargement and material costs.

The wide-ranging production costs are articulated as:

$$PC_m = \left(b_1 p + \frac{b_2}{p} + b_3\right) d \tag{15}$$

The producer's total costs are expressed as:

$$TCM_1 = OC_m + SC_{m1} + HC_{m1} + PC_m = \frac{o_{m1}}{a_1 T} + \frac{Se_1}{a_1 T} + \frac{da_1}{2}\left[\beta\left(1 - \frac{d}{p}\right) - 1 + \frac{2d}{p}\right] + \left(b_1 p + \frac{b_2}{p} + b_3\right) d \tag{16}$$

The overall costs of the primary chain are as follows:

$$TC_{pc} = TCR_1 + TCM_1 = \sum_{\alpha=1}^{v}\frac{C_{rh} d_\alpha}{T}\left[\frac{(1+\zeta)^2}{2}\ln\left\{\frac{(1+\zeta)}{(1+\zeta-T)}\right\} - \frac{T\{2(1+\zeta)-T\}}{4}\right] + \sum_{\alpha=1}^{v}\frac{o_\alpha \beta}{T} + \sum_{\alpha=1}^{v}\frac{E[\rho] d_\alpha C_{pd}}{T} + \sum_{\alpha=1}^{v}\frac{d_\alpha d_c}{T}\left[\frac{(1+\zeta)^2}{2}\ln\left\{\frac{(1+\zeta)}{(1+\zeta-T)}\right\} - \frac{T\{2(1+\zeta)-T\}}{4} - 1\right] + \frac{o_{m1}}{a_1 T} + \frac{Se_1}{a_1 T} + \frac{da_1}{2}\left[\beta\left(1 - \frac{d}{p}\right) - 1 + \frac{2d}{p}\right] + \left(b_1 p + \frac{b_2}{p} + b_3\right) d \tag{17}$$

3.3 Secondary chain components

Secondary chains encompass third-party logistics (3PL) entities tasked with collecting waste from primary chains, the waste recycling industry and retailers specializing in animal food. Possible container leakage during waste transport has been taken into account. The demand from retailers and manufacturers in the recycling industry is articulated as d_{m2} = d_{r2}. It must be emphasized that animal feed is disbursed entirely. Figure 3 visually elucidates the flow of downgraded products from the primary supply chain stores to the secondary supply chain, as well as the inventory of subsequent participants in the secondary supply chain.

An SSMD policy is established when a third-party logistics (3PL) collects waste from primary chains and transports it to the reuse industry. γ is a unit of measurement that represents the capacity of a container. The fee breakdown is as follows:

Third-party logistics (3PL) collects waste from major chains. The time cycle of third-party logistics (3PL) is synchronized with the time cycle of the primary chain supply chain. In one cycle, the quantity of waste acquired from first-level chain retailers is calculated as follows:

$$\sum_{\alpha=1}^{v} \frac{d_\alpha}{T}\left[\frac{(1+\zeta)^2}{2}\ln\left\{\frac{(1+\zeta)}{(1+\zeta-T)}\right\}-\frac{T\{2(1+\zeta)-T\}}{4}-T\right] \tag{18}$$

The collection costs per cycle are calculated based on the waste units collected as follows:

$$CC_{3pl}=\frac{C_c}{aT}\sum_{\alpha=1}^{v} d_\alpha\left[\frac{(1+\zeta)^2}{2}\ln\left\{\frac{(1+\zeta)}{(1+\zeta-T)}\right\}-\frac{T\{2(1+\zeta)-T\}}{4}-T\right] \tag{19}$$

Transporting waste from third-party logistics (3PL) to the recycling industry incurs costs and is done on a n_1 equivalent transport basis. If any quantity of goods needs to be shipped beyond a fixed shipment, variable costs need to be taken into account.

Therefore, the transport costs per period are articulated as follows:

$$TC_w=\frac{n_1F_c}{aT}+\frac{C_{vt}\sum_{\alpha=1}^{v} d_\alpha\left[\frac{(1+\zeta)^2}{2}\ln\left\{\frac{(1+\zeta)}{(1+\zeta-T)}\right\}-\frac{T\{2(1+\zeta)-T\}}{4}-T\right]}{\gamma aT} \tag{20}$$

Containers convey waste from third-party logistics to the recycling industry and it is recognized that leaks may transpire during transportation. Let γ represent the capacity of the container. There will be a cost to repair or replace a leaking container.

Therefore, the cycle leakage costs can be articulated as:

$$C_{leak}=\frac{\sum_{\alpha=1}^{v} d_\alpha\left[\frac{(1+\zeta)^2}{2}\ln\left\{\frac{(1+\zeta)}{(1+\zeta-T)}\right\}-\frac{T\{2(1+\zeta)-T\}}{4}-T\right]}{\gamma aT}C_lE[\delta] \tag{21}$$

The total costs incurred by third-party logistics (3PL) per cycle are as follows:

$$TC_{3PL} = CC_{3pl} + TC_w + C_{leak} = \frac{\sum_{\alpha=1}^{v} d_\alpha \left[\frac{(1+\zeta)^2}{2}\ln\left\{\frac{(1+\zeta)}{(1+\zeta-T)}\right\} - \frac{T\{2(1+\zeta)-T\}}{4} - T\right]}{aT} \left[C_c + \frac{C_{vt}}{\gamma} + \frac{C_l E[\delta]}{\gamma}\right] + \frac{n_1 F_c}{aT} \tag{22}$$

3.4 Recycling industry cost structure

Scrap from third-party logistics (3PL) is transported to the recycling sector for use in the production of animal feed. Leakage during transportation leads to the loss of waste.

The expression for the amount of waste received and recycled by the recycling industry is as follows:

$$Q_{recy} = \frac{\sum_{\alpha=1}^{v} d_\alpha \left[\frac{(1+\zeta)^2}{2}\ln\left\{\frac{(1+\zeta)}{(1+\zeta-T)}\right\} - \frac{T\{2(1+\zeta)-T\}}{4} - T\right]}{\gamma}(1 - E[\delta]) \tag{23}$$

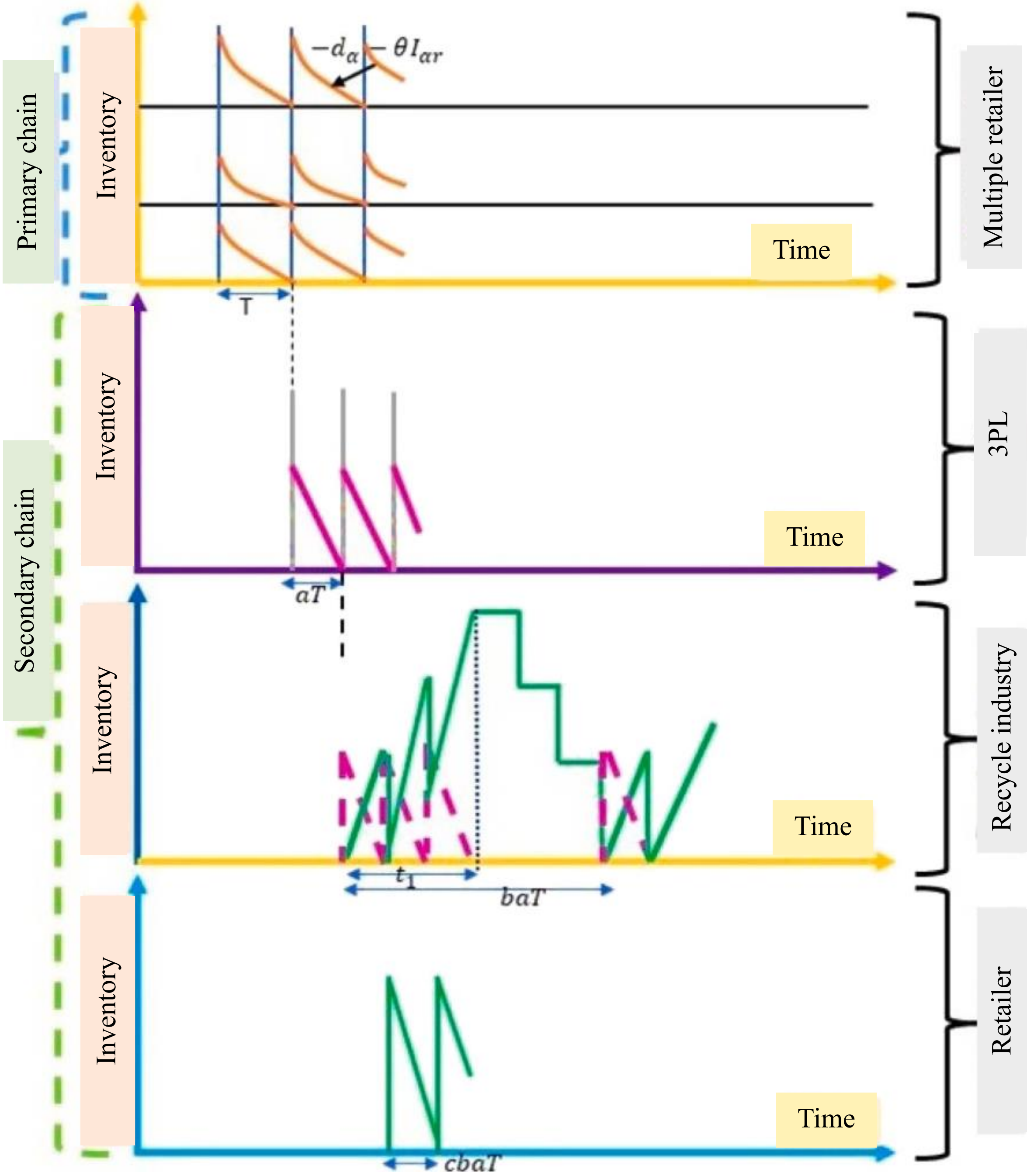
The recycling industry initiates the production of recycled products, requiring both fresh raw materials and waste. The production rate of recycled items is denoted as P_{m2} and the demand is d_{m2}. During the production runtime, the inventory of waste depletes and is immediately replenished by third-party logistics (3PL).

3.4.1 Set-up costs

The recycling industry bears the total set-up costs of installing recycling machines, testing, preparing and maintaining the warehouses used to store recycled finished products. The set-up costs per cycle in the recycling industry are as follows:

$$SC_{rc} = \frac{Se_{rc}}{baT} \tag{24}$$

Figure 3: Flow of downgraded products from primary supply chain stores to secondary supply chain



Source: Authors' own elaboration

In the primary chain inventory, the yellow line symbolizes the finished product inventory and intuitively represents the continuous stages of deterioration. The pink line signifies the waste inventory composed by third-party logistics in the secondary chain. The emerald line denotes the inventories of recycled products within both the recycling industry and retailers, offering insights into the flow and status of these items within the secondary supply chain.

The recycling industry obtains waste from third-party logistics (3PL) and manufacturers are required to procure specific additional items for the production of animal feed. Let the manufacturer's purchase quantity in each period be denoted as Q_{mat}.

Therefore, the costs of material procurement for the recycling industry can be articulated as follows:

$$MPC = \frac{C_{nwm}Q_{mat}}{baT} + \frac{C_{wt}Q_{recy}}{baT} \tag{25}$$

3.4.2 Carrying costs

The total batch size of deteriorated items received by the recycling industry can be expressed as $Q_{recy} = b_aT \times d_{m2}$. The area of the triangle shown in Figure 3 represents the raw material inventory of the reprocessing industry; its calculation formula is:

$$\frac{1}{2}\left(\frac{Q_{\text{recy}}}{n_1}\right)\left(\frac{Q_{\text{recy}}}{P_{m2}}\right) = \frac{(baTd_{m2})^2}{2P_{m2}n_1} \tag{26}$$

The raw material holding costs per cycle in the recycling industry can be calculated as follows:

$$HC_{cm2} = h_{cm2}\left(\frac{Q_{\text{recy}}}{2P_{m2}}\right)\left(\frac{Q_{\text{recy}}}{n_1}\right)\left(\frac{1}{baT}\right) = h_{cm2}\frac{baTd_{m2}^2}{2P_{m2}n_1} \tag{27}$$

Therefore, the typical comprehensive inventory can be articulated as:

$$\frac{(P_{m2}-d_{m2})baT}{2P_{m2}} \tag{28}$$

Subtracting the average inventory of retailers from Equation (28), the finished product can be expressed as:

$$\frac{(P_{m2}-d_{m2})baT}{2P_{m2}} - \frac{cbaTd_{r2}}{2} \tag{29}$$

The holding costs for finished products can be stated as:

$$HC_{fp} = \frac{h_{crecy}baT}{2}\left[1 - \frac{d_{m2}}{P_{m2}} - cd_{r2}\right] \tag{30}$$

The overall holding costs for finished goods are represented as follows:

$$HC_{m2} = h_{cm2}\frac{baTd_{m2}^2}{2P_{m2}n_1} + \frac{h_{crecy}baT}{2}\left[1 - \frac{d_{m2}}{P_{m2}} - cd_{r2}\right] \tag{31}$$

3.4.3 Subscription fees

The recycling industry purchases raw materials in batches of $n1$ and the ordering cost of each cycle in the recycling industry is expressed as:

$$OC_{m2} = \frac{n_1 o_{m2}}{baT} \tag{32}$$

Thus, the total costs incurred per cycle by the recycling industry are as follows:

$$\begin{aligned} TC_{recy} &= HC_{m2} + OC_{m2} + SC_{rc} + MPC \\ &= h_{cm2}\frac{baTd_{m2}^2}{2P_{m2}n_1} + \frac{h_{crecy}baT}{2}\left[1 - \frac{d_{m2}}{P_{m2}} - cd_{r2}\right] + \frac{n_1 o_{m2}}{baT} + \frac{Se_{rc}}{baT} \\ &+ \frac{C_{nwm}Q_{mat}}{baT} + \frac{C_{wt}Q_{recy}}{baT} \end{aligned} \tag{33}$$

3.5 Retailer's cost structure

The retailer's demand is expressed as d_{r2} = d_{m2}. The following sections outline the costs incurred by retailers.

3.5.1 Holding costs

For a retailer, the total quantity of product received over some time is expressed as $cbaTd_{r2}$. The quantity of this product batch is $\frac{cbaTd_{r2}}{n_2}$.

The usual inventory held by the seller is articulated as follows:

$$INV_{r2} = \frac{cbaTd_{r2}}{2} \tag{34}$$

The carrying cost per period is articulated as follows:

$$IHC_{r2} = \frac{C_{h2}d_{r2}cbaT}{2} \tag{35}$$

3.5.2 Ordering costs

Ordering expenses incurred by retailers refer to the combined costs of ordering, delivery and accounting operations. The cost per ordering cycle is expressed in the following manner:

$$OC_{r2} = \frac{n_2 o_{r2}}{cbaT} \tag{36}$$

The total costs for the retailer in each cycle are outlined as follows:

$$\begin{aligned} TCR_2 &= IHC_{r2} + OC_{r2} \\ &= \frac{C_{h2} d_{r2} cbaT}{2} + \frac{n_2 o_{r2}}{cbaT} \end{aligned} \tag{37}$$

The total costs incurred in each cycle of the secondary supply chain are designed as follows:

$$\begin{aligned} TC_{sc} &= TC_{3PL} + TC_{recy} + TCR_2 \\ &= \frac{\sum_{\alpha=1}^{v} d_\alpha \left[\frac{(1+\zeta)^2}{2}\ln\left\{\frac{(1+\zeta)}{(1+\zeta-T)}\right\} - \frac{T\{2(1+\zeta)-T\}}{4} - T\right]}{aT} + \frac{C_{h2} d_{r2} cbaT}{2} \\ &+ \left[C_c + \frac{C_{vt}}{\gamma} + \frac{C_l E[\delta]}{\gamma}\right] + \frac{n_1 F_c}{aT} + h_{cm2}\frac{baT d_{m2}^2}{2P_{m2} n_1} + \frac{n_1 o_{m2}}{baT} + \frac{Se_{rc}}{baT} \\ &+ \frac{h_{crecy} baT}{2}\left[1 - \frac{d_{m2}}{P_{m2}} - cd_{r2}\right] + \frac{C_{nwm} Q_{mat}}{baT} + \frac{C_{wt} Q_{recy}}{baT} + \frac{n_2 o_{r2}}{cbaT} \end{aligned} \tag{38}$$

The total costs of both supply chains are determined using the following formula.

$$\begin{aligned} & TC(T,\beta,\gamma,a_1,a,b,c,n_1,n_2) = TC_{pc} + TC_{sc} \\ &= \sum_{\alpha=1}^{v} \frac{C_{rh} d_\alpha}{T}\left[\frac{(1+\zeta)^2}{2}\ln\left\{\frac{(1+\zeta)}{(1+\zeta-T)}\right\} - \frac{T\{2(1+\zeta)-T\}}{4}\right] \\ &+ \sum_{\alpha=1}^{v} \frac{o_\alpha \beta}{T} + + \frac{C_{h2} d_{r2} cbaT}{2} \\ &+ \sum_{\alpha=1}^{v} \frac{E[\rho] d_\alpha C_{pd}}{T} + \sum_{\alpha=1}^{v} \frac{d_\alpha d_c}{T}\left[\frac{(1+\zeta)^2}{2}\ln\left\{\frac{(1+\zeta)}{(1+\zeta-T)}\right\} - \frac{T\{2(1+\zeta)-T\}}{4} - T\right] \\ &\quad + \frac{o_{m1}}{a_1 T} + \frac{Se_1}{a_1 T} + \frac{d}{2}\left[\beta\left(1 - \frac{d}{p}\right) - 1 + \frac{2d}{p}\right] \\ &\qquad + \left(b_1 p + \frac{b_2}{p} + b_3\right) d + \frac{C_{nwm} Q_{\text{mat}}}{baT} + \frac{C_{wt} Q_{\text{recy}}}{baT} \end{aligned} \tag{39}$$

$$\begin{aligned} &+ \frac{\sum_{\alpha=1}^{v} d_\alpha \left[\frac{(1+\zeta)^2}{2}\ln\left\{\frac{(1+\zeta)}{(1+\zeta-T)}\right\} - \frac{T\{2(1+\zeta)-T\}}{4} - T\right]}{aT} \\ &+ \left[C_c + \frac{C_{vt}}{\gamma} + \frac{C_l E[\delta]}{\gamma}\right] \\ &+ \frac{n_1 F_c}{aT} + h_{cm2}\frac{baT d_{m2}^2}{2P_{m2} n_1} + \frac{n_1 o_{m2}}{baT} + \frac{Se_{rc}}{baT} \\ &+ \frac{h_{\text{crecy}}\, baT}{2}\left[1 - \frac{d_{m2}}{P_{m2}} - cd_{r2}\right] + \frac{n_2 o_{r2}}{cbaT} \end{aligned}$$

3.6 Approach to problem resolution

Minimizing the total costs (TC) of the supply chain is of paramount importance. In the present study, a similar approach was adopted, utilizing calculus and algebraic methods, as demonstrated in Equation (39). As shown in Equation (39), the total costs incurred by both supply chains are optimized using the classical method. To determine the optimal value of the variable T, differentiate the equation and set it to zero. Assuming that the other decision variables are integers, algebraic methods are used to determine the minimum costs for these variables.

Initially, the costs are differentiated and the result is:

$$\frac{\delta TC(T,\beta,\gamma,a_1,a,b,c,n_1,n_2)}{\delta T} = 0 \tag{40}$$

The optimal value of T is:

$$T^* = \sqrt{\frac{A_2}{A_1}} \tag{41}$$

The expressions of A_1 and A_2 are as follows:

$$\begin{aligned} A_1 = {} & \left[-\frac{(1+\zeta)^2}{1+\zeta-T^*} + \frac{T^*}{2} - \frac{1+\zeta}{2}\right] \\ & \times \sum_{\alpha=1}^{v} \frac{d_\alpha}{T^*}\left(C_{rh} + d_c + C_c + \frac{c_{vt}}{\gamma} + \frac{C_l E[\delta]}{\gamma}\right) \\ & + \left[-\frac{(1+\zeta)^2}{1+\zeta-T^*} + \frac{T^*}{2} - \frac{1+\zeta}{2}\right] \\ & \times \sum_{\alpha=1}^{v} \frac{d_\alpha}{T^*}\begin{pmatrix} \frac{(k_2-1)d_{m2}}{2P_{m2}} h_{\text{crecy}} \\ -\frac{h_{cm2}(k_2^2+2k_2)}{2K_2^2} + \frac{c_{wt}+c_{nwm}}{T^*} \end{pmatrix}(1-E[\delta]) \end{aligned} \tag{42}$$

$$A_2 = \frac{1}{T^{*2}}\begin{bmatrix} \sum_{\alpha=1}^{v} d_\alpha C_{rh}\left[-\frac{(1+\zeta)^2}{2}\ln\left\{\frac{(1+\zeta)}{(1+\zeta-T^*)}\right\} + \frac{T^*\{2(1+\zeta)-T^*\}}{4}\right] \\ +d_\alpha d_c\left[-\frac{(1+\zeta)^2}{2}\ln\left\{\frac{(1+\zeta)}{(1+\zeta-T^*)}\right\} + \frac{T^*\{2(1+\zeta)-T^*\}}{4} + 1\right] - o_{m1} \\ -\left(Se_1 + F_c + Se_{rc} + c_{wt}Q_{recy} + C_{nwm}Q_{mat} + o_{m2}\right) + \\ \sum_{\alpha=1}^{v} o_\alpha \beta^* d_\alpha\left[-\frac{(1+\zeta)^2}{2}\ln\left\{\frac{(1+\zeta)}{(1+\zeta-T^*)}\right\} + \frac{T^*\{2(1+\zeta)-T^*\}}{4} + 1 \\ \left[C_c + \frac{C_{vt}+C_1E[\delta]}{\gamma^*}\right] - E[\rho]d_\alpha c_{pd} \end{bmatrix} \tag{43}$$

3.6.1 SDCA procedure

In this study, to determine the optimal value of the variable T, the following algorithm is applied: In step 1, input all parameters for the two supply chain participants, including data for the random variables T, a, b, c and assign initial values to these variables. In step 2, utilize Equation (41) to compute the value of the variable T. Proceed to step 3, iteratively repeating steps 1 and 2 until convergence is achieved. Step 4 involves substituting the converged T into Equation (39) to optimize the total costs to the time variable, as indicated in Equation (44). Finally, step 5 marks the conclusion of the process.

By employing this procedure, the optimal value can be attained through repetitions. Then, substitute the value T into the total cost equation (Equation 39) and the costs are expressed as:

$$\begin{aligned} TC\,&(\beta,\gamma,a_1,a,b,c,n_1,n_2) \\ =\;& \sum_{\alpha=1}^{v}\frac{C_{rh}d_\alpha}{T^*}\left[\frac{(1+\zeta)^2}{2}\ln\left\{\frac{(1+\zeta)}{(1+\zeta-T^*)}\right\}-\frac{T^*\{2(1+\zeta)-T^*\}}{4}\right]+\sum_{\alpha=1}^{v}\frac{o_\alpha\beta}{T^*}+\frac{n_1o_{m2}}{baT^*} \\ +\;& \sum_{\alpha=1}^{v}\frac{E[\rho]d_\alpha C_{pd}}{T^*}+\sum_{\alpha=1}^{v}\frac{d_\alpha d_c}{T^*}\left[\frac{(1+\zeta)^2}{2}\ln\left\{\frac{(1+\zeta)}{(1+\zeta-T^*)}\right\}-\frac{T^*\{2(1+\zeta)-T^*\}}{4}-T^*\right] \\ &+\frac{o_{m1}}{a_1T^*}+\frac{Se_1}{a_1T^*}+\frac{d}{2}\left[\beta\left(1-\frac{d}{p}\right)-1+\frac{2d}{p}\right]+\left(b_1p+\frac{b_2}{p}+b_3\right)d+\frac{n_2o_{r2}}{cbaT^*} \\ &+\frac{\sum_{\alpha=1}^{v}d_\alpha\left[\frac{(1+\zeta)^2}{2}\ln\left\{\frac{(1+\zeta)}{(1+\zeta-T^*)}\right\}-\frac{T^*\{2(1+\zeta)-T^*\}}{4}-T^*\right]}{aT^*}\left[C_c+\frac{C_{vt}}{\gamma}+\frac{C_lE[\delta]}{\gamma}\right] \\ +\;& \frac{h_{crecy}baT^*}{2}\left[1-\frac{d_{m2}}{P_{m2}}-cd_{r2}\right]+\frac{C_{nwm}Q_{mat}}{baT^*}+\frac{C_{wt}Q_{recy}}{baT^*}+h_{cm2}\frac{baT^*d_{m2}^2}{2P_{m2}n_1} \\ +\;& \frac{C_{h2}d_{r2}cbaT^*}{2}+\frac{Se_{rc}}{baT^*}+\frac{n_1F_c}{aT^*} \end{aligned} \tag{44}$$

The cost function (denoted as C) will produce an optimal value for any integration variable x when the following inequality is satisfied:

$$C(x-1)\geq C(x)\leq C(x+1) \tag{45}$$

Using Equation (45), the subsequent inequalities can be formulated for the integrating variables β, γ, a_1, a, b, c, n_1 and n_2:

$$\frac{1}{a_1^*-1}v_1\geq TC(a_1^*)\leq\frac{1}{a_1^*+1}v_1 \tag{46}$$

$$(\beta^*-1)\chi\geq TC(\beta^*)\leq(\beta^*+1)\chi \tag{47}$$

$$\frac{1}{(\gamma^*-1)}\xi\geq TC(\gamma^*)\leq\frac{1}{(\gamma^*+1)} \tag{48}$$

$$\frac{1}{a^*-1}v_2 + (a^*-1)v_3 \geq TC(a^*) \leq \frac{1}{a^*+1}v_2 + (a^*+1)v_3 \quad (49)$$

$$\frac{1}{b^*-1}v_4 + (b^*-1)v_5 \geq TC(b^*) \leq \frac{1}{b^*+1}v_4 + (b^*+1)v_5 \quad (50)$$

$$\frac{1}{c^*-1}v_6 + (c^*-1)v_7 \geq TC(c^*) \leq \frac{1}{c^*+1}v_6 + (c^*+1)v_7 \quad (51)$$

$$\frac{1}{n_1^*-1}v_8 + (n_1^*-1)v_9 \geq TC(n_1^*) \leq \frac{1}{n_1^*+1}v_8 + (n_1^*+1)v_9 \quad (52)$$

$$(n_2^*-1)v_{10} \geq TC(n_2^*) \leq (n_2^*+1)v_{10} \quad (53)$$

For the above calculation of integer variables, the equations on both sides should hold simultaneously. The expressions v_1, v_2, v_3, v_4, v_5, v_6, v_7, v_8, v_9, v_{10}, χ and ξ are expressed as follows:

$$\chi = \sum_{\alpha=1}^{v} \frac{o_\alpha}{T^*} + \frac{dT^*}{2}\left(1 - \frac{d}{p}\right) \quad (54)$$

$$\xi = \frac{\left[\frac{(1+\zeta)^2}{2}\ln\left\{\frac{(1+\zeta)}{(1+\zeta-T^*)}\right\} - \frac{T^*\{2(1+\zeta)-T^*\}}{4} - T^*\right]}{T^*}\left[C_{vt} + C_l E[\delta]\right] \quad (55)$$

$$v_1 = \frac{o_{m1} + Se_1}{T^*} \quad (56)$$

$$\times\left[C_c + \frac{C_{vt}}{\gamma^*} + \frac{C_l E[\delta]}{\gamma^*}\right] + \frac{n_1^* F_c}{T^*} + \frac{n_1^* o_{m2} + Se_{rc} + C_{nwm}Q_{mat} + C_{wt}Q_{recy}}{b^*T^*} + \frac{n_2^* o_{r2}}{c^* b^* T^*} \quad (57)$$

$$v_3 = \frac{h_{cm2} b^* T^* d_{m2}^2}{2P_{m2} n_1^*} + \frac{h_{crecy} b^* T^*}{2}\left[1 - \frac{d_{m2}}{P_{m2}} - c^* d_{r2}\right] + \frac{C_{h2} d_{r2} c^* b^* T^*}{2} \quad (58)$$

$$v_4 = \frac{n_1^* o_{m2} + Se_{rc} + C_{nwm}Q_{mat} + C_{wt}Q_{recy}}{a^*T^*} + \frac{n_2^* o_{r2}^*}{c^* a^* T^*} \quad (59)$$

$$v_5 = \frac{h_{cm2} a^* T^* d_{m2}^2}{2P_{m2} n_1^*} + \frac{h_{\text{crecy}}\, a^* T^*}{2}\left[1 - \frac{d_{m2}}{P_{m2}} - c^* d_{r2}\right] + \frac{C_{h2} d_{r2} c^* a^* T^*}{2} \quad (60)$$

$$v_6 = \frac{n_2^* o_{r2}^*}{b^* a^* T^*} \quad (61)$$

$$v_7 = -\frac{h_{\text{crecy}}\, b^* a^* T^* d_{r2}}{2} + \frac{C_{h2} d_{r2} a^* b^* T^*}{2} \quad (62)$$

$$v_8 = h_{cm2}\frac{b^* a^* T^* d_{m2}^2}{2P_{m2}} \quad (63)$$

$$v_9 = \frac{F_c}{a^*T^*} + \frac{o_{m2}}{b^* a^* T^*} \quad (64)$$

3.6.2 Numerical study

These results need to be validated and compared with previous data or findings in the Discussion section. The numerical study employs a multi-retailer model featuring three retailers in this instance. The algorithm is executed to ascertain the optimal values of decision variables and overall costs. The information necessary for numerical calculations is also adjusted accordingly.

Table 2: Numerical values of player parameters

d_1, d_2, d_3 (units)	117, 116, 116	o_1, o_2, o_3 ($/order)	95, 0.95, 0.95
C_{rh1} ($/unit/year)	0.004, 0.004, 0.004	d_c ($/unit)	2.01
C_{pd} ($/unit)	1	o_{m1} ($/order)	40
S_{e1} ($/setup)	300	h_{cm} ($/unit/year)	0.001
b_1 ($/unit)	0.1	b_2	15
b_3 ($/unit)	100	p (unit/cycle)	400
Cc ($/unit)	1.11	F_c ($/shipment)	3.79
C_{vt} ($/quantity)	0.8	o_{m2} ($/order)	10
C_l ($/container)	10	δ	0.2
d_{m2} (units)	300	h_{cm2} ($/unit/time)	0.09
h_{crecy} ($/unit/year)	0.001	S_{erc} ($/setup)	350
Q_{mat} ($/unit)	200	C_{nwm} ($/unit)	0.05
C_{wt} ($/unit)	0.007	C_{h2} ($/unit/year)	1
d_{r2} (units)	300	o_{r2} ($/order)	2

Note: The results are displayed in tabular format in Tables 3, 4 and 5.
Source: Authors' own calculations

4. Results and Discussion

The most favourable results are presented in Tables 2 and 3, indicating that the optimal time is 0.007 years, a duration deemed acceptable for the food supply chain. The periods within the model remain consistent with those observed in previous studies. Earlier studies did not consider waste recovery from spills or price discounts for reducing waste.

Another noteworthy observation from Table 5 is that when the leakage costs reach $10, there is an immediate and substantial decrease in the overall costs compared to the preceding costs.

Table 3: Costs and values of variables

Year	Important compound	Batch count	Container capacity	Batch	Batch	Integer	Integer	Integer	Total costs
(T_*)	(a^*_1)	(β^*)	$(\gamma^*$ (kg))	(n^*_1)	(n^*_2)	(a^*)	(b^*)	(c^*)	$(TC$ in \$)
0.007	1	5	34	5	1	2	1	1	3,929.3

Source: Authors' own calculations

Table 4: Comparative Analysis of container capacity under single-setup-multiple-delivery (SSMD) policy and total supply chain costs

No.	Integer	Batch Count	Container capacity	Important compound	Integer	Integer	Batch	Batch	Total costs
	(a_1)	(β^*)	(γ^*)	(a)	(b)	(c)	(n^*_1)	$(n^*_2$ (kg))	$(TC$ in \$)
1	1	1	34	2	1	1	1	1	–
2	1	1	34	2	1	1	5	1	3,929.29
3	1	1	34	2	1	1	6	1	49,006.1
4	1	1	34	2	1	1	4	1	–
5	1	1	35	2	1	1	5	1	38,375.8
6	1	1	34	3	1	1	5	1	51,715.2
7	1	1	33	2	1	1	5	1	–

Source: Authors' own calculations

Table 5: Total costs and leakage costs

No.	Leakage cost (per container)	Total costs
1	9.9	27,266
2	10	3,929.3
3	10.1	–

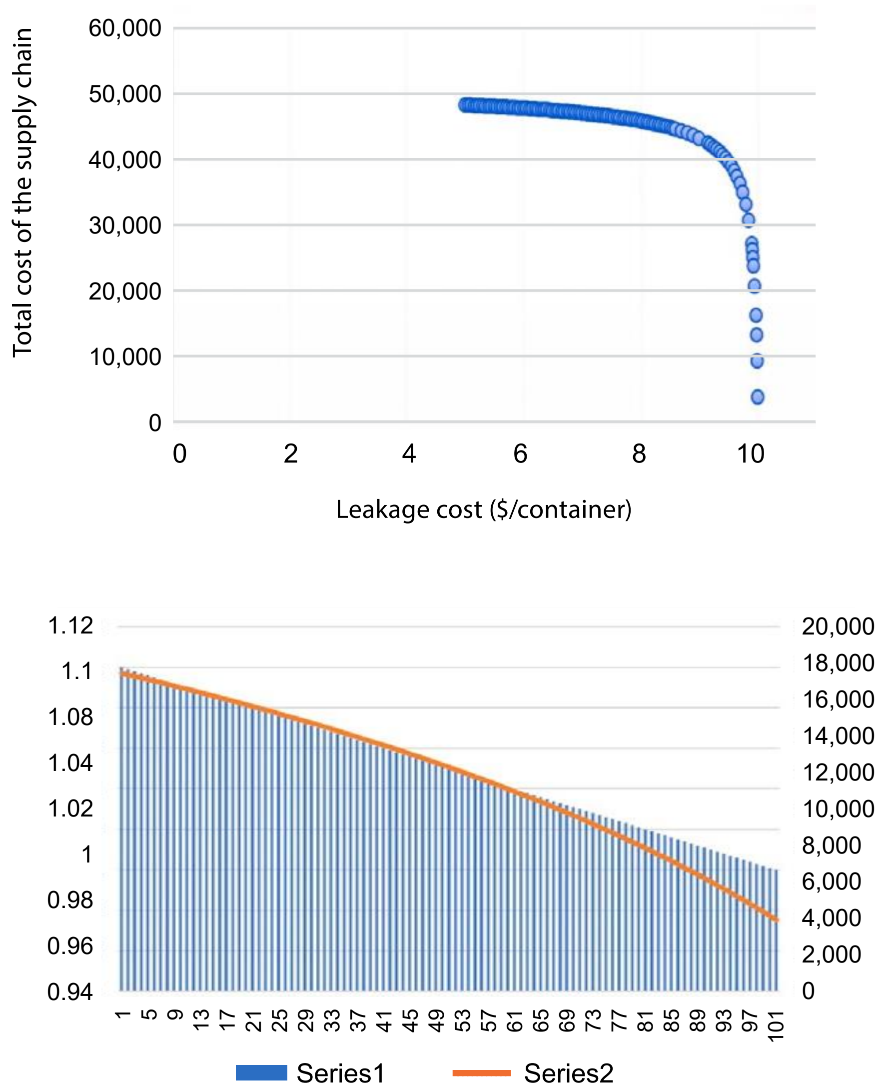
Source: Authors' own calculations

In the food supply chain, it is evident that extremely short periods are crucial for consistently supplying goods to retailers. Table 3 indicates that the productivity parameter values for the manufacturer is persistently higher than the aggregate demands of all the sellers.

The SSMD policy implemented in the food transportation primary chain helps reduce the costs of the supply chain. Table 4 demonstrates the optimality of integer variables to total supply chain costs. The most effective adjustment for the leakage costs is $10 per container. Significantly increasing leakage or container maintenance costs has proven to be a means of reducing overall supply chain costs. Additionally, an increase in mass is achieved and waste leakage is diminished. Figure 4(a) illustrates that as the leakage costs increase, the overall supply chain costs decrease accordingly. It underscores the significance of preventing waste losses, contributing significantly to the economic and environmentally sustainable development of supply chains. Waste recycling aims to recover raw materials in the supply chain and is in line with the core concepts of the CE. The capacity of the waste removal container is optimized to match the actual solution.

Similarly, we use 100 data points to calculate price discounts relative to total supply chain costs. Price discounts are somewhat reduced, resulting in lower overall costs. Figure 4(b) visually depicts the relationship between the price discount factor and total supply chain costs. In addition, excessive price discounts may impose additional costs on the supply chain. The influence of variations in these two crucial parameters on model cost optimization confirms the significance and applicability of this study to real-life scenarios.

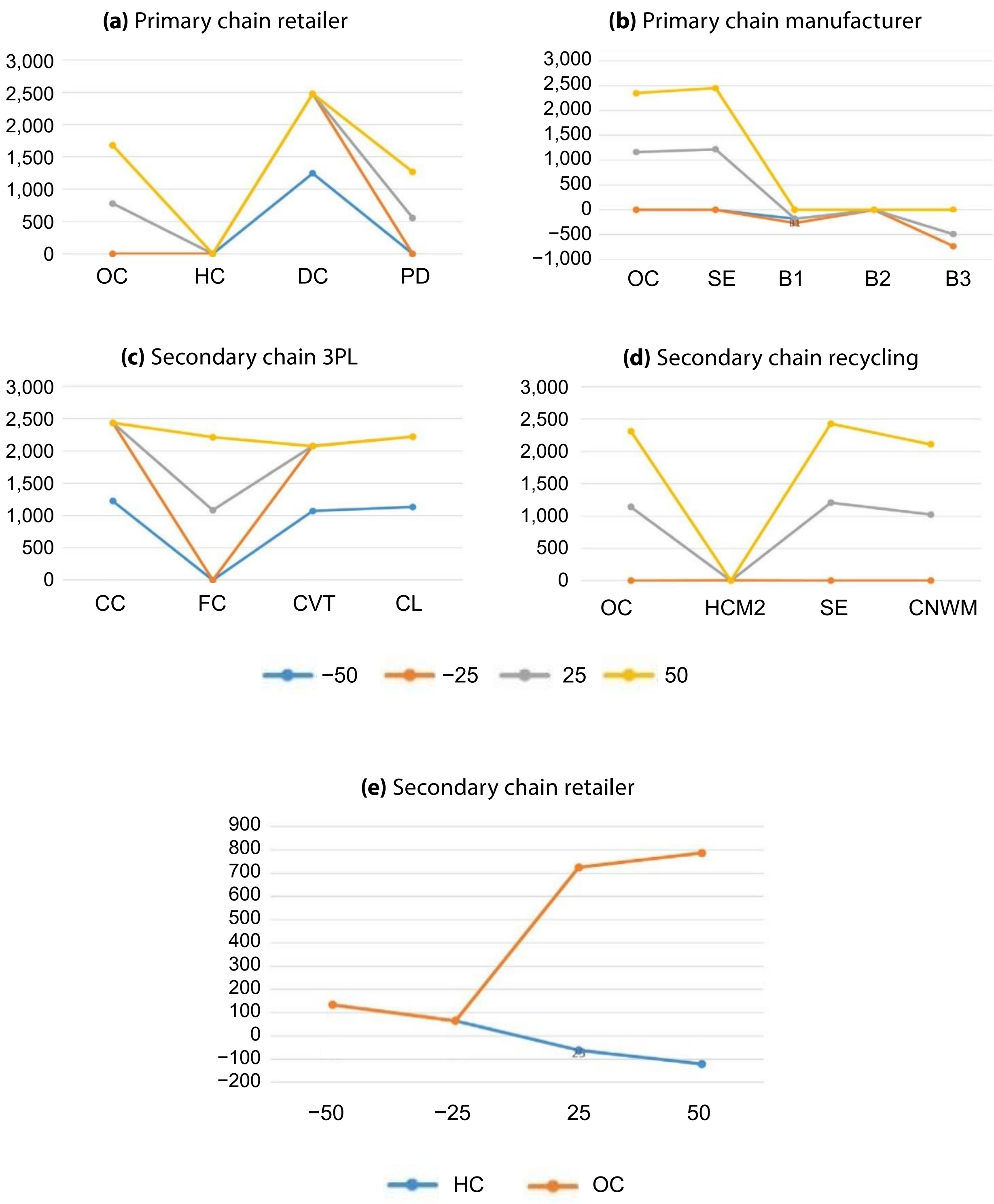
Figure 4: Model validation for key study parameters



Note: (a) Cost graph of the supply chain against the increase; (b) Cost graph of the supply chain against the price discount of container leakage costs.

Source: Authors' own elaboration

Figure 5: Sensitivity plots for two supply chain parameters



Source: Authors' own elaboration

4.1 Sensitivity analysis

The present study introduces a dual supply chain model centred on waste elimination within a CE framework (redesign/reuse, recovery and recycling). We check parameter sensitivity over a range of values (−50%, −25%, +25%, +50%). Figure 5 depicts the sensitivity of parameters in a dual supply chain. Parameter sensitivity analysis leads to the following conclusions:

1. **Ordering costs:** Costs are very sensitive to all players. Given the short timeframes of the food supply chain, the standard costs of ordering materials needs to be optimized. Even slight percentage changes can exert a notable influence on the overall costs of the supply chain, leading to optimal outcomes.
2. **Set-up costs:** Both manufacturers and the recycling industry show high sensitivity to set-up costs. The manufacturer's set-up remains almost unchanged, whereas, for the recycling industry with short waste removal time cycles, set-up costs must be optimized.
3. **Holding costs:** The holding cost of food per unit of time exhibits lower sensitivity and is consistent with real-time conditions to extended food storage, resulting in heightened waste production, underscoring the relevance of this model.
4. **Deterioration, transport and collection costs:** These costs are highly sensitive. Considering that food must be transported within a specific timeframe, any alteration in shipping time will lead to heightened transportation costs, affecting the overall supply chain costs.

4.2 Management insights

This study is bolstered by numerical results and corresponding sensitivity analyses, offering valuable insights for decision-making and management perspectives. These include:

Insight 1:

Emission reduction plays a crucial role in any conceptual model aiming to achieve CE objectives. In a sustainable development model, waste reduction is essential from economic, societal and ecological perspectives. Various societies are adopting CE concepts to address multiple social and environmental challenges. The distribution of low-volume products in any supply chain generates large amounts of waste. Improved supply chain policies will ensure that products are primarily consumed in multiple ways. Retail or wholesale chain management can consider economic, societal and ecological aspects by incorporating price discounts, making decisions to minimize waste and mitigate ongoing losses, thereby promoting the sale of items nearing expiration.

Insight 2:

Waste can be recycled, eliminating waste through the production of by-products. In the supply chain, the waste generated can be recycled, in line with the principles of CE. An earlier study discussed sustainable policies for food supply chains, in which food suppliers rent recycling plants to produce by-products from food waste. The research also recommended the elimination of waste through recycling in the secondary supply chains. As key players in the supply chain, managers of any company have the option to implement waste-neutral policies by actively supporting recycling in the recycling industry. This strategic approach aims to achieve business, environmental and social sustainability.

5. Conclusions

This study is based on the principles of 3R (Reduce, Recover, Recycle), which are one of the foundations of CE. We studied a realistic case scenario of food goods and waste management. Thus, the optimal lifespan was much shorter. Since much less lead time is needed for things such as waste disposal and manufacturer shipments, a retail facility can essentially be set up overnight. It was concluded that the best time is short. Another novel finding concerns reducing waste production via implementing price discounts at the primary retailer level. It becomes a very important element in the entire supply chain. The collection of waste in the secondary chain can be carried out by third-party logistics (3PL), which means that the recycling sector will receive the same types of inputs, but transformed into animal feed. The leakage during waste transportation (quality of recovery) is a major cost factor in the optimization model. An important finding offers a new perspective on preventing waste loss digitally as the price of container leakage is considered. According to the research, as we expose greater leakage costs through a certain level of additional permeability expense (see below), total supply chain costs decrease. Once past this threshold, however, the cost function starts to yield unrealistic features. Model validation required that we use 100 observations about leakage costs and price discounts.

5.1 Limitations and future recommendations

Results showed that while total cost optimization is mostly influenced by the ability to prevent leaks from containers, the raw material spillage (material loss) can be successfully prevented. Similarly, waste utilization schemes are intended to redirect some of this waste into completely new supply chains so that any by-products or complete materials would be able to act as raw inputs in another supply chain. The direct influence (CF) of the CE factor on SCS indicates that it could be a candidate to integrate into greener production systems. This study can further be extended for future studies through the application of the vehicle routing problem to optimize waste collection and distribution. Moreover, the method can be further strengthened with suitable heuristics to improve the analysis and results. Such extensions can encourage greater sustainability in waste handling and distribution both of which belong within the broader concept of CE.

5.2 Practical and policy implications

The importance of CE principles concerning food waste supply chain management was demonstrated in the present study. A holistic approach based on zero waste, resource efficiency and economic optimization can be applied by practitioners. This integration can provide creative solutions: for example, reengineering supply chains to maximize utility and minimize waste production; converting waste into wealth. In addition to a decrease in environmental impact, the study identified price discounting strategies that could be applied at the retailer level. Retailers could also move to dynamic pricing models where prices are lowered on perishable products nearing shelf life expiry, thereby coaxing shoppers into consuming items about to expire. The method works well to eliminate food waste and can provide accessible, cheap food for people.

This research serves as empirical evidence that can inform policymakers who wish to create and support policies that will help facilitate moving towards a CE. These could include financial incentives for businesses to adopt CE practices, such as tax breaks for companies that implement waste reduction strategies or invest in recycling technologies. This study may inform a regulatory framework that encourages retailers to risk price discounting for perishable foods to limit waste. Dynamic pricing models can be incentivized with appropriate guidance provided to stakeholders to avoid trade-offs between food safety and waste minimization.

These findings have important practical and policy implications that emphasize the importance of an integrated food waste management approach that employs CE principles. The gaps in the literature reviewed and the strategies discussed in this paper represent an important step in connecting stakeholders and advancing progress towards food systems that are sustainable and globally aligned with UN Sustainable Development Goals. All of these actions not only enhance environmental outcomes but also build economic resilience and social equity in food supply chains.

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