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Reusable food primary packaging in retail supply chain: A multi-objective optimization framework

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A R T I C L E I N F O

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A B S T R A C T

The increasing demand for sustainable and equitable raw material utilization underscores the potential of reusable packaging as an effective solution. The food retail sector, a significant contributor to packaging waste, faces a clear need for comprehensive decision support systems to manage the complexities of reusable packaging circular networks. Managing these networks requires balancing environmental efficiency with economic viability, considering enabling conditions like consumer return attitude, packaging design properties (weight, size, and stackability), and players' logistic proximity. This paper presents a multi-stage and multi-objective optimization framework designed to select optimal product-package combinations and establish a circular network that encourages the adoption of reusable food packaging in retail. The framework is applied to a significant real-world application consisting of two nationwide retailers in France. The findings confirm that high return rates (>60–70 %) are essential for the viability of the circular system whilst ensuring low scrap rates (<15 %) tip the balance for environmental benefits. Lightweight and stackable packaging solutions enhance resilience in systems with uncertain return and scrap rates. Packaging properties must be evaluated alongside logistics network configuration, as packaging selection is tied to production sites, shaping network adaptability. We introduce a new metric that evaluates packaging and network suitability by assessing packaging weight and transportation distances. A lower value indicates improved resilience and supports the long-term viability of the system. The results emphasize the role of Reusable Vending Machines (RVMs) in reducing environmental burdens, as a higher number of installations leads to greater impact reductions. However, RVM costs account for 70–87 % of differential expenses, depending on deployment scale and budget constraints. To address this, we propose a RVM allocation strategy that optimizes distribution while balancing economic and environmental trade-offs. This multi-objective optimization framework provides valuable insights for policymakers and businesses striving to scale reusable food packaging initiatives effectively.

1. Introduction

Packaging waste has become a major environmental concern. The urgent need for more sustainable and equitable use of raw materials is evident, as 40 % of virgin plastics and 50 % of paper used in the European Union (EU) are designated for packaging purposes (Bradley and Corsini, 2023; Coelho et al., 2020). Without proactive measures, the EU is projected to see an additional 19 % increase in packaging waste by 2030, with plastic packaging waste expected to rise even more sharply (European Commission, 2022a). The EU Waste Framework Directive prioritizes prevention as the primary strategy for waste management, placing it at the top of the waste hierarchy (European Commission, 2022b). However, the agri-food sector depends heavily on packaging, which is essential for protecting food throughout its shelf life.

Packaging not only preserves product quality during handling and transportation but also provides vital information to consumers. Since packaging is often unavoidable, the waste hierarchy outlines a clear management strategy: reuse, which is the second most recommended approach, just ahead of recycling. There is growing interest in this focus on reuse from policymakers and industries, especially within the food sector, where perishable products have short shelflife and generate huge amounts of packaging waste rapidly. This increasing attention from stakeholders is driven by policies such as the Green Deal, which aims to

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Nomenclature

Acronyms

B2B	Business-to-Business
B2C	Business-to-Consumer
EoL	End-of-Life
EPR	Extended Producer Responsibility
LCA	Life Cycle Assess
MILP	Mixed Integer Linear Programming
MPL	Manufacturer Pallet Loading
RVM	Reusable Vending Machine

Circular system design problem

Sets

$p \in P$ Packaging producer facilities
$f \in F$ Food packager facilities
$d \in D$ Distribution center warehouses
$s \in S$ Store locations (demand points)
$r \in R$ Reverse Vending Machine typologies
$w \in W$ Packaging washing facilities
$o \in O$ Sorter facilities
$a \in A$ Packaged products (specific reusable packaging containing a defined quantity of food for a specific brand)
$c \in C$ Set of components of the Bill of Materials (BOM). The set includes both reusable packaging containers and raw food
$m \in M \subset C$ Subset of components (set C) representing reusable packaging containers
$j \in J \subset C$ Subset of components (set C) representing a defined quantity of raw food of a specific brand
$(a, c) \in AC \subset (A \times C)$ Packaged products BOM: each product $a \in A$ is composed of a specific raw food j $\in J$ and a reusable packaging $m \in M$
$t \in T$ Available transportation modes

Parameters

Packaging and product properties

w_a Weight of one unit of packaged product a [kg]
w_m Weight of one unit of packaging m [kg]
q_{ac} Quantity of component (food items/packaging) c to produce one unit of product a [pcs]

Demand parameter

δ_{sj} Demand of food items j in store s [pcs]

Cost parameters

c_m^{disp} Disposal cost of reusable packaging m [€/pc]
c_t^{tra} Transportation cost of a full truck t [€/km • truck]
c_{pm}^{prod} Unitary production cost of reusable packaging m at packaging producer p [€/pc]
c_{fa}^{fill} Filling cost for packaged product a at food packager f [€/piece]
c_{da}^{h} Handling cost for packaged products a at distribution center d [€/pc]
c_r^{rvm} Installation cost for RVM of typology r [€]
c_{om}^{sort} Sorting cost of reusable packaging m at sorting facility o [€/pc]
c_{wm}^{wash} Unitary washing cost of reusable packaging m at washer w [€/pc]

Environmental parameters

e_{pm}^{prod} Unitary production emission of reusable packaging m at packaging producer p [$kgCO_2eq$/pc]
e_{wm}^{wash} Unitary washing emission of reusable packaging m at washer w [$kgCO_2eq$/pc]
e_t^{tra} Transportation emission of a full truck t [$kgCO_2eq$ /km • truck]
e_m^{disp} Emission due to disposal operations of reusable packaging m [$kgCO_2eq$/pc]

Social parameters

φ^{return} Citizen return likelihood [%]
c^{return} Cost to citizens to return dirty packaging [€/pc]
e^{return} Emissions from the route traveled by citizens to return dirty packaging [kgCO2eq/km pc]

Network properties

d_{pf} Distance between packaging producer p and food packager f [km]
d_{fd} Distance between food packager f and distribution center d [km]
d_{ds} Distance between distribution center d and store s [km]
d_{so} Distance between store s and sorter o [km]
d_{ss1} Distance between store s and store s1 [km]
d_{ow} Distance between sorter o and washer w [km]
d_{wf} Distance between washer w and food packager f [km]
ψ_{pm}^{prod} Production line capacity at packaging producer p for reusable packaging m [pcs]
ψ_{fa}^{fill} Filling line capacity at food packager f for the packaged product a [pcs]
ψ_d^{stock} Storage capacity for packaged products at distribution center d [pallet]
ψ_o^{sort} Storage capacity at sorting facility o [pallet]
ψ_w^{wash} Washing line throughput at washer w [pcs]
ψ_r^{rvm} RVM r capacity [pcs]
ψ_t^{tra} Pallet capacity of transportation mode t [pallet]

Operational and logistics parameters

T_{da} Turn Index of packaged products a at distribution center d
T_r Emptying frequency of RVM r
T_o Turn index sorting facility o
θ_m Scrap-rate of reusable packaging m due to logistic and washing operations [%]
σ_a Total units of packaged product a contained in a homogeneous pallet [pcs]
σ_m Number of containers m contained in a homogeneous pallet [pcs]

Decision variables

y_{rs} $r \in R, s \in S$ Integer variable which assumes value 1 if RVM typology r is activated in store s; 0 otherwise
x_{pfmt} $(p, f, m, t) \in PFMT$ Flow of reusable packaging m from packaging producer p to food packager f with transportation mode t [pcs]
x_{fdat} $(f, d, a, t) \in FDAT$ Flow of packaged product a from food packager f to distribution center d with transportation mode t [pcs]
x_{dsat} $(d, s, a, t) \in DSAT$ Flow of packaged product a from distribution center d to store s with transportation mode t [pcs]
x_{ss_1rm} $(s, s_1, r, m) \in SSRM$ Flow of reusable packaging m from dweller district dd to RVM typology rvm located in store s [pcs]
x_{sm}^{disp} $s \in S, m \in M$ The flow of non-returned disposed packaging m from customers of the store s [pcs]
x_{rsomt} $(r, s, o, m, t) \in RSOMT$ Flow of reusable packaging m from RVM typology rvm located in store s to sorter o with transportation mode t [pcs]
x_{owmt} $(o, w, m, t) \in OWM \in OWMT$ Flow of reusable packaging m from sorter o to washer package w with transportation mode t [pcs]
x_{wfmt} $(w, f, m, t) \in WFMT$ Flow of reusable packaging m from washer package w to food packager f with transportation mode t [pcs]

Manufacturer Loading Problem (MPL)

Sets

$\chi \in X$ x-Coordinates for placing a package (crate) on a crate

	(pallet)
$\upsilon \in \Upsilon$	y-Coordinates for placing a package (crate) on a crate (pallet)
$\kappa \in K$	Package (crate) orientations on a crate (pallet)
$z \in Z$	Crates (secondary package)
$b \in B$	Pallets
Parameters	
l_{mk}	Length of package m with orientation k
w_{mk}	Width of package m with orientation k
h_m	Height of package m
L_z	Length of crate z
W_z	Width of crate z
H_z	Height of crate z
L_b	Length of pallet b
W_b	Width of pallet b
σ_χ^x	Distance of x-coordinate χ from the crate's bottom left corner
σ_υ^y	Distance of y-coordinate υ from the crate's bottom left corner
$g_{\iota\chi\upsilon\kappa} \in \{0,1\}$	1 if a placement at $(\sigma_\iota^x, \sigma_\iota^y)$ with orientation κ overlaps with $(\sigma_\chi^x, \sigma_\upsilon^y)$, 0 otherwise
$stack_{mzb} \in \{0,1\}$	1 if crate z containing package m can be stacked on pallet b, 0 otherwise
Decision variables	
$a_{\iota\kappa} \in \{0,1\}$	1 if a package is placed at position $(\sigma_\iota^x, \sigma_\iota^y)$ with orientation κ, 0 otherwise
$a_{\iota\kappa z} \in \{0,1\}$	1 if a crate z is placed on the a pallet at position $(\sigma_\iota^x, \sigma_\iota^y)$ with orientation κ, 0 otherwise
$\varpi_{mzb} \in \{0,1\}$	1 if crate z is selected for package m and pallet b, 0 otherwise
Other parameters	
γ	Total supply chain cost [€]
ε	Total supply chain environmental impact [kgCO_2eq]
N	Number of reuse cycles
M_{xyi}^{Log}	Logistic Moment of item i defined from the origin node x to the destination node y

guide the packaging sector toward climate neutrality by 2050 (Oo et al., 2024). Such a shift toward reusable packaging not only requires redesigning containers and materials (Kazancoglu et al., 2023; Schmidt Rivera et al., 2019), but also necessitates a drastic change in business models and supply chain systems that have traditionally relied on single-use products (Tukker et al., 2024). The organization and efficiency of forward production and distribution processes must be balanced with the effectiveness and economic viability of return flows. In this regard, the logistical proximity of the stakeholders and facilities involved in delivering packaged products to consumers can significantly influence the distances required for the collection and sanitization processes after use (Cottafava et al., 2021; Tenhunen-Lunkka et al., 2024). The extensive fragmentation and geographical spread of return processes can pose economic challenges that may deter industrial actors from completing the closed-loop cycle. Moreover, the sizes and design of packaging, along with the choice of materials, should support efficient material handling and distribution for both the packaged product and the returned empty container. It is essential to ensure stackability and the effective use of truckload spaces, while also considering the performance and durability of the packaging over time, factoring in wear and tear as well as the requirements for washing and sanitization during each cycle.

The transition to competitive and environmentally sustainable circular packaging systems for specific food items is contingent upon the interaction of several key drivers. These include package design characteristics such as size, shape, weight, and stackability, alongside the strategic locations of both forward and reverse logistics facilities. In this paper, we present a multi-objective optimization framework designed to establish a feasible multi-stakeholder circular system that encourages the adoption of returnable food packaging in retail (Ellsworth-Krebs et al., 2022). The proposed model advances existing practices by incorporating washable food containers within the entire packaging hierarchy, including primary, secondary, and tertiary layers. Furthermore, this approach emphasizes the importance of consumer behavior, evaluates differential environmental burdens, and enhances the logistic efficiency of different industrial stakeholders (Balatsas-Lekkas et al., 2024). This work aims to address the following research questions:

- RQ1: What is the relationship between environmental efficiency and economic performance in the primary food packaging reuse network for nation-wide retailers?
- RQ2: Which are the enabling conditions affecting primary packaging reuse systems' economic and environmental performance?
- RQ3: How can the transition to reuse systems in the food industry be supported through economic incentives?

The reuse of primary packaging in the food supply chain is often presented in the literature as an environmentally favorable alternative to single-use systems. However, the economic implications of scaling such systems to an international distribution network remain underexplored. This study seeks to address this gap by investigating the interplay between environmental efficiency and economic performance in reuse systems (RQ1). Understanding this relationship is critical, particularly given the potential trade-offs where environmental benefits might coincide with either cost reductions or increased expenses depending on system design and implementation. To further elucidate these dynamics, the study identifies the key factors driving economic and environmental performance (RQ2), focusing on packaging characteristics (such as weight, material, and stackability) and logistical parameters, including the distances between supply chain actors. Finally, acknowledging the challenges of transitioning to reuse systems, this research explores how economic incentives could support their adoption in scenarios where additional costs might emerge (RQ3). Through the proposed optimization framework, the study evaluates various scenarios to provide actionable insights for policy-makers, enabling effective design of incentive schemes to foster the implementation of reuse practices across the food supply chain.

The remainder of this paper is organized as follows. Section 2 provides a literature's review as a benchmark for this framework. Section 3 introduces a cascade methodology for solving pallet loading and network design optimization problems presenting the case study. Section 4 illustrates the results of the framework application to two French retailer's networks. Section 5 discusses the findings whilst Section 6 concludes the study with suggestions for future developments.

2. Literature review

The shift toward reusable packaging is widely recognized as a viable option to reduce the environmental impact of the packaging sector. Several studies emphasize the environmental and potential economic benefits of reusable packaging systems over traditional single-use options (Lu et al., 2022). Such systems compel with circular economy principles, but the adoption remains limited, primarily due to the challenges in shifting from a linear model (produce-use-dispose) to a closed-loop system (Arijeniwa et al., 2024; Johansen et al., 2022). Despite the growing focus on reusable packaging in the last decade, most researches concentrate on secondary and tertiary packaging systems rather than primary packaging used directly by consumers (Mahmoudi and Parviziomran, 2020; Ronzoni et al., 2022; Sazdovski et al., 2024). This gap in the literature highlights a critical need to explore primary reusable packaging, especially in the food supply chain, where the complexities of consumer-facing systems hide unique challenges (Bartolotti et al., 2025).

Fig. 1 overviews the recent literature on the field, highlighting the divergent perspectives of inquiry. Life Cycle Assessment (LCA) studies confirm the environmental benefits of adopting reusable packaging systems in the agri-food sector. Key factors contributing to the sustainability of reusable packaging include the optimization of return systems and the design of durable containers (Accorsi et al., 2022a, 2022b; Yadav et al., 2024). However, these systems are highly dependent on the number of reuses (Espinoza-Orias and Lundquist, 2025). Therefore, reusable packaging only outperforms single-use alternatives after exceeding a specific number of reuses, often referred to as the "transition point" (Camps-Posino et al., 2021).

When comparing Business-to-Business (B2B) and Business-to-Consumer (B2C) markets, the literature shows a stronger prevalence of reusable packaging in the B2B context. The environmental benefits in B2C markets are more uncertain, due to consumer behavior and lower reuse rates (Hitt et al., 2023). For instance, consumer decisions regarding packaging return are influenced by factors such as material, size, and ease of reuse (Farrell et al., 2024; Greenwood et al., 2021). Studies outline consumers may become unwilling to reuse containers if they perceive them as dirty or inconvenient, significantly impacting the reuse rate (Baird et al., 2022). The success of reusable packaging systems is closely tied to consumer awareness and behavior (Hoseini et al., 2024; Song et al., 2023). Enhanced environmental knowledge can lead to higher adoption rates, suggesting that educational campaigns (Norton et al., 2023a) and clear labeling are critical in driving this change (Norton et al., 2023b). Additionally, socio-demographic factors such as age, gender, and income level determine consumer willingness to adopt and pay for reusable packaging systems (Escario et al., 2020; Schuermann and Woo, 2022). Policies that promote sustainable behaviors and highlight the advantages of reusable packaging could facilitate its broader adoption (Babader et al., 2016).

The establishment of closed-loop networks for reusable packaging requires a combination of commercial, regulatory(Sundqvist et al., 2024), and logistical frameworks (Beswick-Parsons et al., 2023). Harmonizing regional policies, such as waste and collection systems management, facilitates the adoption of closed-loop networks (Trubetskaya et al., 2022). Niero (2023) outlines the European Union (EU) regulation's necessity of comprehensive systematic changes to reduce the negative environmental impacts of packaging waste. The EU's Extended Producer Responsibility (EPR) policy promotes circular packaging networks, where all actors are responsible for managing packaging end-of-life (EoL) (Meherishi et al., 2019; Rossi and Bianchini, 2022). Such complex systems require prescriptive and operational tools to support supply chain design and management. The operations research literature overcomes the descriptive approach of LCA case-specific studies to comprehensively tackle circular supply chain structure. Table 1 overviews circular packaging systems. These contributions are classified by the packaging properties, network boundaries, and modeling aspects. While reusable packaging paradigms are well-integrated into secondary and tertiary packaging networks, primary packaging systems have received less attention, both in research and in practice, due to consumers rejection.

Studies investigating returnable plastic containers (RPCs) in food supply chains typically focus on secondary packaging, optimizing the use of reusable and disposable containers for a food catering supply chain (Accorsi et al., 2014; Bortolini et al., 2018). Numerous studies model logistics networks leveraging on the economic and environmental benefits of adopting Returnable Transport Items (RTIs) (Chung et al., 2018). Some papers investigate tactical-operative aspects of the RTI flows, such as inventory-sharing strategy (Liu et al., 2020) and production delivery policies (Sarkar et al., 2019). Yavrucu et al. (2024) showcase the benefits stemming from horizontal collaboration in a closed-loop supply chain for RTIs. Zhang et al. (2024, 2022) present an inventory routing problem managing the selection of multi-type RTIs for perishable food. There is a clear need to extend these models to primary packaging, incorporating variables such as packaging design, material properties, and logistics drives into supply chain management. In addition to these operational challenges, uncertainties related to

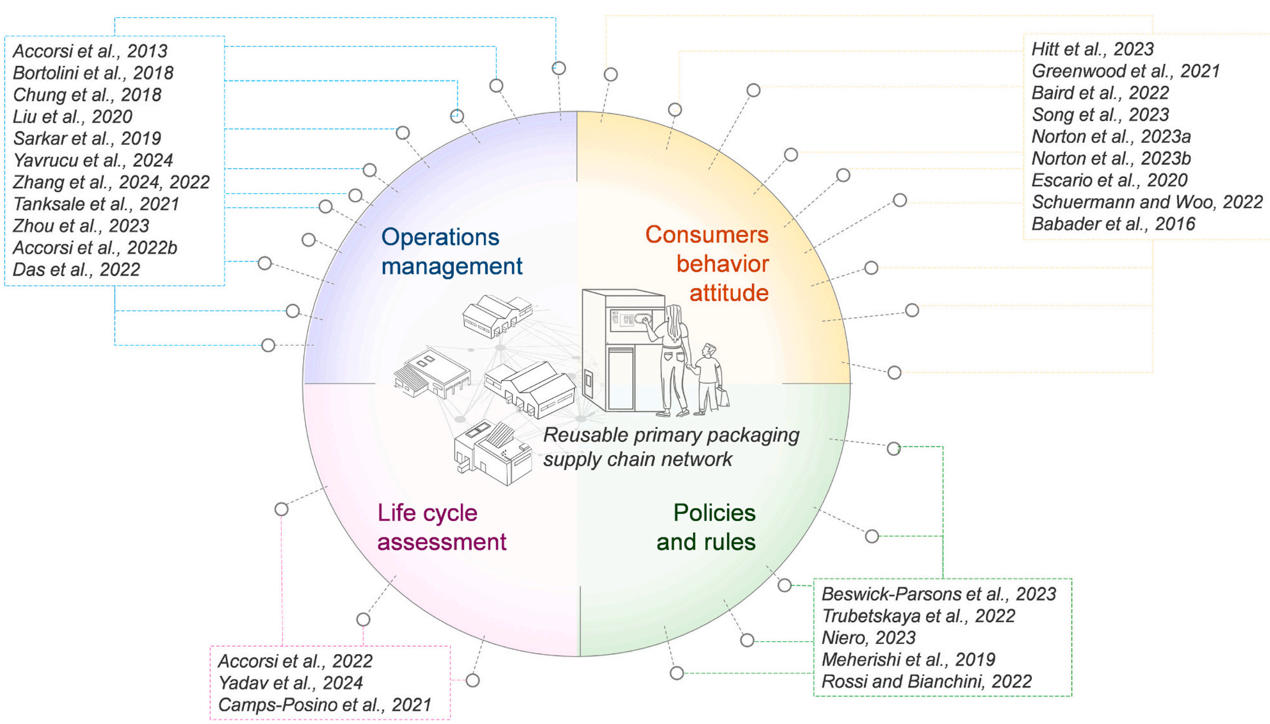


Fig. 1. Reusable packaging literature state of the art.

Table 1

Comparative literature review on circular packaging supply chains (LIPD = Logistic impact of packaging design; PPC = Product packaging combination; SMA = Solving Method Approach; MO = Multi-objective optimization; CCB = Cardboard Crates; DWC = Disposable Wooden Crates; RPC = Reusable Plastic Containers; RTI = Returnable Transport Items; PPkg = Primary Packaging; RS = Raw material supplier; PP = Packaging producer; FF = Food supplier; FP = Filling point; DC = Distribution center; DP = Demand point; CP = Collection point; SC = Sorting centers; PO = Poolers; OEM = Original equipment manufacturer; WP = Washing center; RC = Recycling center; WT = Waste treatment node; MOHGATS = Multi-objective hybrid genetic algorithm-tabu search; AUGMECON = Augmented Epsilon Constraint Method; NNCM = Normalized Normal Constraint Method; GA-H = Modified Genetic Algorithm with Crossing Date heuristic; IPt = Interior Point method; GA = Genetic Algorithm; PSO = Particle swarm optimization; De = Decomposition; VND = Variable neighborhood descent; WSA = Weighted Superposition Attraction)

Paper	Packaging properties								Network boundaries				Modeling approach				
	Packaging type	Recyclable	Reusable	Level	Multi-packaging	LIPD	PPC	Multi-material	Consumer attitude	Food Industry	Stakeholders	Supply stages	SMA	Constraints	MO	Economic	Environment
Bortolini et al. (2018)	CCB - DWC - RPC	●	●	II	●			●		●	Network	PP - FF - DC - RC - WT	NNCM	Capacity; Demand; Flow; Lifespan	●	●	●
Chung et al. (2018)	RTI		●	III	●			●			Network	FP -DC - DP - PP	GA-H	Capacity; Flow		●	
Sarkar et al. (2019)	RTI		●	III							Network	RS - PP -FP - DP	Ipt - GA - PSO	Capacity	●	●	●
Liu et al. (2020)	RTI		●	III							Network	PO - DP	De	Capacity; Demand; Flow		●	
Accorsi et al. (2020)	RPC	●	●	II						●	Producer - Pooler	PO - FF - DC	GUROBI	Capacity; Flow; Lifespan; Time		●	
Tanksale et al. (2021)	PPkg	●		I	●				●	●	Network	RS - PP - FP - DP - SC - RC	AUGMECON	Capacity; Flow	●	●	●
Accorsi et al. (2022a, 2022b)	RPC		●	II						●	Pooler	FP - DC - DP - PO	GUROBI	Capacity; Demand; Flow		●	
Das et al. (2022)	RTI		●	III	●						Network	PP - DC - FP - OEM	GUROBI - CVaR	Demand; Capacity; Flow		●	●
Zhang et al. (2022)	RTI		●	II/III	●					●	Network	FP - DP	CPLEX	Capacity; Demand; Flow; Inventory; Time		●	
Zhou et al. (2023)	PPkg	●		I	●			●	●		Network	DP - RVM - RC	MOHGATS	Capacity; Demand; Flow	●	●	●
Zhang et al. (2024)	RTI		●	II/III	●		●			●	Network	FF - FP - DP	CPLEX	Capacity; Demand; Flow; Time		●	
Yavrucu et al. (2024)	RTI		●	III							Network	FP - DP	VND-WSA	Capacity; Demand; Flow			
This paper	PPkg		●	I	●	●	●	●	●	●	Network	PP - FP -DC - DP - SC - WP	GUROBI	Capacity; Demand; Flow	●	●	●

consumer behavior further complicate the adoption of reusable packaging. Tanksale et al. (2021) propose a multi-objective optimization model comprising an incentive mechanism for customers and the selection of green suppliers. Even Zhou et al. (2023) integrate a customer incentive mechanism into a reverse logistics network where containers should be returned to recycling stations. They focus on modeling a closed-loop supply chain network for recyclable primary containers, rather than for returnable packaging. Factors like demand variability, reuse rates, and inventory levels introduce stochastic elements that need to be managed. The variability aspects are analyzed in (Accorsi et al., 2022b), which also investigates how fluctuations in operational and logistics costs influence reusable container supply chains through sensitivity analysis. Addressing these challenges requires innovative modeling approaches that integrate risk-averse strategies into supply chain optimization (Das et al., 2022).

This literature review reveals that the current research on reusable packaging has largely focused on secondary and tertiary systems, leaving gaps in understanding the full potential of primary reusable packaging in consumer markets (Thomassen et al., 2024). Uncertainties associated with consumer behavior are not taken into account, as RTIs and RPCs are typically used in B2B contexts. The complexities introduced by consumer behavior, logistical considerations, and packaging design require further exploration. To address these gaps, this paper proposes a multi-echelon linear optimization model for primary packaging in the food retailer supply chain, integrating both forward and reverse flows triggered by consumer behavior. By incorporating sustainability pillars across the entire supply chain, this study aims to foster the transition toward environmentally, economically, and socially sustainable packaging systems. This study supports the food supply chain's sustainable transition by promoting reusable primary packaging and analyzing the effects of packaging choices on network design. The model addresses the limitations outlined in the literature on retailer networks by considering the implication of different product-packaging combinations. Operational and logistical aspects related to packaging transport are embedded through a preliminary Pallet Loading problem for optimizing the unit load configuration. The model solution provides the optimal product-packaging combination for each food item, choosing from a set of multi-material and multi-shape containers. This strategy supports the seamless integration of the new business model into current networks by potentially leveraging other logistic networks of reusable or disposable containers and RTIs.

3. Methods

The logistics network is dedicated to managing reusable packaging within a closed-loop supply chain specifically designed for food retailers. The proposed framework accommodates various products and packaging types, ensuring the best combinations of food and containers. Two logistical phases can be defined: one where packaging is coupled with food (A) and another where packaging is empty (M). The supply chain consists of two interconnected logistical flows depicted in Fig. 2. The forward supply chain includes packaging producers (P), who manufacture the packaging; food packagers (F), who fill the packaging with products; distribution centers (D), which consolidate the food products; and retailers (S), which represent the demand points. The model assumes that both virgin raw materials for packaging production and raw food are available at the packaging suppliers and food packagers, respectively. Consumer actions drive the reverse flow. Empty packaging is returned to designated collection points known as Reverse Vending Machines (RVMs). The reverse flow involves RVMs, sorters (O) who consolidate and prepare clean pallets of used packaging, and washers (W) responsible for cleaning the containers. The complete list of set, parameter and decision variable of the model are outlined in the nomenclature section while a complete list of the subsets is available in Supplementary Information S1.

3.1. The research framework and the main parameters

The proposed framework includes a Mixed Integer Linear Programming (MILP) model that falls under Location Allocation Problems (LAP). The optimal logistic scenario resulting from the model resolution provides a two-fold decision: determining the optimal material flows between supply chain actors and selecting the strategic sites for the RVMs. The model does not account for opening new facilities, as it assumes the conversion of existing infrastructure previously used for managing disposable packaging, proposing a new business model centered on the

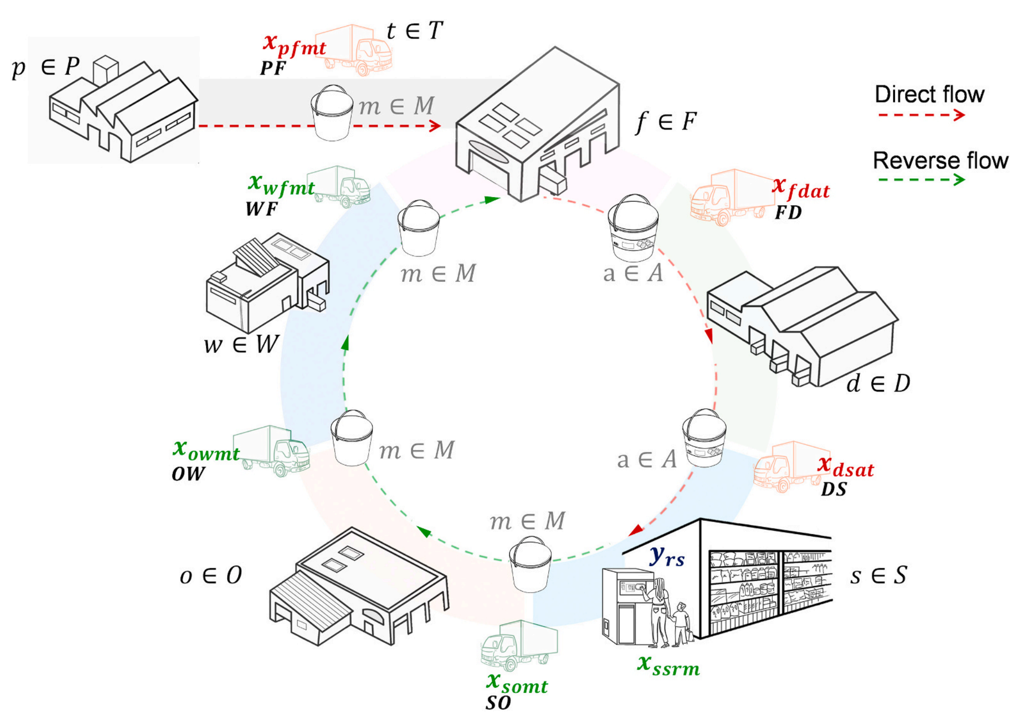


Fig. 2. The closed-loop supply chain for reusable primary packaging.

reusable packaging paradigm. Decisions are steered by both a cost and an emission-based objective function, seeking to make reusable packaging economically and environmentally sustainable for all supply chain actors. The strategic model is designed for a single period, as it evaluates the economic and environmental benefits of adopting reusable packaging within the network in a steady-state scenario. The proposed framework introduces a structured multi-stage methodology for quantifying some strategic parameters of the optimization model. The parameter q_{ac} delineates the Bill of Materials (BOM) by identifying both the food item and the corresponding reusable packaging. This combination results in a distinct packaged product a. Each packaged product a is uniquely defined by the pairing of a food item j with a specific reusable packaging option m. The modeling of product-packaging combinations and the associated parameters are illustrated in Fig. 3. Demand for the food product j is assessed for each store s (δ_{sj}), taking into account specific portion sizes and brand considerations. Various packaging options m are available for the food product j, which creates multiple packaged product a alternatives for the item.

Economic parameters identify the differential costs (c) incurred by all stakeholders in the supply chain when choosing reuse instead of disposal. Social parameters assess the uncertainty related to consumer behavior in promoting a consumer-driven reverse supply chain. The parameter φ^{return} represents the average steady-state probability that citizens will return used packaging to reverse vending machines (RVMs). This model aims to minimize the distance that citizens need to travel to return packaging by incorporating the cost parameter c^{return}, which means the cost per kilometer associated with backhaul transportation.

To embrace all three dimensions of sustainability, the framework incorporates emission parameters that account for differential emissions (e) resulting from production, washing, disposal, and transportation activities. Strategic parameters modeled through operational and logistic factors influence network design and product-packaging combinations. These factors reflect operational aspects within a short-term time frame. The turn index T_{da} is applied to retailer's distribution centers to align storage capacity to continuous flows. The time products spend on warehouse shelves is a component of their overall shelf life.

The turn index is also defined for sorters (T_o). Additionally, the parameter T_r denotes the frequency with which RVMs are emptied, impacting the number of RVMs that need to be installed in the network. The parameter θ_m defines the average scrap rate resulting from logistical operations such as transportation and washing. This aspect, combined with the probability of packaging return (φ^{return}), significantly influences the lifespan of packaging within the network.

3.2. Two-stage pallet loading problem

Transport logistics operations involve a hierarchical packaging structure that includes primary, secondary, and tertiary packaging. Optimizing these transport operations aims to enhance overall performance, directly contributing to lowering costs and reducing emissions. In this context, achieving logistical efficiency allows for the maximization of the number of packages transported. The optimization model employs a multi-stage approach, where the parameters representing the number of primary packages per pallet (σ_a, σ_m) are determined by solving a two-stage Manufacturer Pallet Loading problem (MPL) as delineated in *Alg.S1* of Supplementary Information S2.

This formulation optimizes reusable primary package within each secondary package (i.e. crate) and crates-stack within a tertiary package (i.e. pallet). A first application of the MPL, referred to as MPL_{mz} i.e. *Alg. S1 – Step 1*, allows for determining the optimal placing of primary package m for each combination of secondary packaging z of sizes L_z, W_z and H_z. Then, *Alg.S1 – Step 2*, referred to MPL^*_{ml}, entails selecting the secondary package for each primary package m maximizing the number of primary packaging loaded onto a pallet b with sizes L_b and W_b. We quantify the number of items per secondary and tertiary packaging considering both empty (*stacked* = 1) and full (*stacked* = 0) cases. Firstly, maximizing the loaded packages requires considering all feasible coordinates $X = \{1, 2, \ldots, |X|\}, \Upsilon = \{1, 2, \ldots, |\Upsilon|\}$ and orientations K of an item with sizes l_{mk}, w_{mk} and h_m. A position (o_ι^x, o_ι^y) with orientation $\kappa \in K$ is overlapped by any position (o_χ^x, o_υ^y) such as:

$$o_i^x \le o_\chi^x \le o_i^x + l_k - 1 \forall i, \chi \in X \tag{1}$$

$$o_\iota^y \le o_\upsilon^y \le o_\iota^y + w_k - 1 \forall \iota, \upsilon \in \Upsilon \tag{2}$$

Therefore, the function $g_{i\iota\chi\upsilon\kappa}$ is 1 if positions (o_i^x, o_ι^y) and (o_χ^x, o_υ^y) are in constrant and 0 otherwise. The binary decision variable $a_{i\iota\kappa}$ will be 1 if an item is placed in a position $\left(o_i^x, o_\iota^y\right)$ with orientation κ and 0 otherwise. The MPL_{mz} formulation solved in Step 1. is:

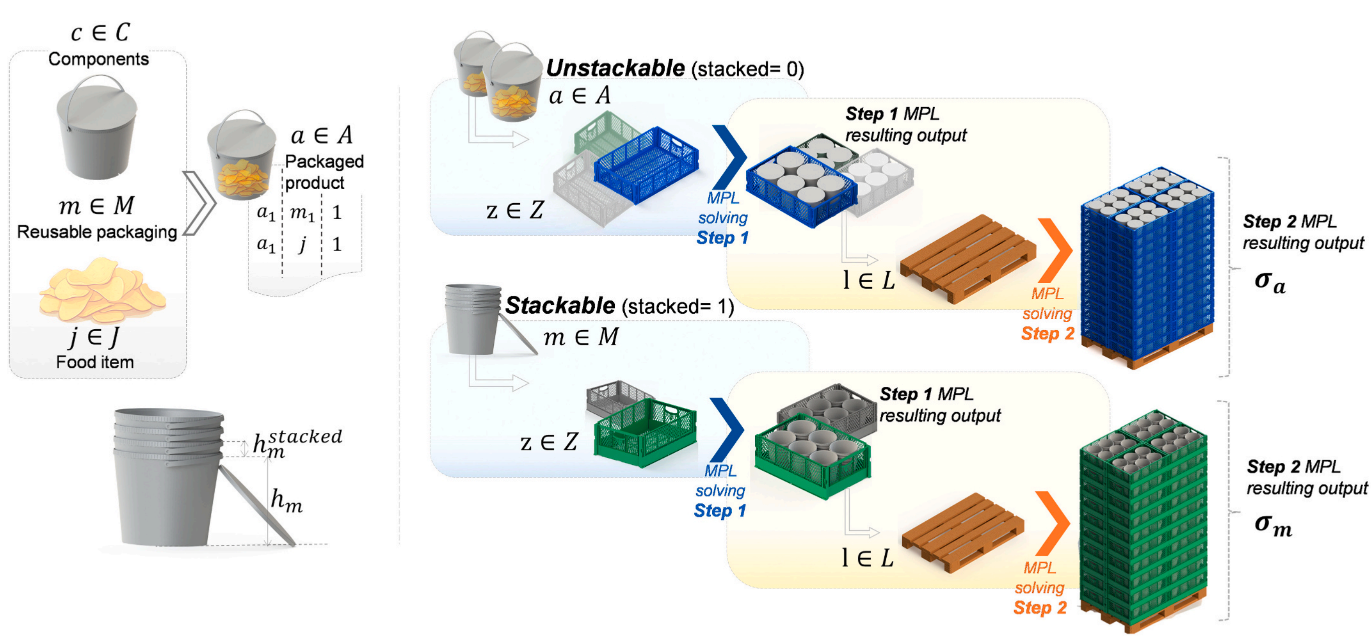


Fig. 3. Product-packaging combination and MPL input and output.

$$\Phi = max\sum_{\kappa\in K}\sum_{i\in X: o_i^x \le L_z - l_{mk}}\sum_{\iota\in \Upsilon: o_\iota^y \le W_z - w_{mk}} a_{i\iota\kappa} \quad (3)$$

subject to

$$\sum_{\kappa\in K}\sum_{i\in X}\sum_{\iota\in\Upsilon} g_{i\iota\chi\upsilon\kappa}\cdot a_{i\iota\kappa} \le 1 \forall \chi \in X, \upsilon \in \Upsilon \quad (4)$$

In Step 2. we solve MPL^*_{mb} as $\Phi^* = max \sum_{\kappa\in K}\sum_{z\in Z}\sum_{i\in X: o_i^x\le L_b - l_{zk}}\sum_{\iota\in\Upsilon: o_\iota^y \le W_b - w_{zk}} a_{i\iota\kappa z} \bullet stack_{mzb}$ subject to the following constraints:

from the cost objective, as they do not differ between reusable and disposable packaging scenarios.

On the other hand, the emissions objective function, denoted as ε, assesses the environmental impact of adopting reusable packaging by focusing on three primary sources of emissions. These include operational emissions (E_1), which are proportional to the managed flow and encompass the production of unreturned packaging, emissions arising from the washing and sanitization, and those related to transportation (E_2). The emissions function also accounts for those generated from the waste treatment of unreturned or damaged packaging (E_3) and produced from the routes traveled by consumers to return dirty packaging (E_4).

$$\gamma = min(C_1 + C_2 + C_3 + C_4 + C_5) \quad (7)$$

$$\varepsilon = min(E_1 + E_2 + E_3 + E_4) \quad (8)$$

O.F γ

$$[C_1] \quad \sum_{s\in S}\sum_{r\in R} c_r^{rvm} \bullet y_{rs}$$

$$[C_2] \quad + \sum_{(p,f,m,t)\in PFMT} x_{pfmt} \bullet c_{pm}^{prod} + \sum_{(o,w,m,t)\in OWMT} x_{owmt} \bullet c_{om}^{sort} + \sum_{(w,f,m,t)\in WFMT} x_{wfmt} \bullet c_{wm}^{wash}$$

$$+ \sum_{(p,f,m,t)\in PFMT} \frac{x_{pfmt}}{\sigma_m \bullet \psi_t^{tra}} \bullet d_{pf} \bullet c_t^{tra} + \sum_{(f,d,a,t)\in FDAT} \frac{x_{fdat}}{\sigma_a \bullet \psi_t^{tra}} \bullet d_{fd} \bullet c_t^{tra} + \sum_{(d,s,a,t)\in DSAT} \frac{x_{dsat}}{\sigma_a \bullet \psi_t^{tra}} \bullet d_{ds} \bullet c_t^{tra} + \sum_{(r,s,o,m,t)\in RSOMT} \frac{x_{rsomt}}{\sigma_m \bullet \psi_t^{tra}} \bullet d_{so} \bullet c_t^{tra} +$$

$$[C_3] \quad \sum_{(o,w,m,t)\in OWMT} \frac{x_{owmt}}{\sigma_m \bullet \psi_t^{tra}} \bullet d_{ow} \bullet c_t^{tra} + \sum_{(w,f,m,t)\in WFMT} \frac{x_{wfmt}}{\sigma_m \bullet \psi_t^{tra}} \bullet d_{wf} \bullet c_t^{tra}$$

$$[C_4] \quad + \sum_{s\in S}\sum_{m\in M} x_{sm}^{disp} \bullet c_m^{disp}$$

$$[C_5] \quad + \sum_{(s,s_1,r,m)\in SSRM} x_{ss_1rm} \bullet d_{ss_1} \bullet c^{return}$$

O.F. ε

$$[E_1] \quad \sum_{(p,f,m,t)\in PFMT} x_{pfmt} \bullet e_{pm}^{prod} + \sum_{(w,f,m,t)\in WFMT} x_{wfmt} \bullet e_{wm}^{wash}$$

$$+ \sum_{(p,f,m,t)\in PFMT} x_{pfmt} \bullet w_m \bullet d_{pf} \bullet e_t^{tra} + \sum_{(f,d,a,t)\in FDAT} x_{fdat} \bullet w_a \bullet d_{fd} \bullet e_t^{tra}$$

$$+ \sum_{(d,s,a,t)\in DSAT} x_{dsat} \bullet w_a \bullet d_{ds} \bullet e_t^{tra} + \sum_{(r,s,o,m,t)\in RSOMT} x_{rsomt} \bullet w_m \bullet d_{so} \bullet e_t^{tra}$$

$$[E_2] \quad + \sum_{(o,w,m,t)\in OWMT} x_{owmt} \bullet w_m \bullet d_{ow} \bullet e_t^{tra} + \sum_{(w,f,m,t)\in WFMT} x_{wfmt} \bullet w_m \bullet d_{wf} \bullet e_t^{tra}$$

$$[E_3] \quad + \sum_{s\in S}\sum_{m\in M} x_{sm}^{disp} \bullet e_m^{disp}$$

$$[E_4] \quad + \sum_{(s,s_1,r,m)\in SSRM} x_{ss_1rm} \bullet d_{ss_1} \bullet e^{return}$$

$$\sum_{\kappa\in K}\sum_{i\in X}\sum_{\iota\in\Upsilon} g_{i\iota\chi\upsilon\kappa z}\cdot a_{i\iota\kappa z} \le \varpi_{mzb} \forall \chi \in X, \upsilon \in \Upsilon, z \in Z \quad (5)$$

$$\sum_{z\in Z} \varpi_{mzb} = 1 \quad (6)$$

where $\varpi_{mzb}$is 1if the secondary packaging z is chosen for primary packaging m and pallet b and 0 otherwise.

3.3. Circular system design problem

3.3.1. Objective functions

The cost objective function, denoted as γ, evaluates the differential costs associated with adopting reusable packaging in comparison to a disposable packaging scenario. This function includes the installation costs of the RVMs, which are represented by binary opening variables (C_1), as well as operational costs that are proportional to flow variables (C_2). The operational costs encompass the production of reusable packaging and the reverse logistics costs associated with sorting and washing operations. Additionally, production costs refer to the manufacture of extra packaging required to meet demand due to unreturned or damaged units. The logistics cost component (C_3) in γ is calculated by determining the theoretical number of trucks needed and the cost per kilometer, which depends on the distance traveled. Furthermore, the cost function also accounts for the end-of-life management of packaging that is either not returned by consumers or damaged during logistics operations, necessitating disposal (C_4). The objective function γ also takes into consideration costs incurred by consumers when returning packaging, with a focus on minimizing the distance they must travel (C_5). Handling and filling costs at food packaging facilities are excluded

3.3.2. Constraints

The set of constraints can be clustered in three different groups. Constraints (9)–(14) ensure that the flow handled by the facilities does not exceed their production and storage capacities; Constraint (15) guarantees that the demand for food products is met at each store; and (16)–(22) to regulate the flows of the reusable packaging and packaged product among the nodes of the network.

$$\sum_{f\in F}\sum_{t\in T:(p,f)\in PF} x_{pfmt} \le \psi_{pm}^{prod} \qquad \forall (p,m) \in PM \quad (9)$$

$$\sum_{d\in D}\sum_{t\in T:[(f,d)\in FD \wedge (d,a)\in DA]} x_{fdat} \le \psi_{fa}^{fill} \qquad \forall (f,a) \in FA \quad (10)$$

$$\sum_{s\in S}\sum_{a\in A}\sum_{t\in T:[(s,a)\in SA \wedge (d,a)\in DA \wedge (d,s)\in DS]} \frac{x_{dsat}}{\sigma_a} \bullet \frac{1}{T_{da}} \le \psi_d^{stock} \qquad \forall d \in D \quad (11)$$

$$\sum_{w\in W}\sum_{t\in T:(w,m)\in WM} \frac{x_{owmt}}{\sigma_m} \le \psi_o^{sort} \bullet T_o \qquad \forall o \in O, \forall m \in M \quad (12)$$

$$\sum_{f\in F}\sum_{t\in T:[(w,f)\in WF \wedge (f,m)\in FM]} x_{wfmt} \le \psi_w^{wash} \qquad \forall (w,m) \in WM \quad (13)$$

$$\sum_{s\in S}\sum_{m\in M:(s,s_1)\in SS} x_{ss_1rm} \le \psi_r^{rvm} \bullet T_r \bullet y_{rs_1} \qquad \forall s_1 \in S, \forall r \in R \quad (14)$$

$$\sum_{d\in D}\sum_{a\in A}\sum_{t\in T:[(d,a)\in DA \wedge (d,s)\in DS \wedge (s,a)\in SA \wedge (a,j)\in AC]} x_{dsat} \le \delta_{sj} \qquad \forall (s,j) \in SJ \quad (15)$$

$$\sum_{p\in P}\sum_{t\in T:[(p,f)\in PF\wedge(p,m)\in PM]} x_{pfmt} + \sum_{w\in W}\sum_{t\in T:[(w,m)\in WM\wedge(w,f)\in WF]} x_{wfmt} = \sum_{d\in D}\sum_{t\in T}\sum_{a\in A}\sum_{m\in M:[(a,m)\in AC\wedge(f,a)\in FA\wedge(d,a)\in DA\wedge(f,d)\in FD]} x_{fdat}\bullet q_{ac} \quad \forall (f,m)\in FM \tag{16}$$

$$\sum_{f\in F}\sum_{t\in T:[(f,a)\in FA\wedge(f,d)\in FD]} x_{fdat} \geq \sum_{s\in S}\sum_{t\in T:(d,s)\in DS\wedge(s,a)\in SA} x_{dsat} \quad \forall (d,a)\in DA \tag{17}$$

$$\sum_{d\in D}\sum_{a\in A}\sum_{t\in T:[(a,m)\in AC\wedge(d,a)\in DA\wedge(d,s)\in DS\wedge(s,a)\in SA]} x_{dsat}\bullet q_{ac}\bullet \varphi^{return} = \sum_{s_1\in S}\sum_{r\in R:(s,s_1)\in SS} x_{ss_1rm} \quad \forall s\in S,\forall m\in M \tag{18}$$

$$\sum_{d\in D}\sum_{a\in A}\sum_{t\in T:[(a,m)\in AC\wedge(d,a)\in DA\wedge(d,s)\in DS\wedge(s,a)\in SA]} x_{dsat}\bullet q_{ac}\bullet (1-\varphi^{return}) = x_{sm}^{disp} \quad \forall s\in S,\forall m\in M \tag{19}$$

$$\sum_{s\in S}\sum_{m\in M:(s,s_1)\in SS} x_{ss_1rm} = \sum_{O\in O}\sum_{m\in M}\sum_{t\in T:(s_1,o)\in SO} x_{rsomt} \quad \forall s_1\in S,\forall r\in R \tag{20}$$

$$\sum_{s_1\in S}\sum_{r\in R}\sum_{t\in T:(s_1,o)\in SO} x_{rsomt} = \sum_{w\in W}\sum_{t\in T:(w,m)\in WM} x_{owmt} \quad \forall o\in O, m\in M \tag{21}$$

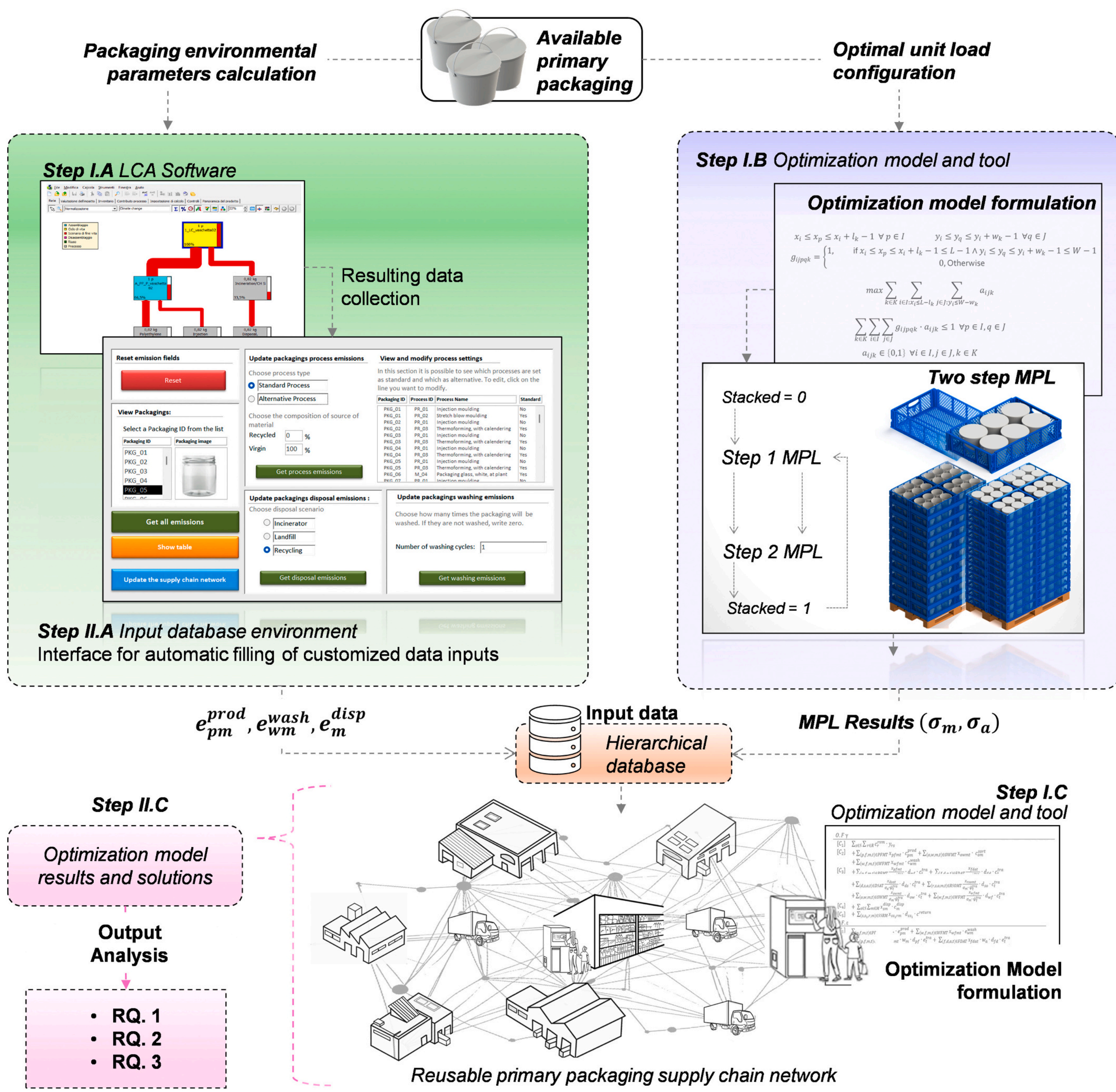


Fig. 4. The multi-stage approach applied.

$$\sum_{o\in O}\sum_{t\in T}x_{owmt}\bullet(1-\theta_m)=\sum_{f\in F}\sum_{t\in T:[(w,f)\in WF\bigwedge(f,m)FM]}x_{wfmt}\qquad\forall(w,m)\in WM\tag{22}$$

Eqs. (9) and (10) ensure that the production of reusable packaging and the packaging of food items do not exceed the throughput capacities of their respective packaging producers and food packagers. Eq. (11) requires that the distribution center's storage capacity is not exceeded, while Eq. (12) addresses the storage capacity limits of the sorting facilities. Eq. (13) establishes the throughput for washing lines. Eq. (14) ensures that the flow of reusable packaging does not exceed the maximum receiving capacity of the RVMs. Eq. (15) ensures that each store meets its demand for every food item *j*, specifying the required quantity, brand, and packaging producer. This constraint guarantees the association of an appropriate reusable packaging option for creating the packaged product configuration *a*. Eq. (16) mandates that the quantity of packaged products from food packager *f* corresponds to the amount of reusable packaging received from packaging producer *p* and washer *w*, in line with the BOM. Eq. (17) balances the goods' flow through the distribution center. Eq. (18) regulates the quantity of reusable packaging collected in RVMs at stores, based on the estimated likelihood of citizens returning such items. Constraint (19) determines the quantity of reusable packaging that will not be reintegrated into the logistics network. Finally, Eq. (20) outlines the inbound flows of reusable dirty packaging managed by sorting facilities. Eq. (21) ensures the flow balance inside and outside sorters facilities. Eq. (22) fixes the quantity of reusable, clean packaging that leaves the washing facility *w* and returns to the food packager *f* according to the scrap rate (θ_m).

3.4. A multi-stage methodology

To develop an optimization model that closely reflects real-world conditions, a multi-stage approach is adopted, consisting of some steps that precede the resolution of the optimization model. The available reusable primary packaging options present unique parameters related to environmental impacts and packaging configurations. The process begins with a preliminary Life Cycle Assessment (LCA) (Step I.A), which estimates environmental burden parameters, including CO_2 emissions resulting from the production, washing, and disposal of each reusable packaging option. Each type of packaging involves different production processes, washing systems, disposal scenarios, and recycling mixes, leading to varying environmental impacts. An interface has been developed to connect with LCA commercial databases and software (Step I·B). Such an interface allows for calculating the model's environmental parameters considering different production technologies, washing methods, and disposal scenarios. The packaging hierarchy design parameters are estimated by solving the Mixed-Integer Linear Programming (MPL) model discussed in Section 3.2. Given the parameters presetting, the optimization model (Step I·C) proposed in Section 3.3. determines the optimal configuration for the circular packaging network. The analysis and findings (Step II·C) contribute to addressing the research questions RQ1, RQ2, and RQ3, providing stakeholders with quantitative evidence of the economic and environmental performance of a reuse system for food retailer networks. Fig. 4 outlines the steps of the adopted methodology, aiming to make the process replicable in other supply chains where reusable primary packaging and network configurations may vary.

3.5. Case study and framework application

This methodology is applied to foster the transition to reusable packaging in the logistics networks of two major food retailers in France. This approach addresses a multi-product, multi-packaging scenario by analyzing the coupling of 13 food products presented in Table 2 with 36 packaging alternatives whose characteristics are shown in the plots in Fig. 5. Table 2 specifies the eligible combination between products and reusable containers. Each product (*j*) combined with its packaging (*m*) shaping a unique item (*a*) identified by an EAN code and associated with a specific food packager's brand. However, these items can be packaged at different food production facilities. Since the two retailers operate separately, the products also vary between Retailer 1 and Retailer 2, as shown in Table 2.

Fig. 5 illustrates the characteristics of the 36 reusable primary packages. The packaging differs in terms of material composition (Fig. 5 (a) - PP, PET, GLASS), sizes, and weight. As a result, the packaging is clustered into six distinct packaging types according to their volume and product compatibility (Fig. 5(b) - *Medium size for fruit and vegetables, Small size packaging, Big size non-liquid products, Big size bucket, Packaging for liquid products, Extreme big size buckets*). Applying the multi-stage methodology outlined in Section 3.4, a preliminary LCA analysis is performed to estimate emission parameters. Concurrently, the resolution of the MPL model allows for the determination of pallet saturation parameters. σ_m and σ_a. Fig. 5(c) summarizes the MPL model's solution presented in Section 3.2. It quantifies the pieces per pallet in both stacked σ_m (y-axis) and unstacked σ_a (x-axis) unit load configurations. Fig. 5(d) plots the package carbon footprint resulting from an LCA analysis confined to the production (e_{pm}^{prod}), washing (e_{wm}^{wash}), and disposal phases (e_{m}^{disp}).

The map in Fig. 6 illustrates the network characteristics, including

Table 2
Food product description and store retailers' compatibility.

Product J	Description	Size	Units	Available packaging	F. packager brand	Retailer 1	Retailer 2
P02	Biscuits	160	*g*	PKG_22, PKG_23, PKG_24, PKG_25, PKG_26, PKG_33, PKG_34, PKG_35, PKG_36, PKG_38, PKG_39, PKG_40	F_B3	●	
P04	Milk	1	*l*	PKG_44, PKG_45, PKG_46, PKG_47	F_B4	●	●
P05	Chips	125	*g*	PKG_39, PKG_40	F_B2	●	●
P09	Cyder	75	*g*	PKG_44, PKG_45, PKG_46, PKG_47	F_B1	●	●
P13	Cheese	2000	*g*	PKG_22, PKG_25, PKG_33, PKG_34, PKG_35, PKG_36, PKG_38	F_B8	●	●
P16	Juice	1	*l*	PKG_44, PKG_45, PKG_46, PKG_47	F_B7	●	
P18	Prepared salade	330	*g*	PKG_19, PKG_20, PKG_21, PKG_23, PKG_24, PKG_25, PKG_26	F_B9	●	●
P19	Salade	250	*g*	PKG_19, PKG_20, PKG_21, PKG_23, PKG_24, PKG_25, PKG_26	F_B7	●	
P27	Sweets	380	*g*	PKG_22, PKG_23, PKG_24, PKG_25, PKG_26, PKG_33, PKG_34, PKG_35, PKG_36, PKG_38, PKG_39, PKG_40	F_B5	●	●
P28	Prepared vegetables	180	*g*	PKG_01, PKG_02, PKG_03, PKG_04, PKG_05, PKG_06, PKG_07, PKG_08	F_B6	●	●
P29	Prepared vegetables	350	*g*	PKG_09, PKG_10, PKG_11, PKG_12, PKG_13, PKG_15, PKG_16, PKG_17, PKG_18, PKG_19, PKG_20	F_B6	●	●
P31	Biscuits	160	*g*	PKG_22, PKG_23, PKG_24, PKG_25, PKG_26, PKG_33, PKG_34, PKG_35, PKG_36, PKG_38, PKG_39, PKG_40	F_B3		●
P39	Juice	1	*l*	PKG_44, PKG_45, PKG_46, PKG_47	F_B7		●

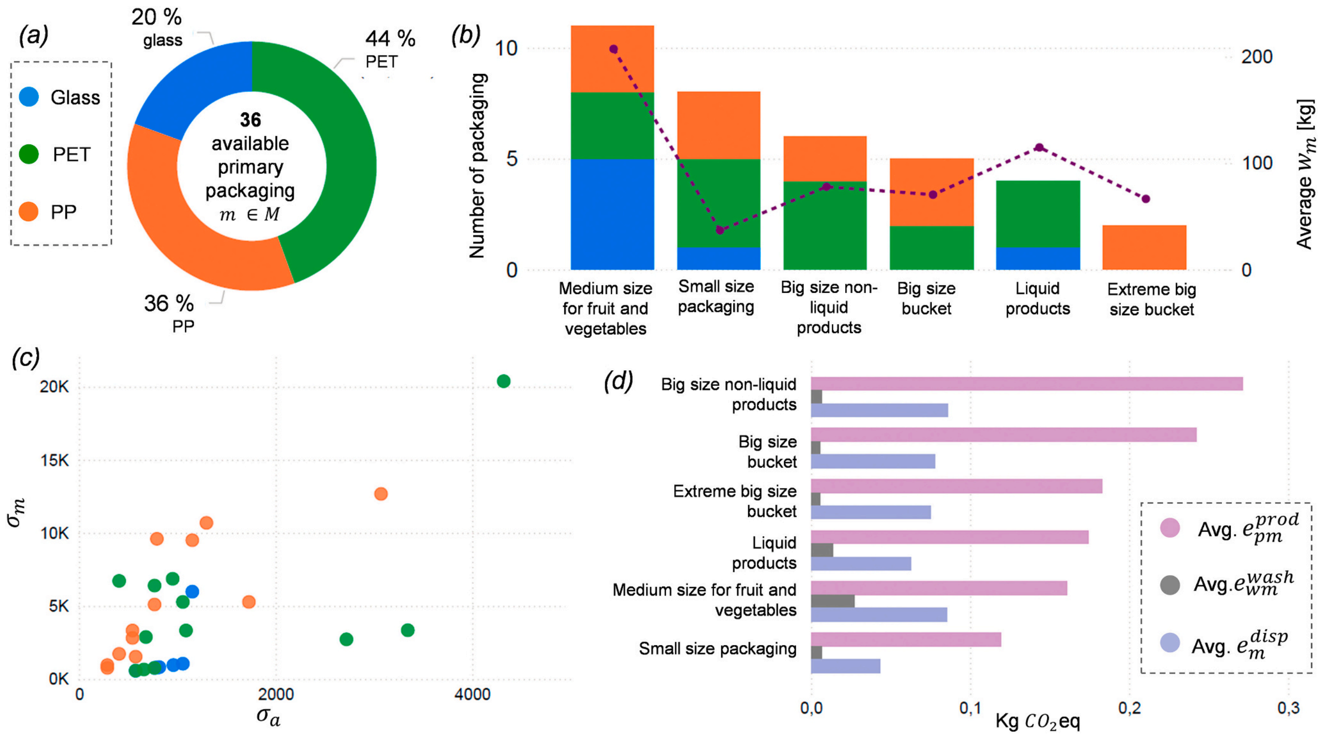


Fig. 5. (a) Available reusable primary packaging clusterization for material type; (b) Clusterization for packaging type and average weight for packaging type; (c) MPL results for packaging material (σ_m and σ_a for material); (d) LCA results for packaging type.

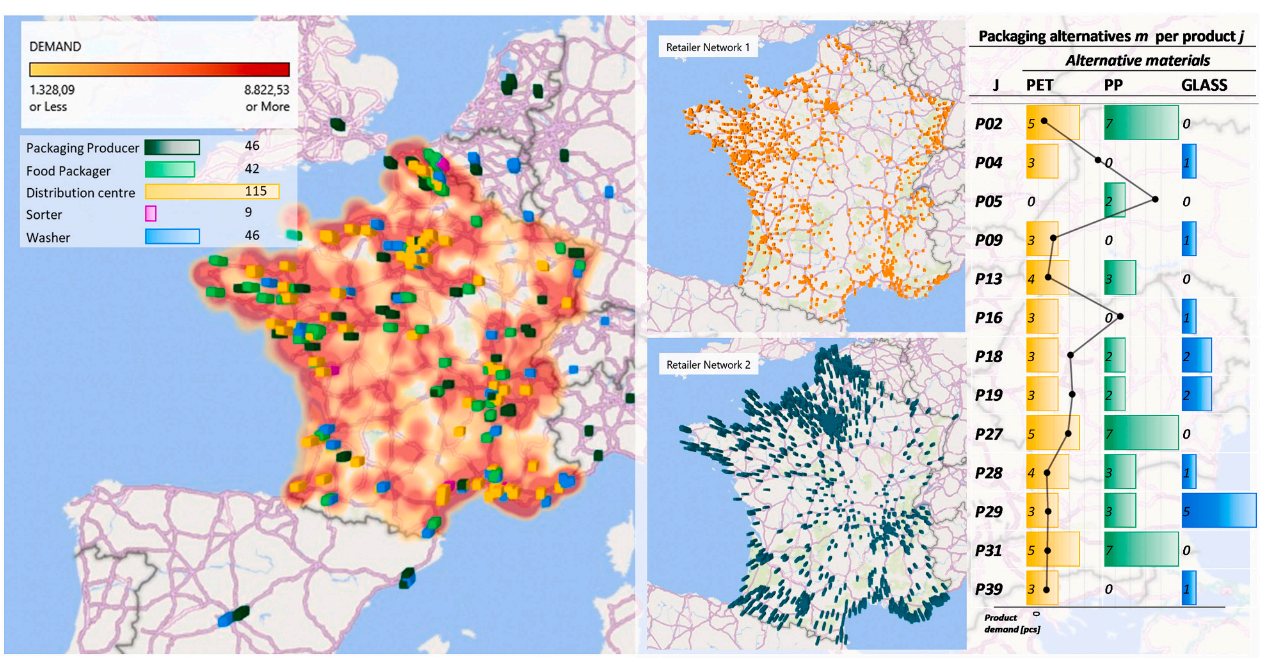


Fig. 6. Logistics network structure and packaging compatibility matrix for reusable packaging in France.

facilities location and food demand. This is assumed as 30 % of the current yearly demand. The network incorporates existing packaging production facilities (*46 packaging producer nodes*), food packagers (*42 nodes*), and retailer distribution centers (*115 nodes*), while choosing the best location for sorting (9) and washing (46) nodes already established in the area. Table 3 presents the main characteristics of the network's logistic nodes underlining lack of complete interchangeably and constrained allocations. Packaging producers are dedicated to specific types of packaging, while food packagers combine the packaging with food products to create branded items sold to retailers. Distribution centers are owned by retailers, and washers are committed to cleaning given material types. In contrast, sorters are capable of handling all packaging options. As shown in Fig. 6, shop nodes are distributed across France, with 1186 stores belonging to Retailer 1 and 1153 stores belonging to Retailer 2.

Shops are clustered by size into three types: *Hyper*, *Super*, and *Proxi*.

Table 3
Network nodes details.

Store			
Brand	Hyper shops	Super shops	Proxi shops
Retailer 1	233		953
Retailer 2	62	712	379

Distribution centers			
Brand	N. of facilities	Average L [m]	Average l [m]
Retailer 1	86	236.48	86.97
Retailer 2	30	252.53	95.65

Packaging producers			Food packagers		
Brand	N. of facilities	Managed products	Brand	N. of facilities	Managed products
PP_B1	1	PKG_01	*F_B1*	4	P09
PP_B2	1	PKG_16, PKG_18, PKG_19	*F_B2*	2	P05
PP_B3	3	PKG_04, PKG_05, PKG_23, PKG_40	*F_B3*	11	P02, P31
PP_B4	3	PKG_17	*F_B4*	6	P04
PP_B5	1	PKG_20	*F_B5*	2	P27
PP_B6	1	PKG_06, PKG_08, PKG_26	*F_B6*	6	P28, P29
PP_B7	1	PKG_45, PKG_46	*F_B7*	9	P16, P19, P39
PP_B8	11	PKG_02,PKG_03, PKG_10,PKG_11, PKG_21, PKG_24, PKG_34	*F_B8*	1	P13
PP_B9	1	PKG_35, PKG_39	*F_B9*	1	P18
PP_B10	17	PKG_09			
PP_B11	1	PKG_47			
PP_B12	1	PKG_36			
PP_B13	1	PKG_07, PKG_25, PKG_38			
PP_B14	1	PKG_22, PKG_33, PKG_44			
PP_B15	1	PKG_13			
PP_B16	1	PKG_12, PKG_15			

Washers			
Brand	N. of facilities	Glass	Plastic
W_B1	1	●	
W_B2	1	●	
W_B3	1	●	
W_B4	4	●	●
W_B5	1	●	
W_B6	9		●
W_B7	1	●	
W_B8	1	●	
W_B9	1	●	
W_B10	22	●	●
W_B11	1	●	
W_B12	1	●	
W_B13	2	●	●

Table 3 presents a breakdown of the number of stores by size, distinguishing between large, medium, and small, across the two retailer brands. These different store types generate different demands. Although the two retailers operate independently, the circular service is shared, utilizing the same washing and sorting systems.

Traditionally, retail stores function as demand consolidators, serving as a crucial link between the supply chain and consumers. This inherent role positions stores as viable candidates for the installation of Reverse Vending Machines (RVMs). In determining appropriate locations for RVMs, the retailers evaluate the density or isolation of shops within each area. To optimize investments and identify the most promising sites, a threshold of 5 km is established: if a shop is located within 5 km of another, only one can be designated for an RVM due to capacity constraints. Conversely, in more isolated areas that exceed the 5-km threshold, every shop is equipped with an RVM. This strategy effectively distinguishes between densely populated regions and rural areas. RVMs are designed to accommodate a wide range of packaging materials identified in this study. Consequently, sorting operations play a critical role in consolidating packaging flows and generating homogenous unit loads for reverse logistics. Importantly, RVMs are capable of accepting any packaging type, regardless of the retailer it originates from, highlighting the necessity of standardizing packaging for identical food products.

To ensure alignment with real-world and industrial constraints, the case study relies on the following assumptions:

i. A one-year planning horizon is considered, assuming steady operations with constant demand unaffected by seasonality.
ii. Storage capacities are estimated through warehouse's sizes analysis, while production capacities of packaging lines are a portion of the current throughputs.
iii. Carbon footprint parameters result from Life Cycle Assessment (LCA) analyses conducted using SimaPro 7.3.3 tool with the Ecoinvent database and the ReCiPe Midpoint (H) method. Unlike conventional LCA analyses that use secondary data, this model incorporates primary data for the logistics and transportation phase resulting from the optimized solution. Secondary data are used for processes outside the network boundaries, such as raw material extraction and packaging disposal.
iv. Transport operations are based on a 15-pallet truck with an 80 % load utilization rate.
v. An RVM emptying frequency of twice per month is adopted. Regarding the estimation of RVM cost parameters, an amortization period of 10 years is assumed, with an annual installation cost set at €2500.

This system generates a series of instances comprising 11,298,929 continuous variables, 978 integer variables, and 122,305 constraints. The model is formulated in AMPL (A Mathematical Programming Language) and solved with Gurobi 11.0 through a standard dual simplex algorithm on a computer configured with Intel® Quad Core @2.4 GHz processors and 8 GB of RAM. Solutions are obtained within a reasonable time frame, considering the strategic scope of the analysis and the varying number of variables and constraints generated across all testing scenarios.

4. Results

4.1. Optimizing environmental and economic performance

A key question to address within this network is the trade-off between the costs of the circular system and the environmental benefits, considered as decision levers to assess the feasibility of transitioning to a circular system (RQ. 1). This assessment is conducted using the proposed optimization framework, which integrates both objective functions in a multi-objective *ε-constraint* approach. In any circular system, the literature agrees that environmental benefits are measured through the duration of the *transition point (*Camps-Posino et al., 2021*)*, while the economic performance of the investment is evaluated via its *payback* period. There is, therefore, a well-documented parallel in the literature between these two dimensions (Ronzoni et al., 2022). However, in a complex system such as a multi-actor industrial network, this relationship depends on operational management decisions, the network infrastructure, and critical factors such as the likelihood of breakage of the reusable item (θ_m) and the end-user propensity to return it (φ^{return}). The combination of these factors requires precise analysis and

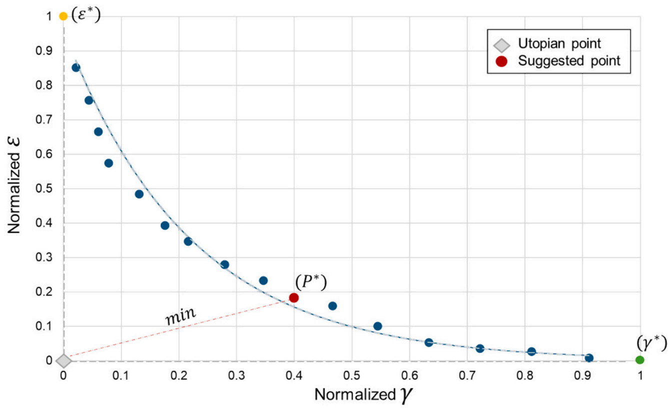


Fig. 7. Pareto frontier trade-off between costs and emissions for ten cycles of reusable packaging.

evaluation for each circular system, discouraging the adoption of general conclusions applicable to every context. Furthermore, among these factors, the reuse of primary packaging in contact with food places the consumer, and their resistance to this practice, as the "tipping point" in determining the number of possible return cycles and, consequently, in identifying the transition point.

The analysis aimed to evaluate the network under ideal conditions, ensuring a minimum of 10 reuse cycles. The number of reuse cycles, *N*, is determined by the parameters θ_m and φ^{return} as in (23).

$$N = \frac{1}{(1-\varphi^{return}) \bullet \varphi^{return} \bullet \theta_m}\ [\textit{reuse cycles}] \tag{23}$$

In this scenario, $\varphi^{return} = 90\%$ and $\theta_m = 0.1\%$ were used.

In multi-objective programming, the objectives are often mutually conflicting, and the proper "trade-off" between solutions must be identified (Mavrotas, 2009). These problems do not provide a single optimal solution but a set of so-called Pareto optimal solutions. Each solution is Pareto-optimal whether is not improvable in one objective without influencing its performance in another one (Varsei and Polyakovskiy, 2017). The plot in Fig. 7 represents the Pareto frontier, where normalized values of costs and emissions were obtained across multiple iterations. Reducing emissions requires an increase in costs, and this relationship is represented by a negative exponential function with a coefficient of determination R^2 of 0.9904. Geometrically, the Pareto frontier suggests a cost-emission pair that minimizes the distance from the utopian point (the theoretical point where both emissions and costs are minimized).

The minimized cost-emission distance configuration (P^*) corresponds to a specific logistics network topology defined by selected nodes, flow allocations, total costs, and emissions, amounting to k€ 7358.3 and 289.403 tCO_2eq, respectively. This configuration increases costs by k€ 415.87 and emissions by 103.413 tCO_2eq compared to the optimal point (γ^*) and (ε^*). The costs and the emissions are distributed across the entire supply chain, which adopts the three distinct configurations in the points $(\gamma^*), (P^*), (\varepsilon^*)$, as shown in Fig. 8. These points correspond to various network configurations. The map highlights that the nodes responsible for filling packages and managing reverse logistics remain largely consistent across all three configurations (i.e., an histogram height equale to 3 means that the node is used in all configurations $(\gamma^*), (P^*), (\varepsilon^*)$). The primary differences among the three scenarios are evident in the packaging choices associated with each one, which subsequently influence the selection of production nodes. The map indicates that certain packaging production nodes are utilized solely within specific configurations. These distinctions underscore the importance of promoting a systematic transition to minimize the environmental impact of packaging production nodes. To support this initiative, it is imperative to implement targeted policies, such as financial incentives, aimed at guiding packaging manufacturers toward the adoption of reusable packaging options or the use of more sustainable materials.

Notably, PKG_24, PKG_39, and PKG_46 are resilient across all solutions, whether minimizing costs or emissions. These packaging types (designed for *big-size non-liquid products, big-size buckets, and liquid*

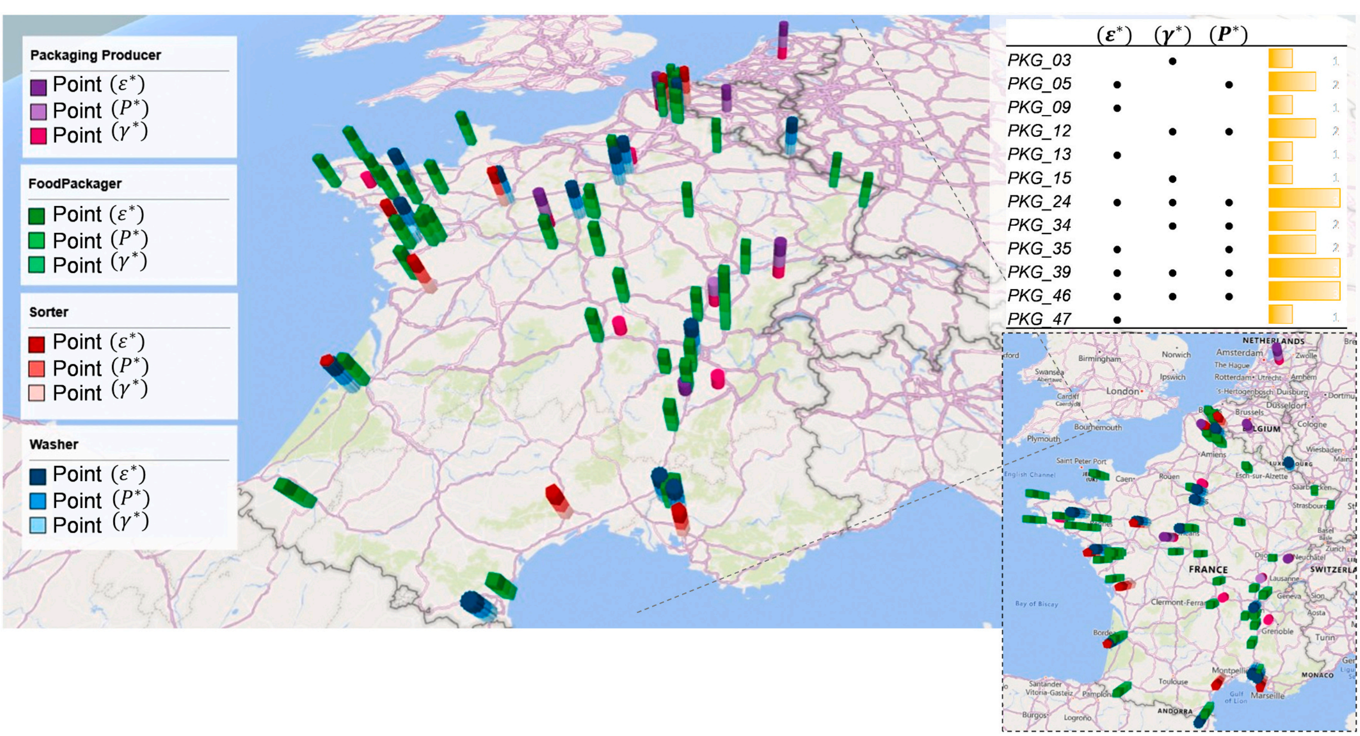
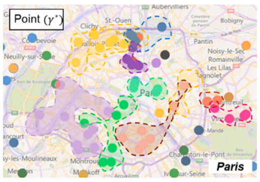
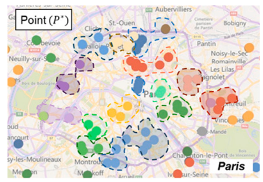
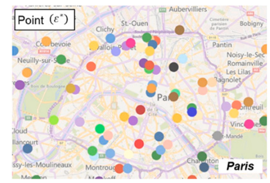


Fig. 8. Supply chain network design resulting in $(\gamma^*), (P^*), (\varepsilon^*)$ and corresponding packaging choices. The height of the histograms shows if in the network configuration corresponding to $(\gamma^*), (P^*), (\varepsilon^*)$ the node is chosen. The table describes the choice of packaging in the three configurations.

Table 4
RVMs installation analysis in $(\gamma^*), (\varepsilon^*), (P^*)$.

Point $(\boldsymbol{\gamma}^*)$			***Point*** $(\boldsymbol{P}^*)$			***Point*** $(\boldsymbol{\varepsilon}^*)$		
Total cost: 6942432 € *Total emission: 555264 kgCO$_2$eq* ***RVM installation cost*** 4,822,500 €			*Total cost: 7358301 €* *Total emission: 289404 kgCO$_2$eq* ***RVM installation cost*** 6,425,000 €			*Total cost: 8431954 €* *Total emission: 185991 kgCO$_2$eq* ***RVM installation cost*** 5,325,000 €		
								
	$\boldsymbol{y_{rs}}$	***Avg RVM Saturation***		$\boldsymbol{y_{rs}}$	***Avg RVM Saturation***		$\boldsymbol{y_{rs}}$	***Avg RVM Saturation***
Hyper	374	73 %	*Hyper*	405	72 %	*Hyper*	528	51 %
Super	603	32 %	*Super*	665	30 %	*Super*	711	28 %
Proxi	952	25 %	*Proxi*	1060	20 %	*Proxi*	1331	16 %
Total	**1929**	**34 %**	***Total***	**2130**	**24 %**	***Total***	**2570**	**24 %**

products) are lighter and maximize stackability, assuming the same lifespan as of glass packages. Their design and weight make them well-suited for adoption in circular networks under specific conditions of φ^{return} and θ_m. This aspect leads to verifying the presence of enabling conditions that make some types of packaging more suitable for adoption in a circular supply chain due to their design and physical properties (RQ.2).

4.1.1. RVMs allocation strategy

The cost analysis reveals that the installation cost of RVMs constitutes the largest portion of the total cost, ranging from 70 % at point $(\boldsymbol{\gamma}^*)$ to 87 % at point $(\boldsymbol{\varepsilon}^*)$. Therefore, one of the main differences among the three points of the Pareto frontier analyzed is the number of RVMs installed, as described in Table 4.

At point $(\boldsymbol{\gamma}^*)$, to minimize total costs, the model installs the least number of RVMs. In clusters of stores within a 5 km radius, if the combined cost of transporting packaging and customer effort is less than the installation cost, only one RVM is installed to meet capacity needs. Customers from these stores are expected to use the shared RVM. However, if a store is isolated with no nearby stores, a dedicated RVM is installed, as it would be inconvenient for customers to travel further for returns. Hence, the number of installed RVMs is lower than the available locations, leading to a high saturation rate. Larger stores tend to generate more return flows and achieve higher RVM saturation compared to smaller stores, facilitating a gradual installation of RVMs across all stores.

At the point that minimizes emissions (ε^*), the optimal solution is to install one or more Reverse Vending Machines (RVMs) in every store. This approach reduces the saturation rate of the RVMs and makes it more convenient for customers to return their packaging. Additionally,

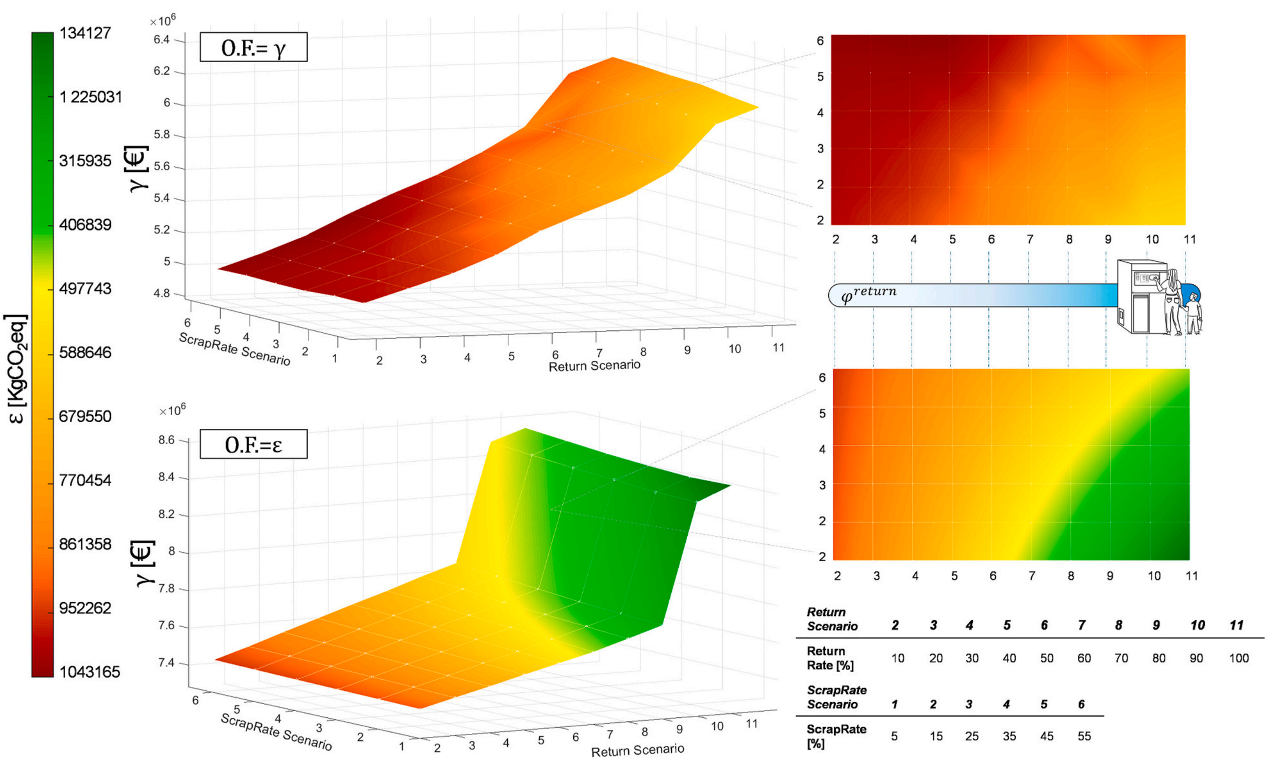


Fig. 9. Impact on costs and emissions of the multi-scenario analysis

depending on hygiene and safety considerations, stores with their own RVMs could adopt lower emptying frequencies. The focus on the maps of Paris, as shown in Table 4, highlights how stores are clustered in the area across the three examined points. Shifting from point ($\boldsymbol{\gamma}^*$) to point ($\boldsymbol{P}^*$), the number of clusters increases until point ($\boldsymbol{\varepsilon}^*$), where each store forms its cluster and has its RVM.

4.1.2. Multi-scenario analysis on uncertainties

The analysis in Section 4.1.1 and 4.1.2 assumes fixed values for the scrap rate θ_m and return rate φ^{return}, exploring conditions that guarantee a minimum of 10 reuse cycles. To assess the supply chain's adaptability during the transition to a circular system, the optimization framework is used to study the impact of lower reuse-cycles $N(\varphi^{return}, \theta_m)$. These adverse conditions may result from low packaging return rates by citizens (φ^{return}) or inefficiencies in reverse logistics flows resulting in (θ_m). A multi-scenario analysis is conducted by varying these two levers and identifying the anchor points in each scenario. Each model scenario independently optimizes costs and carbon emissions, addressing one objective at a time while calculating the value of the non-target objective function for the current optimization. Fig. 9 depicts the direct impact of the multi-scenario analysis on cost and emissions. φ^{return} models citizen behaviors, ranging from highly engaged to less engaged scenarios, reflecting early-stage hesitant adoption of reusable packaging. θ_m accounts for packaging breakage caused by inaccurate handling operations and inherent characteristics of the packaging like material, lifespan, size, and other designs. The return rate varies by 10 % for each scenario within a range of 0–100 %. Similarly, the scrap rate varies by 10 % within a range of 5–55 %, as a breakage rate exceeding half of the total packaging is considered unrealistic.

Overall, with a cost of 5.7 times the initial value, the emission is reduced by a factor of 7.7 compared to the initial value. Evident trends and discontinuities emerge on these surfaces. On both surfaces, as the φ^{return} increases, θ_m becomes a critical factor. When carbon emissions ε are optimized, we experience a spike of costs corresponding to a minimization of environmental burden (i.e., the green surface when the φ^{return} is above 80 %). This reduction is closely linked to the scrap rate values, as highlighted by the clear trend of the yellow line on the surface plot when ε are optimized. Considering the scenarios where the return rate (φ^{return}) ranges from 55 % to 100 %, the same environmental impact achieved at a cost of 8.6 million euros with a 55 % scrap rate and a 90 % return rate (ScrapRate scenario = 6, ReturnRate scenario = 10), can be obtained by reducing the scrap rate to 15 %, with a lower return rate of 50 %, leading to a reduced cost equal to 7.8 million euros. This demonstrates that lowering the θ_m significantly reduces environmental burdens, even in the early stages of adoption, when φ^{return} is equal to 50 %.

These findings highlight the importance of return and scrap rate as enabling conditions to foster the transition to a sustainable circular system. An analysis of these surfaces indicates that low values provide a strong justification for the adoption of reusable packaging. Consequently, it is essential to not only engage citizens but also to support low breakage rates to guarantee the reduction of packaging systems' environmental burdens.

The next section explores these conditions in detail, focusing on the factors that govern the feasibility and effectiveness of reusable packaging systems.

4.2. Leading packaging choices in circular systems

The multi-scenario analysis identifies packaging solutions that are resilient to uncertainty in operational parameters. It provides insights into the conditions necessary to enhance the feasibility of reusable packaging systems (RQ. 2). Fig. 10 showcases the variation in packaging adoption across the 55 scenarios analyzed in Section 4.1.2. under varying return and scrap rates. In the selection of the optimal packaging for each product, two different patterns are identified. Such patterns are defined as follows:

a) ***Single-choice packaging. Unaffected by θ_m and φ_{return}:*** For certain products, the optimization model consistently chooses the same packaging, regardless of changes in operational parameters θ_m and φ_{return}.
b) ***Multi-choice packaging. Influenced by θ_m and φ_{return}:*** Products that exhibit dependency on operational parameters, resulting in multiple packaging options in the 55 examined scenarios when θ_m and φ_{return} vary.

Fig. 10 portrays the optimal product packaging combination under scrap and return rates varying scenarios optimizing the total carbon emissions ε. The same selection for all products is reported in

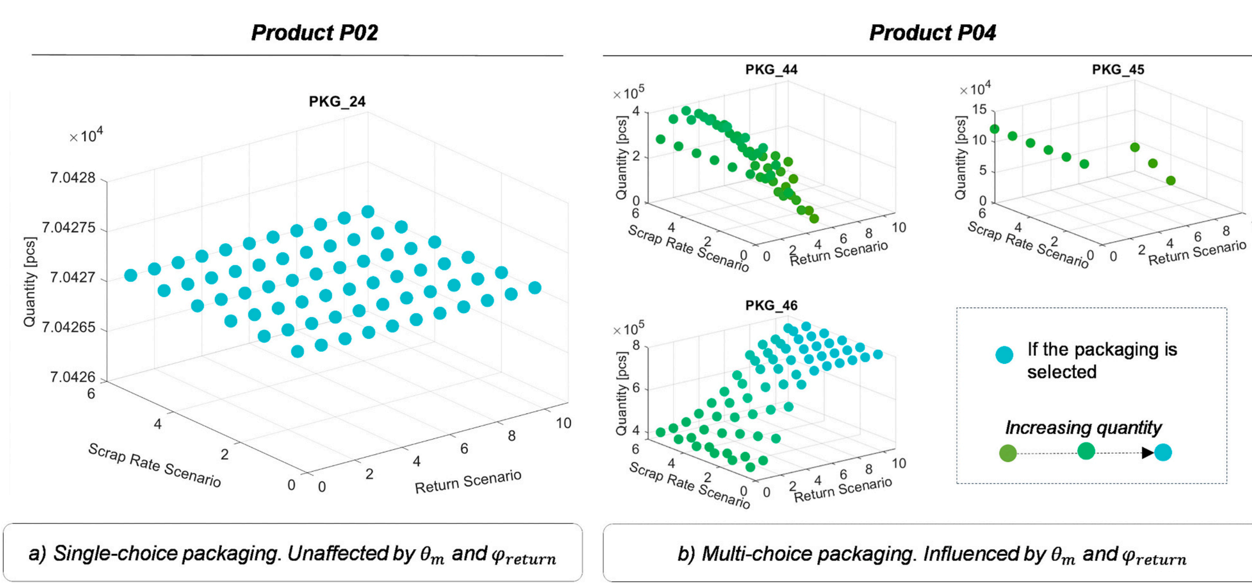


Fig. 10. Impact of return and scrap rate scenarios on packaging quantities per type for selected products.

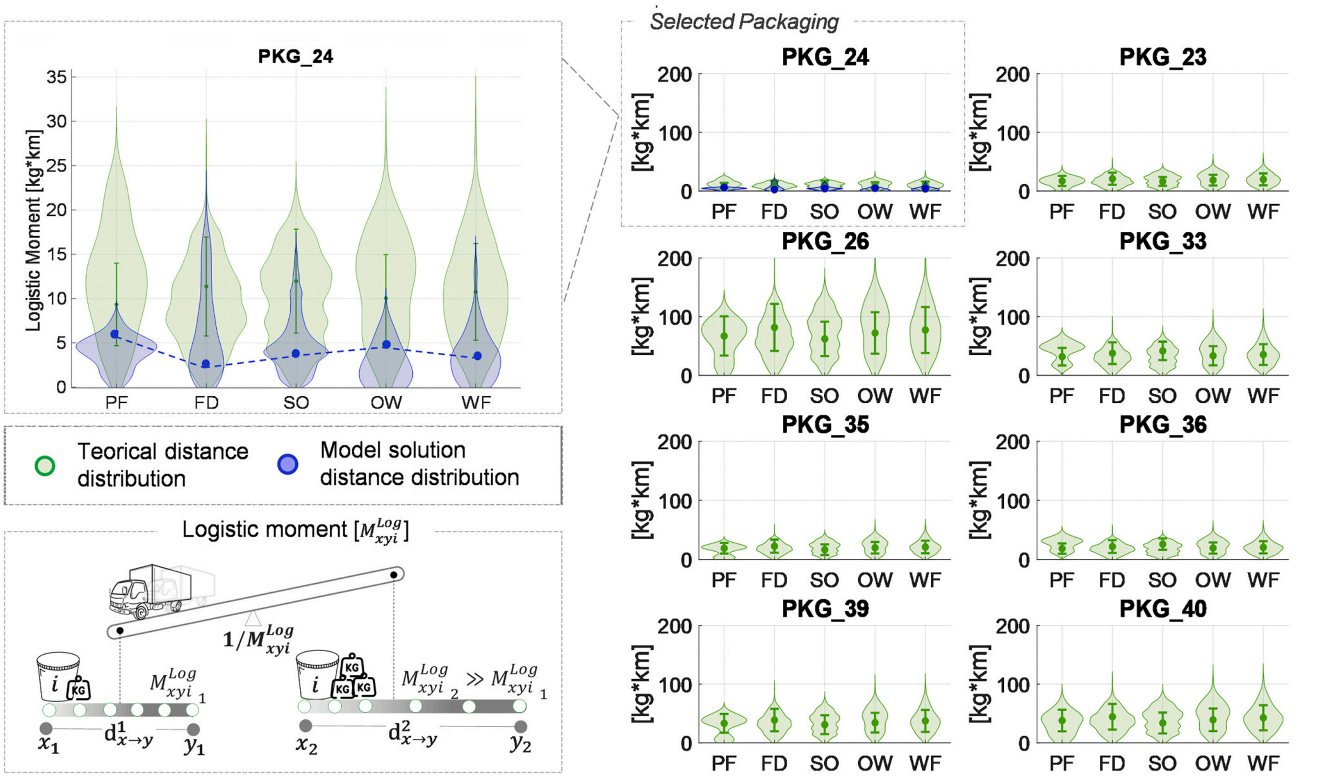


Fig. 11. Logistic Moment distribution for available packaging across supply chain stages. PF: Packaging Producer - Food Packager, FD: Food Packager – Distribution Center, SO: Store – Sorter, OW: Sorter – Washer, WF: Washer – Food Packager. Green Violin plots the theoretical distribution of the Logistic Moment before model solving. Blue Violin plots the distribution of the Logistic Moment obtained by solving the model.

Supplementary Information S.3 and S.4.

This behavior is affected by the inherent characteristics of both the packaging and the logistics network configuration, which guide the optimization process toward uniform solutions. A significant correlation is evident between the weight of the packaging and the logistical network' connection, which can be captured in the concept of hereby defined Logistic Moment M_{xyi}^{Log} where x and y stand for origin and destination nodes, respectively, and ω_i is the unit weight of the item i.

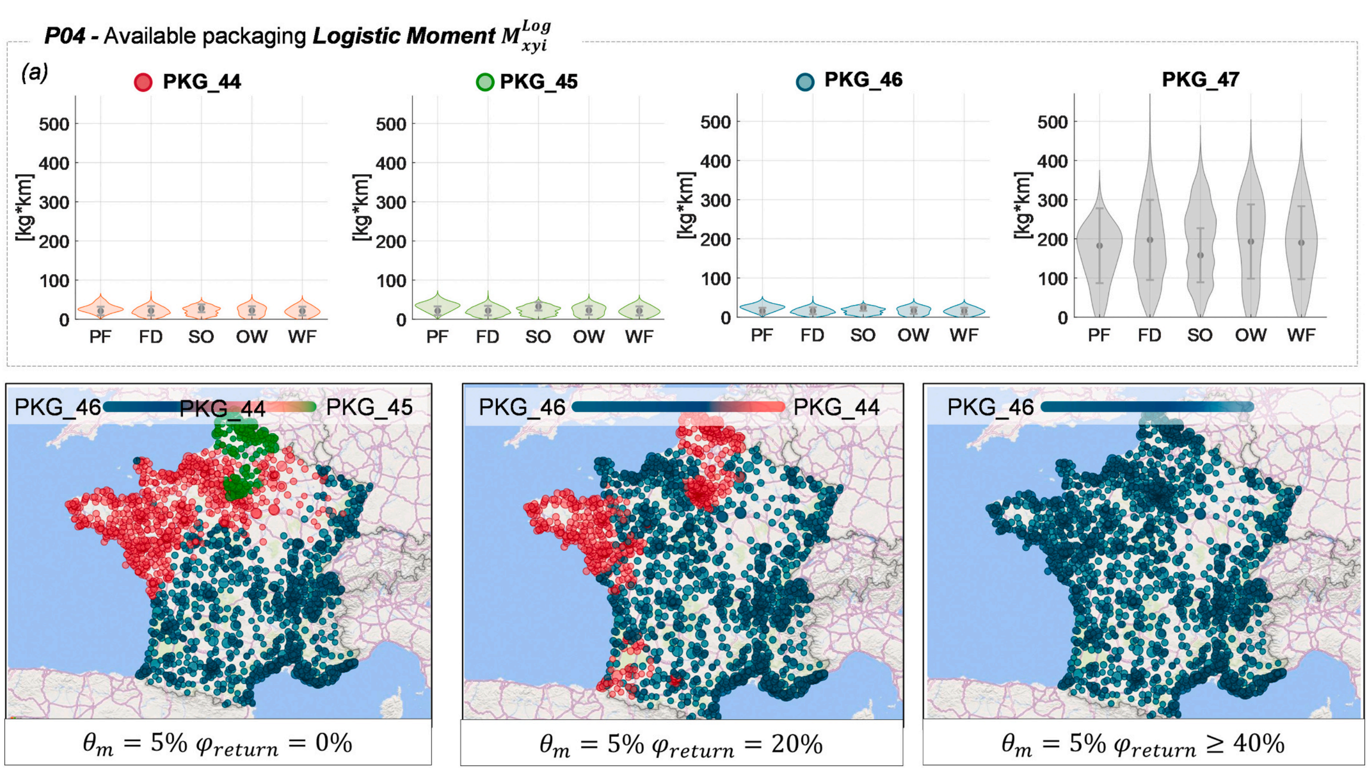


Fig. 12. Packaging adoption distribution with varying return rates for products P04.

$$M_{xyi}^{Log} = d_{x \to y} \bullet \omega_i \ [Km \bullet Kg] \tag{24}$$

The distance between an origin x and a destination y can influence the fatigue of transferring a mass i, as the mass itself, from x to y. Reducing such distance, rather than the mass, minimizes the "moment" of the logistical connection from x to y. Given the delivered item i, M_{xyi}^{Log} is an inherent property of each network connection, reflecting its potential in terms of efficiency, cost and emissions. Thus, M_{xyi}^{Log} provides an early measure of logistic fatigue before any optimization. As depicted in Fig. 11, the Logistic Moment is little when lighter items are transported over shorter connections ($M_{xyi}^{Log}1 < M_{xyi}^{Log}2$). Exemplified for product P02, Fig. 11 shows violin plots illustrating the distribution of the Logistic Moments of all possible connections at any supply chain stage. The a-priori Logistic Moment is compared between alternative packaging and the optimization's choice. Lighter packages and distributed throughout shorter connections (PKG_24), "tilt the lever" toward smaller logistical moments $\left(1/M_{xyi}^{Log}\right)$, are favored. Indeed, the optimal solution aligns with the suggestions from the preliminary Logistic Moment analysis. Thus, the logistical structure of the network that supports a particular type of packaging with a specific design becomes a crucial enabling factor, determining which packaging options are most suitable for reusable circular networks.

Each network's stage consists of multiple connections, driving the calculation of multiple Logistic Moments (i.e. one per each network's arc and packaging option) summarized using statistics as mean and probability density function (PDF). The blue violins in Fig. 11 draw the Logistic Moment distribution for each supply chain stage as determined by the model's solution whilst the green violins represent the Logistic Moment PDF for each feasible packaging. Green violins identify the upper and lower bounds of the optimal solution (i.e. blue ones). By choosing the packaging and facilities, the model addresses the optimal connections for each stage, thereby establishing optimal circular flows that minimize the environmental burden.

As for the case b), the optimal packaging choice can vary with the scrap and return rates. Fig. 12 showcases such choices for product P04 and plots the Logistic Moment for all feasible options. The Logistic Moment's interpretation prevents the adoption of packaging PKG_47, which has a value significantly greater than the others. The maps draw the adoption of different packages at the stores under varying return and scrap rates. As long as φ_{return} increases, we observe a transition from many to a single package corresponding to that with the lowest Logistic Moment in the reverse stages. Such behavior is not influenced by the lack of product capacity (i.e., which is not exceeded) but results from the geographical distribution of the network's facilities. The maps transition in Fig. 12 demonstrates the impact of increasing φ_{return} in unifying packaging choices and reducing the overall circular system's complexity.

4.3. Managing circular network's costs

As mentioned in Section 4.1, the economic aspect is key in driving the transition toward circular paradigms. To achieve environmental sustainability goals (ε), the high installation cost of RVMs, and the adoption of other packages not selected in the economic optimum (γ) underscore the necessity to explore ways to incentivize stakeholders to participate in the circular system. To address RQ3, the operational cost distribution for each stakeholder and the total transportation cost are assessed. As φ_{return} increase, the cost distribution is evaluated by fixing θ_m. The minimized objective function γ is used to assess total costs for each stakeholder across varying return rate scenarios.

Fig. 13 highlights cost deltas relative to the reference scenario $\theta_m =$ 5% and $\varphi_{return} =$ 10%. As the level of returns increases, stakeholders involved in reverse logistics, such as RVM operators, sorting facilities, and washers, face rising costs. Operational cost and carbon emissions quantified per each scenario of φ_{return} are drawn in Supplementary Information S.5. Additionally, costs for consumers also grow due to the increased effort required for packaging returns, which may include additional trips. In contrast, stakeholders in the direct supply chain for single-use packaging benefit from a decrease in costs as the level of returns rises. Transportation costs follow a non-linear trend: they initially increase with higher return levels but begin to decline once the return rate exceeds 50 %. When transportation cost deltas turn negative, it indicates that the total distance from the packaging production facility to the food packager is greater than the additional distance required for reverse logistics. This reduction signifies a strategic adjustment in logistics processes aimed at promoting the adoption of reusable packaging. Consequently, organizations can realize cost savings through shorter travel distances and optimized routing.

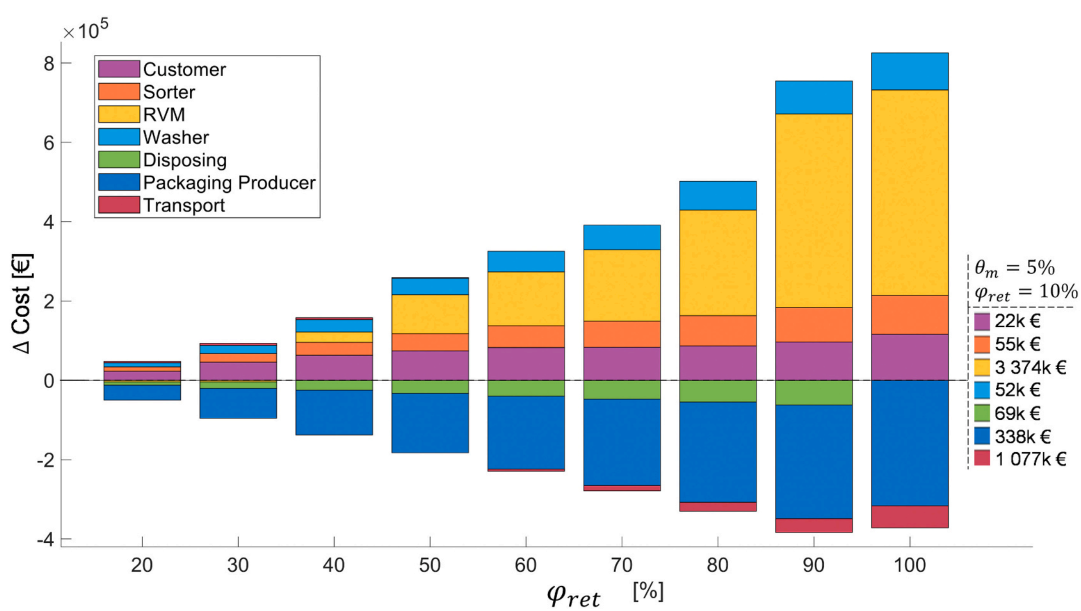


Fig. 13. Cost distribution across stakeholders.

5. Discussion

This study tackles the challenges outlined in the research questions, linking environmental efficiency, economic performance, and the enabling conditions necessary for scaling reusable packaging systems (Miao et al., 2023). Using a real-world case study on a national-scale network in France, the optimization model incorporates packaging properties and consumer behavior, revealing the complex interactions between product selection and network configurations. The research questions are addressed by establishing specific boundary conditions, which sometimes allow for network behavior predictions through early metrics calculation. As network complexity increases and parameter variability becomes more pronounced, the value of the optimization model becomes even more evident. This model identifies the optimal solution within the lower and upper bounds determined from an initial analysis of network properties, allowing the capture of all relevant variabilities and making it possible to identify the global optimum.

5.1. Research implications

Addressing RQ1, the optimization model confirms the trade-off between costs and emissions as identified by Hitt et al., 2025. This aligns with the existing literature, which indicates that reusable packaging networks have the potential to reduce the packaging sector's environmental burdens, provided that the frequency of reuses is increased (Lin et al., 2023). However, achieving this requires an economic investment. The analysis of the Pareto frontier reveals that different cost-emission levels reflect distinct supply chain configurations, primarily affecting packaging selection and packaging producer nodes while leaving food packagers and reverse logistic nodes resilient, transitioning to lower environmental burdens. The analysis indicates RVM installation as a driver in balancing cost and emissions. While achieving optimal emission levels requires at least one RVM per store, cost minimization suggests an alternative strategy: deploying shared RVMs within a 5 km radius. The model supports a phased installation plan, prioritizing strategic locations before scaling up to a full-store coverage approach.

The Pareto frontier (Fig. 7) examines the supply chain under ideal conditions, assuming over ten reuse cycles per packaging. In contrast, the multi-scenario analysis explores the impact of higher scrap rates and lower return rates, which are often seen during early adoption phases due to societal inertia and improper handling operations. The findings indicate that carbon emission reductions become more significant as the number of reuse cycles increases, which is a function of both the return and scrap rates. While the analysis highlights the importance of consumer engagement in activating reverse logistics flows, a high return rate by itself does not guarantee efficiency. When return rates exceed 50 %, maintaining low scrap rates becomes an enabling condition (RQ.2) to ensure the environmental benefits of a circular supply chain and effectively reduce environmental burdens. This transition requires upskilling stakeholders and adapting facilities, reinforcing that successful adoption relies on well-designed packaging and a robust reverse logistics system.

Since the network nodes are dedicated to packaging production and product handling, each packaging design is linked to a specific supply chain configuration. This configuration includes the production nodes and facilities involved in reverse logistics. The properties of the packaging, along with the structure of the supply chain managing it, create conditions that make some types of packaging more suitable for reusable systems, thereby addressing RQ2. The multi-scenario analysis identifies the measure of the "Logistic Moment" as an enabling condition, serving as an indicator of a packaging's suitability for adoption in a circular reuse network. The Logistic Moment (24) is a property of the network, defined as the product of the packaging's weight and the transport distances between stakeholders at various stages of the supply chain that handle the packaging. Packaging that exhibits a significantly lower Logistic Moment compared to feasible alternatives can withstand variations in return and scrap rates, making it a viable option for circular models.

Finally, RQ3 examines the economic incentives required to facilitate the transition to reusable packaging systems. A major challenge in this shift is the economic impact on packaging producers, who face declining demand for single-use solutions. These stakeholders require incentives and support to pivot toward sustainable alternatives to remain competitive. Additionally, RVM management represents a significant cost factor, necessitating financial incentives to drive adoption. The findings underscore the intricate balance between economic feasibility, environmental impact, and operational constraints in reusable packaging networks. The proposed optimization model provides a decision-making framework for stakeholders navigating this transition, offering practical insights for policymakers, businesses, and supply chain managers aiming to implement sustainable packaging strategies at scale.

5.2. Managerial implications

The analysis of the results has identified the key conditions that promote the adoption of reusable packaging. These conditions can be converted into actionable insights for managers, which have practical implications. As a result, it is possible to pinpoint best practices for managers and aid policymakers in outlining the steps needed for transitioning to a reusable packaging supply chain.

i) *Ensure high return rates*. To achieve desirable return rates and ensure the sustainability of reusable packaging supply chains, companies should invest in marketing campaigns that effectively communicate the environmental benefits and build consumer confidence in the safety of these packaging solutions (Plotkina et al., 2025). To encourage the adoption of reusable packaging, using models like the Technology Acceptance Model (TAM) can be beneficial in designing Reverse Vending Machines (RVMs) (Mustofa et al., 2025). This approach aims to enhance user acceptance, simplify the packaging return process, and promote the reintegration of packaging into the supply chain.
ii) *Ensure low scrap rates.* Keeping scrap rates low by optimizing handling systems and logistics operations is essential for the sustainability of reuse systems. When the return rate overcomes 50 %, the scrap rate becomes a critical factor. To preserve the integrity of reusable packaging, efficient handling systems must be designed, suitable reverse vending machines installed, and washing processes improved. Advancements in process engineering and material innovation are required to enhance durability and maintain performance across multiple reuse cycles. Additionally, standardizing packaging across products and industries improves handling, storage operations, and overall efficiency (Sundqvist et al., 2024).
iii) *Choose strategic packaging options*. Reusable packaging selection in a nationwide supply chain depends on more than just material composition and required volumes, though these remain key factors. The logistics network influences packaging selection, as each packaging type is tied to specific production sites, while the product-packaging configuration determines the network structure and topology, shaping its adaptability to reuse practices (Caspers et al., 2025). To evaluate suitability, this paper introduces the Logistical Momentum metric, a normalized KPI that integrates both packaging properties and the characteristics of its associated supply chain. Computing this metric in advance allows for the identification of optimal reusable packaging solutions, prioritizing those that minimize transport distances and weight impact. Additionally, packaging selection is influenced by unit configuration and stackability, which enhance transport efficiency by maximizing load saturation. Users' preferences also influence packaging selection and can be assessed through consumer choice models to ensure market acceptance of reusable containers (Czine et al., 2025).

Table 5
Enabling conditions and managerial best practices to facilitate the adoption of reusable packaging

Enabling conditions	People	Planet	Profit	Actionable insights
Ensure high return rates Ensure low scrap rates	Consumers need to perceive the real environmental benefit of their contribution. Reusable packaging must be perceived as safe and clean. To ensure the integrity of returned packaging, consumers require clear guidance on proper handling and return practices. Installation of user-friendly RVMs.	High rates of return and minimal breakage significantly decrease the necessity for introducing new packaging into the system, thereby reducing packaging waste. This approach not only reduces the environmental impact but also contributes to a reduction in raw material consumption.		• Invest in effective marketing campaigns to enhance consumer willingness to reuse. Design RVMs studying consumer perception with the Technology Acceptance Model (TAM) to maximize the ease of reuse.
Choose strategic packaging options	Consider consumer preferences to identify reusable packaging options for analysis.	After identifying suitable reusable packaging that aligns with consumer preferences, the selection of reusable containers should account not only for their chemical and physical properties but also for the supply chain configurations that manage them.		• Analyze consumer choices and preferences (ex., with a Discrete Choice Experiment). • Perform a preliminary calculation of the Logistic Moment to assess packaging suitability. • Optimization of the unit load configuration.
RVMs strategical location	Study consumer habits to identify whether there are preferred and more frequented locations.	Maximize the number of installed RVMs to minimize the environmental burdens.	If economic constraints limit the installation of an RVM in every store, shared RVMs across multiple retailers must be considered.	• Retailers must be part of a consortium and be able to accept packaging from other stores as well, ensuring the efficiency of the RVM system.
Incentives system	Studying consumer willingness to pay in order to formalize a deposit system that is beneficial for the entire supply chain and encourages return behavior from users.		Reusable packaging represents an additional cost for some supply chain actors that should be supported with an incentive policy	• Development of a deposit system that incentivizes citizens to return packaging. • Development of policies to support packaging producers and retailers in the installation of RVMs.

iv) *RVMs strategic location*. Minimizing emissions in a reusable packaging supply chain requires the establishment of Reverse Vending Machines (RVMs) at every store. However, budget constraints limit the feasibility of installing RVMs across all retail locations. This paper proposes a strategic allocation strategy for RVM placement, optimizing their distribution to meet capacity requirements while adhering to financial limitations.

v) *Developing a structured incentives plan*. The cost-emission trade-off observed in this paper underscores the need for a structured incentive system from policymakers to support the adoption of a nationwide reuse model (Hitt et al., 2025). Packaging manufacturers require clear guidance to facilitate the transition to reusable packaging while retailers need financial support to install RVMs. Additionally, the deposit fee consumers pay for reusable packaging must be carefully calculated. This cost should not only reflect the price of the product but also represent the value of the product-as-a-service.

All proposed best practices take a comprehensive approach, involving all stakeholders throughout the supply chain in the adoption of reusable packaging. As outlined in Table 5, the actionable insights derived from the model's resolution influence all three pillars of sustainability defined by the Triple Bottom Line framework: people, planet, and profit (Biswas et al., 2024).

5.3. Limitations

By evaluating all possible combinations of operational parameters (θ_m and φ_{return}), the model analyses scenarios where real-world constraints may limit feasibility presenting some limitations. In such analysis, the scrap rate, which is assumed to be uniform, varies due to packaging fragility and washing feasibility. Similarly, although the model considers a unique return rate for the whole instance, this is influenced by geographic factors, such as consumer proximity to retailers and access to RVMs. Another limitation involves the resolution time, which is not only affected by the complexity of the problem or the number of variables involved but also significantly influenced by the values assigned to parameters such as scrap rate and return rate. As a result, the time required to solve the model can vary substantially, ranging from a few minutes in simpler cases to up to 10 h in constrained scenarios. However, given the strategic perspective of this model, obtaining a solution within hours, as observed in some constrained cases, is considered an acceptable trade-off.

6. Conclusions

This paper highlights the pressing issue of packaging waste in the food industry and proposes an innovative multi-objective optimization framework designed to encourage the adoption of reusable primary food packages in retail settings. The proposed methodology outlines a multi-step approach that addresses crucial elements of a circular economy, such as creating an efficient packaging hierarchy (from individual items to palletized units), optimizing reverse logistics, and implementing reverse vending machines (RVMs) for convenient package collection post-consumer use. The framework uniquely balances operational and investment costs borne by stakeholders across the circular network while also considering carbon emissions tied to package production, transportation, washing, and disposal. By doing so, it paves the way for exploring conditions that can catalyze the transition to a reuse-focused paradigm in retail, which is fundamentally shaped by consumer attitudes and behaviors. Essential factors explored in the analysis include the return rate of packages, the durability of packaging with respect to scrap rates, key design characteristics (such as size, weight, and stackability), and the configuration of the logistics network.

To validate this framework, we present case studies from two major French retailers, illustrating its practical application and potential impact on reducing packaging waste in the food sector. The conducted analyses highlight the critical trade-off between cost and carbon emissions in reusable packaging networks, emphasizing the role of RVM deployment and packaging properties design in balancing sustainability and economic feasibility. While high return rates are essential, maintaining low scrap rates is a key enabler for environmental benefits. The analysis further introduces the “Logistic Moment” as an indicator of packaging and network suitability for circular models, considering the joint impact of weight and transport distances. A reusable packaging that exhibits a significantly lower Logistic Moment compared to other feasible alternatives can withstand variations in return and scrap rates. Additionally, the findings stress the need for financial incentives to support packaging producers and retailers for RVM installation. The proposed multi-objective optimization model serves as a decision-making framework, providing actionable insights for policymakers and businesses aiming to scale reusable food packaging systems effectively.

The explored levers offer an initial response to how a traditional linear food packaging retail supply chain can adapt to a circular business model. However, future research is needed to examine how to address the varying reuse attitudes of consumers across different locations i.e., how the reuse rates (φ_{return}) differ between shops. Future work could also focus on developing advanced solution algorithms to improve the computational efficiency of the optimization model, enabling more effective analyses. Additionally, it is important to investigate the role of deposits, incentives, and fees in supporting industrial costs and consumers during the transition to a circular model.

CRediT authorship contribution statement

Riccardo Accorsi: Supervision, Project administration, Methodology, Funding acquisition, Conceptualization, Writing – review & editing. **Giorgia Bartolotti:** Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Writing – review & editing, Writing – original draft. **Beatrice Guidani:** Methodology. **Riccardo Manzini:** Supervision. **Michele Ronzoni:** Visualization, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2025.04.003.

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