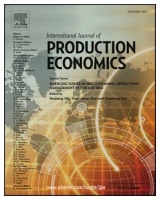
Int. J. Production Economics 301 (2026) 110149



Contents lists available at ScienceDirect

International Journal of Production Economics

journal homepage: www.elsevier.com/locate/ijpe





Integrating returnable and disposable packaging to balance efficiency, resilience, and sustainability in automotive supply chains

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ARTICLE INFO

Keywords:
Returnable packaging
Closed-loop supply chain
Simulation
Supply chain dynamics
Sustainability
Resilience

ABSTRACT

The adoption of returnable packaging systems (RPSs) is widespread in supply chains across many industries due to their potential economic and environmental benefits. However, designing and managing RPSs effectively remains challenging, particularly in volatile, uncertain, and disruption-prone environments such as the automotive sector. To better understand these challenges, we conduct an exploratory analysis involving professionals from one of Europe's largest automotive assembly plants. Drawing on the insights gathered, we develop an empirically grounded simulation model that captures the dynamics of these closed-loop supply chains (CLSCs). The model integrates the RPS with an alternative, non-returnable packaging system (NPS), used as a contingency when returnable items are not available. Through designed experiments, we investigate the operational and economic behaviour of this hybrid packaging system, demonstrating its potential as an effective strategy for achieving efficient, sustainable and resilient supply chains. The study further shows that determining the optimal quantity of returnable packaging items is a complex decision shaped by the interplay of costs, defective item rates, disruption probabilities, and renewal policies. Interestingly, intermediate renewal periods can outperform more frequent replacement cycles in terms of total packaging costs, highlighting the need for a balanced and integrated approach to packaging management.

1. Introduction

Supply chains (SCs) have historically been optimised for efficiency, delivering substantial performance gains under relatively stable conditions, as reflected in paradigms such as mass production and lean operations. However, in recent years, SCs have been exposed to increasing levels of uncertainty, volatility, and disruption, driven by geopolitical tensions, global health crises, and structural changes in production and logistics systems (Ivanov, 2024). These developments have revealed the limitations of purely efficiency-oriented designs. At the same time, firms face growing pressure to support the transition towards a circular economy, further increasing the complexity of SC management (Genovese et al., 2023). Together, these challenges are driving a reconfiguration of traditional linear SCs into closed-loop SCs (CLSCs), where efficiency, resilience, and sustainability must be balanced simultaneously (Mishra et al., 2023).

Within this context, packaging systems, and particularly returnable or reusable packaging systems (RPSs), have emerged as a key dimension of CLSC efficiency and sustainability (Silva and Pålsson, 2022; García-Arca et al., 2025). RPSs could offer clear economic and environmental advantages by enabling the repeated use of packaging assets and reducing material consumption and waste generation (Cozzolino and De Giovanni, 2023). However, their management, within CLSCs, is far from trivial (Katsanakis et al., 2023). Implementing an RPS involves not only selecting appropriate packaging designs but also determining the required quantity of returnable packaging items (RPIs) and managing their stock effectively throughout the CLSCs with a suitable control policy (Betts et al., 2022; Katsanakis et al., 2023). Their operation relies on the timely circulation of RPIs through reverse logistics processes, which are often subject to delays, losses, and coordination challenges and, in practice, requires the control of the defective rate and the renewal period of stock. In disruption-prone environments, these dynamics can compromise packaging availability and, consequently, the continuity of SC operations. As a result, RPSs may become a source of operational vulnerability, unless firms maintain sufficiently high inventory levels, which, in turn, can undermine the efficiency gains they

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https://doi.org/10.1016/j.ijpe.2026.110149
Received 1 September 2025; Received in revised form 5 June 2026; Accepted 18 July 2026
Available online 20 July 2026
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are intended to deliver.

In industrial practice, firms could address these limitations by complementing RPIs with non-returnable packaging items (NPIs), which serve as a flexible fallback option when RPIs are unavailable. This gives rise to hybrid packaging strategies, in which RPIs and NPIs coexist within the same CLSC. Although such configurations are observed in practice, particularly in complex manufacturing sectors such as the automotive industry, their role remains relatively underexplored in the literature with the exception of studies by Bortolini et al. (2018), González-Boubeta et al. (2018) and Na et al. (2019). Existing studies have primarily analysed RPSs and non-returnable packaging systems (NPSs) as alternative choices, often focusing on economic and/or environmental comparisons between them (Mollenkopf et al., 2005; Pålsson and Olsson, 2023). In this context, limited attention has been devoted to understanding RPIs and NPIs as interacting elements within the dynamics of CLSCs, particularly under conditions of uncertainty and disruption.

As a result, we still lack a clear understanding of how hybrid packaging systems behave over time within the broader CLSC. This gap is particularly relevant given the complex interactions between material and information flows, delays, and decision rules that shape CLSC dynamics and determine SC performance (Framinan, 2022). From this perspective, the main objective of this paper is to understand how hybrid packaging strategies can be designed and managed in CLSCs to balance efficiency, resilience, and sustainability under demand variability and reverse logistics disruptions, with a particular focus on their operational and economic implications.

Guided by this objective, our study addresses the following two research questions:

- *RQ1: How do inventory-related decisions (initial stock, control policy, and renewal period) and physical parameters (defective rate and disruption probability) influence the dynamic behaviour and shape performance trade-offs of hybrid packaging systems under uncertainty and disruptions?*
- *RQ2: How do inventory-related decisions (initial stock and renewal period), physical parameters (defective rate and disruption probability), and SC cost structures determine the cost-efficient allocation of returnable packaging in hybrid systems under uncertainty and disruptions?*

To answer these questions, firstly we develop a literature review dealing with aspects of managing CLSCs and packaging systems. In addition, in order to understand and contextualize the practical problem, we conduct an exploratory analysis based on in-depth interviews with managers from a major automotive factory, reinforcing the rigour of this analysis through the use of data triangulation (site visits, review of reports, press releases and the websites of manufacturers and suppliers). The insights obtained serve to develop a system dynamics-inspired simulation model capturing the interactions among forward and reverse flows, packaging availability, and disruption processes, and to identify the key decision variables and system parameters investigated in RQ1 and RQ2. Through a series of designed computational experiments, we analyse both the dynamic operational behaviour and the economic performance of hybrid packaging systems under a wide range of conditions. Taken together, these analyses allow us to link system behaviour to economic outcomes, thereby providing an integrated understanding of how operational dynamics translate into cost trade-offs and inform packaging-related decision-making.

This study makes several contributions to the literature. First, it advances the understanding of packaging systems by conceptualising hybrid packaging as an integrated configuration in which RPIs and NPIs interact dynamically, rather than as mutually exclusive choices, and by examining its role under conditions of uncertainty and disruption. Second, it provides insights into the economic implications of hybrid packaging systems by linking operational dynamics to cost outcomes and identifying the conditions under which different allocations of returnable packaging are cost-efficient. And third, it contributes to the literature on CLSC dynamics by analysing how inventory-related decisions and system parameters shape the behaviour and performance trade-offs of reuse-based systems, a practical context that has received limited attention. Finally, from a managerial perspective, the study offers a decision-oriented framework to support the design and management of hybrid packaging systems, highlighting how CLSCs can balance efficiency, resilience, and sustainability through appropriate configuration and control of packaging resources.

2. Literature review

In line with the objectives of this study, the literature review is organised into two subsections. The first provides a general overview of CLSC management, with a particular focus on improving efficiency, sustainability, and resilience. The second presents the specific context of packaging management, examining the economic costs and environmental impacts associated with RPSs and NPSs, and also reviews the existing literature on hybrid packaging strategies combining both.

2.1. Managing CLSCs

The effective and efficient management of SCs requires a precise understanding of their dynamic behaviour over time, which makes it easier to understand the impact of certain decisions related to the design and management of the packaging system (RPS or NPS). For this reason, the analysis of SC dynamics has become a well-established research field within operations and SC management (Petropoulos et al., 2024). This stream examines how SCs behave over time as a consequence of interactions between material and information flows, decision rules, delays, and feedback loops (Towill, 1991), thereby addressing time-varying, costly phenomena such as inventory oscillations, the bullwhip effect (the amplification of order variability along SCs; Dolgui and Ivanov, 2021) and, more recently, the ripple effect (the propagation of disruptions through SCs; Wang and Disney, 2016). While this discipline was originally developed in the context of traditional (open-loop) SCs, research interest has increasingly extended to CLSCs, particularly over the last decade, in parallel with the rise of the circular economy and sustainability policies (Bayrak et al., 2026). Thus, CLSCs combine the traditional forward SC operations with reverse logistics operations, such as product recovery, product remanufacturing, disassembly and component reusing, including, among them, RPIs (Raza, 2020; Mishra et al., 2023).

Studies show that the dynamic behaviour of CLSCs differs significantly from that of traditional SCs, mainly due to the additional complexity and uncertainty introduced by return flows (Goltsos et al., 2019; Dou et al., 2024)). Within the domain of CLSC dynamics, research has examined how return rates, information transparency, lead times, collection-related decisions, and capacity constraints, among other factors, shape customer service, inventory investment, and bullwhip behaviour (Tang and Naim, 2004; Cannella et al., 2016; Lin et al., 2022). This literature further highlights that reverse flows can generate non-linear and sometimes counterintuitive effects, including the well-documented lead-time paradox, whereby longer lead times in the reverse flow may, under certain conditions, improve overall system performance (Hosoda and Disney, 2018).

Methodologically, this body of knowledge has predominantly relied on analytical and simulation-based approaches rooted in system dynamics and control-theoretic thinking (Goltsos et al., 2019). Accordingly, CLSCs are typically represented through aggregate stock–flow structures, incorporating feedback loops and delays. This modelling approach enables systematic comparisons of forecasting mechanisms, inventory control policies (push versus pull; Lin et al., 2022), collection strategies, and coordination/information sharing mechanisms (Tang and Naim, 2004), as well as the analysis of disruptive events and their system-wide implications (Katsoras and Georgiadis, 2022). In parallel,

agent-based and multi-agent approaches have been employed to represent decentralised decision-making and alternative SC structures (Dominguez et al., 2021), complementing aggregate approaches when decentralised decision-making and behavioural representation are central (Bozdoğan et al., 2023).

Despite these advances, the CLSC dynamics literature remains highly concentrated on remanufacturing loops, with less attention devoted to other circular practices such as reuse (Fernández-Arribas et al., 2024). In particular, RPSs, which involve repeated circulation of returnable assets, losses due to damage, and renewal cycles, represent a practically important CLSC configuration. However, to the best of our knowledge, the dynamics of CLSCs based on RPI loops (and specifically hybrid configurations combining RPIs and NPIs) have not yet been explicitly studied within the literature.

In this context, the occurrence of external disturbances often jeopardises the stability and reliability of these logistic flows in global CLSCs, generating supply disruptions (Haren and Simchi-Levi, 2020; Ramani et al., 2022; Kilpatrick, 2022; Ivanov, 2024). These disruptions can be more or less predictable, can last for varying lengths of time (even becoming quasi-permanent), and can have varying degrees of impact on efficiency and sustainability. Therefore, the current challenge in CLSC design would be not only to seek efficient and sustainable alternatives, but also resilient ones. Woods and Hollnagel (2006) state that "*a system is resilient if it can adjust its functioning prior to, during, or following events (changes, disturbances, and opportunities), and thereby sustain required operations under both expected and unexpected conditions*". According to Tombido (2025), in the context of CLSC implementation, resilience has traditionally been analysed as a way to promote sustainability. However, the promotion of resilience and sustainability should be considered with a certain degree of balance, as both may have different objectives that could conflict with each other.

On the other hand, recent literature has identified two different levels to characterise the resilience of CLSCs (Ivanov, 2024). Thus, a resilient CLSC would pursue rapid recovery (with the least possible impact) of its initial functioning (prior to a disruption that is assumed to be of short duration); this traditional perspective is called the "stability-based view" (SBV) and could present different lines of work, such as improving coordination and visibility in different parts of the chain or increasing safety stocks. Complementarily, a resilient CLSC could also be considered for its ability to adapt to a disruption with a greater impact (which typically lasts longer); this last perspective would recommend an organisational reconfiguration of the CLSC itself as a way of ensuring its long-term viability and survival in what is called the "adaptation-based view" (ABV).

2.2. Managing packaging systems

The design and management of the packaging system are key elements that can help to improve the efficiency, sustainability and resilience of CLSCs by eliminating, or reducing, various inefficiencies (Garcia-Arca et al., 2021). These include wasted space in warehouses, inefficient transportation utilisation, excessive material usage, product damage, productivity losses during packing and unpacking operations, and waste generation (Hellström and Olsson, 2017; Pålsson and Olsson, 2023; Sihombing et al., 2025; García-Arca et al., 2025). Among the potential design alternatives, a RPS is a solution in which RPIs circulate among CLSC partners (Fleckenstein and Pihlstroem, 2015; Škerlič and Muha, 2020; Mahmoudi and Parviziomran, 2020; Katsanakis et al., 2023). This CLSC configuration increases the complexity of managing the system as a whole, in terms of stocks, return flows, and coordination (Battini et al., 2017).

In the academic literature, the adoption of RPSs is usually proposed as an alternative to NPSs, also referred to as single-use, expendable, or disposable packaging solutions (Mollenkopf et al., 2005; Pålsson and Olsson, 2023). According to the Reusable Packaging Association (2025), RPIs are designed for long-term use within systems that ensure their effective recovery and return for repeated use. RPSs are primarily promoted for its potential economic and environmental benefits across the CLSC, thereby supporting sustainability objectives (Hellström and Johansson, 2010; Cozzolino and De Giovanni, 2023). However, the literature also highlights several challenges associated with their implementation, including return transport costs, losses, maintenance costs, limited availability, lack of traceability, and the substantial initial investment required (Mason et al., 2012). Additionally, the procurement of new RPIs tends to be more complex, particularly in terms of lead time, availability, and minimum purchase quantities.

Regarding the RPS *vs.* NPS dilemma (the main research stream in literature according to the study of Glock in 2017), it is important to recognise that while RPSs often emerge as the preferred option, their superiority cannot be universally asserted, as noted by Pålsson et al. (2013). The suitability of RPSs depends on specific internal and external parameters, as well as their integration within the wider CLSC context. Thus, a range of cost-related parameters and environmental metrics have been employed in comparative studies to evaluate RPSs and NPSs (Yi et al., 2017; Tua et al., 2019; Park and Waqar, 2022; Pålsson and Olsson, 2023). A foundational economic framework for measuring design alternatives is provided by Mollenkopf et al. (2005), who include key cost groups such as packaging material purchases, direct and reverse transportation costs, handling and storage expenses, and end-of-life disposal costs. These categories are consistent with other contributions in the literature, while some incorporated additional cost elements, particularly maintenance-related costs, such as inspection, cleaning, and repair of RPIs (among others, González-Boubeta et al., 2018; Na et al., 2019; Škerlič and Muha, 2020; Taschner, 2023). From an environmental perspective, Pålsson and Olsson (2023) offer a literature review, comparing both systems primarily through Life Cycle Assessment (LCA). Their findings indicate that RPSs often emerge as the environmentally preferable option, or, at the very least, exhibit performance on par with NPSs. However, the lack of standardization of tools for developing LCA hinders their comparison, and extrapolation (Harris et al., 2021; Testa et al., 2022).

Faced with this difficulty, some authors have proposed measuring environmental impact indirectly through costs themselves (Garcia-Arca et al., 2021; 2025). Thus, it seems reasonable to assume that there is a certain connection between economic and environmental aspects; for example, the amount and type of materials conditions the cost and the environmental impact (amount of waste for disposal); a similar connection could be raised at the transport level in terms of the link between the cost of transportation (conditioned by the filling rate or the distance) and its environmental impact. Likewise, dual-assessment approaches (integrating cost and CO_2 emissions) have also been applied to support more holistic evaluations (Pålsson et al., 2013).

In this context, a review of the academic literature developed by the authors suggests that the various types of costs and environmental impacts associated with the adoption of RPSs or NPSs would be related to the processes carried out at the CLSC and could be classified into four main categories (see Table 1): operational category, availability category, storage category and, finally, disposal category. These four categories will be considered later in the proposed model.

Beyond viewing RPSs and NPSs as mutually exclusive, a different perspective is associated with a dual or hybrid strategy that combines both systems, although this approach is quite uncommon in recent literature, as previously noted. Thus, some studies in the retail sector (Bortolini et al., 2018; González-Boubeta et al., 2018) proposed dual models that, based on the consumption point and the origin of the products, determine the optimal solution about adopting RPI or NPI for each daily distribution route. In this context, the final decision to be made (returnable or disposable) does not depend on the availability of RPIs, but rather on how their costs and environmental impacts are integrated into each distribution route (with its associated reverse logistics), thus distancing itself from the hybrid problem posed in the event of

Table 1
Main costs and environmental impacts linked to a packaging system.

Category	Description	Main costs	Main environmental impacts
Operational category	Related to the use of each packaging item in the CLSC	Handling of each packaging item (full-empty) Packing-unpacking Transportation of the packaging items (full-empty), including direct and reverse logistics with Reverse Logistics Provider (only RPIs) Maintenance (only RPIs; inspection, cleaning and repair at the Reverse Logistics Provider facilities) Administration of packaging items	CO_2 emissions in transportation, due to fuel consumption (full-empty) Energy required for direct operations (packing, unpacking, handling) and reverse operations (RPIs maintenance) Materials consumptions and waste generated in direct operations and reverse operations (RPIs)
Availability category	Related with the availability of each packaging item in the CLSC	Purchases (new packaging items). Associated with materials quantity, materials type and specific design	Resource consumption and waste generation in production and supplying phases of new packaging items
Storage category	Maintenance of the stock of packaging items (full-empty) throughout the CLSC	Warehousing and financial costs. The higher the stock of these RPIs and NPIs, the greater these costs	Resource consumption and waste generation in warehouses related to keeping stock of packaging items. The higher the stock of these items, the greater the environmental impacts
Disposal category	Waste management after using NPI or when RPI has finished its lifespan (it cannot be maintained anymore, its design is no useful for new needs, or because it has been lost directly)	Disposal of each packaging item. These costs are usually associated with the quantity and typology of materials used in each discarded packaging item	Resource consumption during waste treatment of packaging items. These environmental impacts usually associated with quantity and typology of materials used in each item

a disruption. In this same dual perspective, Na et al. (2019) propose an optimisation model to calculate the batch of initial purchase of RPIs in the automotive sector, which also contemplates the extra costs of incorporating NPIs. However, in their model, they propose two rather restrictive hypotheses that distance it from the current problem: the authors do not contemplate losses of RPIs in the logistics flow and consider that the RPIs, once emptied, are returned immediately to the CLSC.

3. Empirical grounding

In order to complete the literature review with the perspective of the automotive industry, this section aims to understand and contextualize the current problem of managing packaging systems through an exploratory analysis. Thus, firstly, a short contextualisation of automotive sector is provided. After that, the methodology used in the exploratory analysis is described. Finally, the study's primary conclusions and insights are presented, building the foundation for the development of our mathematical model.

3.1. Automotive CLSCs and RPSs

The automotive sector is a prime example of a mature industry characterised by strong competition, operating with low margins in turbulent global markets that demand high levels of quality, service, and cost (Zhang et al., 2015). Simultaneously, regulatory changes in terms of safety and environmental protection have further challenged SC operations (Jasiński et al., 2021; Onat et al., 2021; Jones et al., 2024). For these reasons, automotive companies have opted for greater functional diversity, innovation and personalisation, which has also led to changes in the configuration of the CLSC itself, including the deployment of modularity strategies across different vehicles and brands (Lampón, 2023).

Thus, these strategies have allowed automotive manufacturers to concentrate their activities on the assembly of a smaller number of components or modules (albeit more complex) supplied by a smaller number of suppliers (TIER 1), that can represent more than 75% of the vehicle's value (Kerkow et al., 2012). Likewise, CLSCs have also achieved an overall reduction in inventory levels (Paluch et al., 2020; Llopis-Albert et al., 2021), a trend further driven by a greater coordination between car manufacturers and suppliers. However, this configuration (with virtually no stock) is highly sensitive to uncertainty.

In this context, the automotive sector has been a prominent field of application for RPSs (Pålsson et al., 2013; Zhang et al., 2015; White et al., 2015; Katephap and Limnararat, 2017; Fleckenstein and Pihlstroem, 2015; Na et al., 2019; Škerlič and Muha, 2020; Jones et al., 2024), although without delving deeply into the impact of potential disruptions and hybrid strategies. From a managerial perspective, the disruptions could imply unforeseen effects such as the accumulation of full or empty RPIs in some parts of the chain, and their unavailability in others, even conditioning, if not interrupting, the logistic flows.

3.2. Methodology

We conducted in-depth interviews with two production and logistics executives of one of the most important car assembly factories in Europe. This Spanish factory belongs to one of the world's largest groups. It is a multi-brand and multi-platform plant with an annual production exceeding 400,000 vehicles and a workforce of over 6000 workers. The two executives (with more than 25 years of experience, including assorted brands and factories) were chosen, not only for their relevant expertise in the design and management of these RPSs, but also for their knowledge about their impact on processes throughout the CLSC. The interviews were conducted on two different days to allow the authors to assimilate, nuance and identify challenges, enriching the analysis. The questionnaire was structured in four parts: A general description of the CLSCs and the packaging systems adopted; The decisions and responsibilities for designing and managing the packaging systems; The costs and environmental impacts affected by the packaging systems adopted; Finally, the problems, challenges and future needs. The details of the questionnaire used are presented in Supplementary Material S1.

In this exploratory process, the production and logistics facilities of the factory were also visited, as well as those of some of its TIER 1 suppliers to enrich the analysis. In this analysis we have had access to RPIs management data, which will be useful as a reference in the subsequent simulation stage using the proposed model. The rigour of the analysis was supported by the adoption of data triangulation (Stewart, 2009; Carter et al., 2014), including the interviews, but also in-person visits to factories, the study of reports, announcements and company websites (manufacturers and suppliers). Likewise, the authors' conclusions in this analysis were also shared and discussed with the interviewees in order to validate and enrich them.

3.3. Insights and reflections

The exploratory analysis shows that there are three interrelated phases in the design process, which feed back into the integration with the product design and the CLSC: Packaging System selection (RPS or NPS); RPIs selection (if a RPS is adopted); Initial RPIs stock definition. In the **first phase**, automotive manufacturers conceptually decide whether to implement either an RPS or an NPS as the main packaging system for each procurement flow of a new component. In this sense, the RPS predominates as the primary choice, whereas NPS is primarily considered in long-distance circuits with low demand for components and bad logistics connection for sharing transportation reverse flows. When opting for an RPS as the main modality, in a **second phase**, the aspects of which RPI format would be the most suitable to adapt to the needs of the product and CLSC would be delved into. There is a tendency to use old formats of RPIs available in a catalogue of previous options (already adopted in other components and/or vehicles) to reduce new investments.

Simultaneously to the evaluation and format selection, in a **third phase**, it is essential to determine the theoretical number of RPIs (initial stock) required as a function of cycle time for all processes throughout the CLSC, the demand for the component and the filling rate in each RPI. Likewise, an extra percentage (safety stock) is usually added to the initial theoretical stock to contemplate slight variations in times of productive and logistics processes and/or demand. Moreover, it is important during the operation of the CLSC to identify potential 'losses' or damages of RPIs in order to renew the initial stock with new purchases.

The availability of components on the assembly lines of automotive manufacturers is critical, so it is necessary that these components are at the right time and in the right place, and all this despite the complexity, variability in demand and potential disruptions in the system. To solve situations of RPI unavailability, supply contracts generally include, in addition to the main packaging solution (RPI), an alternative packaging, typically disposable cardboard box (NPI) with worse productive, logistics, and environmental performance. This poorer performance of the alternative packaging would be understandable in the context of the first design phase; thus, if NPS had been considered as the best alternative, this option would have been selected and implemented initially as the main option. The potential extra costs and environmental impacts of using alternative NPI can be justified, for example, by a lower quantity of parts per packaging (filling rate), less product protection, poorer productivity in packing/unpacking, or greater difficulty in stacking load units in warehouses. Furthermore, the rationalisation and automation in many packing stations at TIER 1 supplier factories, as well as at unpacking stations in assembly factories, may practically require that parts placed in alternative NPI cannot be directly used in the production flow and must be repacked at supplier or manufacturer warehouses. However, supplying alternative NPIs is often quicker and more flexible than that of RPIs, including working with smaller purchase quantities.

In this context, when including an alternative NPI (when the main RPI is unavailable due to some type of disruption or problem), it is necessary to find a certain economic and environmental balance related to the selective use of both formats (returnable and disposable). In addition, this dual or hybrid approach would provide SBV ("stability-based view") resilience to the CLSC, based on the assumption of a short duration of the disruption and the simulation of this hybrid or dual strategy could help automotive companies to adopt better RPIs stock decisions (including, the initial stock and the renewal period). However, in the definition of the initial stock of RPIs, the most used methods for this calculation apply to stable demand and CLSC behaviours. Thus, beyond the definition of the initial stock of RPIs for operating a CLSC under disruptions, it would be necessary to apply a suitable management of this stock, affected by parameters such as the control policy or the defective rate. These decisions and parameters will be taken into account when designing our model.

4. Supply chain model

The objective of this section is to develop a dynamic model that enables the analysis of how hybrid packaging systems, integrating RPIs and NPIs, perform over time under uncertainty and disruptions. Building on the exploratory analysis presented in Section 3, the model incorporates the key operational decisions and system parameters identified in industrial practice. In line with the research questions posed in Section 1, the model is intended not only to analyse the operational behaviour of hybrid packaging systems, but also to examine how this behaviour translates into economic outcomes and decision-making.

To this end, we adopt a system dynamics-inspired, aggregate stock–flow modelling approach, implemented through difference equations. This approach is suitable for capturing the feedback effects, delays, and interactions between forward and reverse flows that characterise CLSCs and shape their dynamic behaviour over time. While prior research on RPSs has predominantly relied on optimisation-based approaches (Glock, 2017; Na et al., 2019; Škerlič and Muha, 2020), the simulation-based perspective adopted here enables a richer analysis of how operational decisions and system parameters jointly shape the performance of hybrid packaging systems under more realistic operating conditions.

4.1. Conceptual structure, key assumptions, and model parameters

Fig. 1 illustrates the conceptual structure of the CLSC considered in this study. Our model involves three main actors: the Tier-1 Component Supplier (CS), the Automotive Manufacturer (AM), and the Reverse Logistics Provider (RLP), together with the packaging suppliers. This structure reflects the type of closed-loop packaging flows commonly observed in the automotive and other industries, where RPIs circulate within predefined supplier–manufacturer loops.

The AM places orders for components to the CS and receives the parts packed in RPIs or, when necessary, in NPIs. After unpacking, used RPIs enter a reverse logistics flow managed by the RLP, where packaging items are collected, inspected, maintained, and returned to the CS for reuse. Damaged RPIs are removed from circulation and periodically replaced through purchases from the packaging supplier. In contrast, NPIs are not recirculated within the CLSC after use.

In line with both the reviewed literature and industrial practice, RPIs are modelled as the preferred packaging option due to the economic and environmental advantages associated with their repeated reuse (Cozzolino and De Giovanni, 2023). However, the effective operation of RPSs depends on the continuous availability and circulation of packaging items within the CLSC. In this context, NPIs provide operational flexibility as a contingency mechanism when RPIs are temporarily unavailable, for example due to delays, disruptions, losses (Na et al., 2019).

The model assumes that the CS has sufficient manufacturing capacity and packaging availability to always fulfil the entire demand from the AM, either through RPIs or NPIs. Accordingly, shortages of RPIs do not prevent product deliveries, but instead trigger the temporary use of NPIs. In line with practice, the supply of NPIs is thus assumed to be faster and more flexible, as these packaging items can typically be sourced from nearby or readily accessible suppliers.

In the following subsections, we describe the operational logic associated with the three main actors, identify the key modelling assumptions, and formalise the resulting CLSC dynamics in discrete time through difference equations. In line with common industrial practice, inventory management is modelled using periodic-review policies, where time periods can be interpreted as inventory review intervals (days or weeks). Before presenting the model equations and variables, Table 2 presents the main parameters considered in the simulation model, together with their units and classification as physical or decision-related parameters.

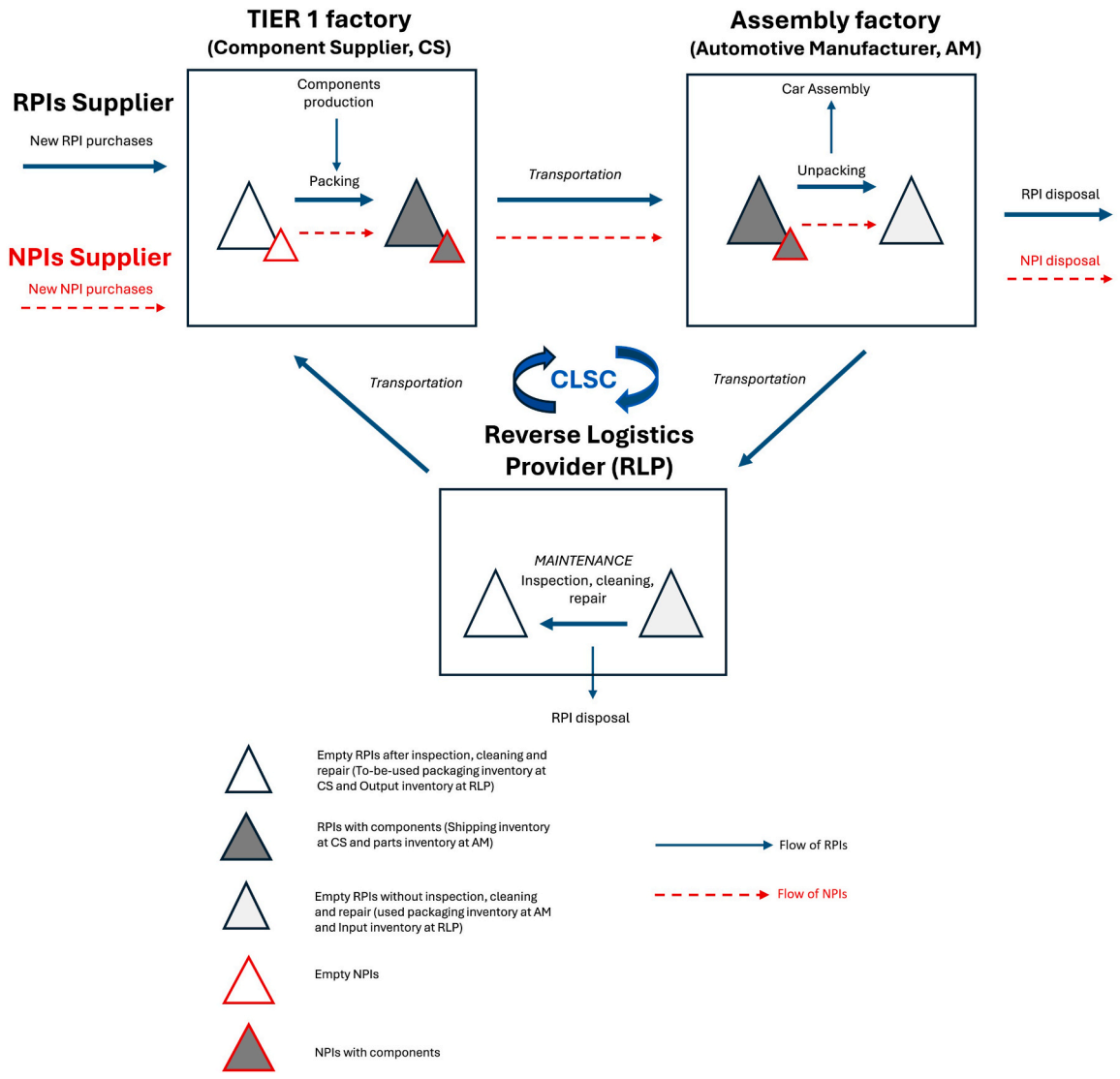


Fig. 1. Structure of the CLSC under consideration.

4.2. Automotive manufacturer (AM)

To support vehicle production, the AM manages an inventory of purchased parts (PI) supplied by the CS. Table 3, in Eqs. (1)–(13), formalises the inventory dynamics associated with the PI.

Eqs. (1)–(4) update the available stock of parts at the beginning of each period. Incoming receipts are determined by the orders previously shipped by the CS after the corresponding transportation lead time. These receipts are added to the inventory carried over from the previous period, after which any outstanding backlog is fulfilled. The resulting inventory level defines the available stock used to satisfy the production requirements of the current period.

Eqs. (5)–(9) describe how production orders affect the inventory position. Production orders are modelled as a stochastic process with normally distributed quantities, capturing the variability typically observed in the AM's production system. When sufficient inventory is available, production orders are fully satisfied. Otherwise, available inventory is allocated as much as possible to current demands, and the unmet quantity is accumulated as backlog for subsequent periods. Finally, the on-hand inventory and the in-transit inventory are updated to close the period.

Eqs. (10)–(13) define the replenishment decision made by the AM at the end of each period. Two alternative policies are considered: (1) a push-oriented Order-Up-To (OUT) policy; and (2) a pull-oriented kanban (KB) policy. Comparing these two different policies is particularly relevant in the context of hybrid packaging systems, since replenishment logic influences not only part inventory dynamics, but also the circulation and availability of RPIs within the CLSC.

Under the OUT policy ($\delta = 0$, Eq. 13-a), purchase orders are determined based on demand forecasts, which are obtained through simple exponential smoothing (SES). Specifically, the order is calculated as the forecast plus the adjustment required to align the actual inventory position (both on-hand and in-transit) with the desired inventory levels. In line with established mechanisms in the literature (Cannella et al., 2021), the safety stock is computed as the product of the safety factor and the forecast, while the target in-transit inventory is estimated as the transportation lead time minus one period multiplied by the forecast. In contrast, under the KB policy ($\delta = 1$, Eq. 13-b), purchase orders are directly set equal to production orders, thereby representing a replenishment logic driven by actual consumption requirements.

We assume that each purchased component is delivered in an individual packaging unit, either an RPI or, when the former is unavailable, an NPI. NPIs exit the CLSC immediately after use. In contrast, the AM maintains an inventory of used RPIs (UPI), where empty RPIs are temporarily stored after unpacking and consumption, and before being collected by the RLP. The dynamics associated with this packaging

Table 2
Parameters used in the simulation model (in order of appearance).

Symbol	Parameter	Units	Nature
T_s	Shipping lead time for parts (CS → AM)	*periods*	physical
μ	Mean of production orders	*parts/ period*	physical
σ	Standard deviation of production orders	*parts/ period*	physical
α	SES smoothing parameter	-	decision
γ	Safety factor	-	decision
δ	Replenishment policy selector at the AM	-	decision
T_{t1}	Transport lead time for returned packaging (AM → RLP)	*periods*	physical
μ_y	Mean of defective rate	-	physical
σ_y	Standard deviation of defective rate	-	physical
T_i	Inspection and maintenance lead time for used packaging (RLP)	*periods*	physical
T_r	Renewal period for replacing damaged packaging	*periods*	decision
P_d	Probability of disruption	-	physical
D_d	Maximum duration of disruption	*periods*	physical
T_{t2}	Transport lead time for recovered packaging (RLP → CS)	*periods*	physical
T_{sp}	Shipping lead time for new packaging (→ CS)	*periods*	physical

Notes: Physical parameters represent exogenous system characteristics and stochastic process descriptors that are not directly controlled by decision-makers. Decision parameters represent managerial or policy choices that define inventory control, forecasting, and renewal strategies and are set *ex ante* in the simulation experiments.

Table 3
Mathematical model of the parts inventory (PI) at the Automotive Manufacturer (AM).

Variable	Difference equation	Ref.
Receipts	${r_t}^{am} = {so_{t-T_s}}^{cs}$	(1)
Initial inventory (PI)	${ii_t}^{am} = {fi_{t-1}}^{am} + {r_t}^{am}$	(2)
Satisfied backlog	${sb_t}^{am} = \begin{cases} {b_{t-1}}^{am}, \text{if } {ii_t}^{am} \geq {b_{t-1}}^{am} \\ {ii_t}^{am}, \text{otherwise} \end{cases}$	(3)
Available inventory (PI)	${ai_t}^{am} = {ii_t}^{am} - {sb_t}^{am}$	(4)
Production orders	${po_t}^{am} = [x_t]^+; x \rightarrow \mathbb{N}(\mu, \sigma^2)$	(5)
Satisfied orders	${so_t}^{am} = \begin{cases} {po_t}^{am}, \text{if } {ai_t}^{am} \geq {po_t}^{am} \\ {ai_t}^{am}, \text{otherwise} \end{cases}$	(6)
Backlog	${b_t}^{am} = {b_{t-1}}^{am} - {sb_t}^{am} + ({po_t}^{am} - {so_t}^{am})$	(7)
Final inventory (PI)	${fi_t}^{am} = {ai_t}^{am} - {so_t}^{am}$	(8)
In-transit inventory	${it_t}^{am} = {it_{t-1}}^{am} + {o_{t-1}}^{am} - {r_t}^{am}$	(9)
Forecast	${f_t}^{am} = \alpha {po_t}^{am} + (1-\alpha){f_{t-1}}^{am}$	(10)
Safety stock	${ss_t}^{am} = \gamma {f_t}^{am}$	(11)
Target in-transit inventory	${tit_t}^{am} = (T_s - 1){f_t}^{am}$	(12)
Purchase order	if $\delta = 0$: ${o_t}^{am} = \left[{f_t}^{am} + ({ss_t}^{am} + {b_t}^{am} + {tit_t}^{am}) - ({fi_t}^{am} + {it_t}^{am})\right]^+$	(13a)
	if $\delta = 1$: ${o_t}^{am} = {po_t}^{am}$	(13b)

Notes: From this table, $[\cdot]^+ = \max\{\cdot, 0\}$ is the non-negative operator.

inventory are formalised in Table 4 through Eqs. (14)–(17).

Eqs. (14) and (15) track the components received and stored in the PI using NPIs, which result from the temporary substitution of RPIs by the CS when they are unavailable. In the model, we assume that components delivered in NPIs are consumed first, reflecting the operational objective of minimising the presence of disposable packaging within the CLSC. Consequently, RPIs enter the UPI only after the stock of parts delivered in NPIs, if any, has been depleted. Mathematically, Eq. (16) updates the position of the UPI at the end of each period as the non-negative difference between total component consumption and the stock of components delivered in NPIs available at the beginning of the period. Eq. (17) updates the remaining stock of components delivered in NPIs within the PI after production requirements have been satisfied.

Table 4
Mathematical model of the used packaging inventory (UPI) at the Automotive Manufacturer (AM).

Variable	Difference equation	Ref.
Receipts (PI) - Non-returnable packaging	${\check{r}_t}^{am} = {\check{so}_{t-T_s}}^{cs}$	(14)
Initial inventory (PI) - Non-returnable packaging	${\check{ii}_t}^{am} = \left({\check{r}_t}^{am} + {\check{fi}_{t-1}}^{am}\right)$	(15)
Final inventory (UPI) – Returnable packaging	${upi_t}^{am} = \left[({so_t}^{am} + {sb_t}^{am}) - {\check{ii}_t}^{am}\right]^+$	(16)
Final inventory (PI) – Non-returnable packaging	${\check{fi}_t}^{am} = \left[{\check{ii}_t}^{am} - ({so_t}^{am} + {sb_t}^{am})\right]^+$	(17)

4.3. Reverse Logistics Provider (RLP)

The RLP collects used RPIs from the UPI at the AM and transports them to its facilities, where they undergo inspection and maintenance processes before being returned to the CS for reuse. The operational dynamics associated with these activities are formalised in Table 5 through Eqs. (18)–(23), which determine the position and evolution of the RLP's input and output inventories.

Eq. (18) updates the input inventory of the RLP, incorporating the RPIs collected from the AM after the corresponding transportation lead time. Subsequently, Eq. (19) models the defective rate as a stochastic variable with normally distributed values, representing the proportion of RPIs that become unsuitable for reuse after inspection. Consistent with industrial observations, this defective rate captures losses associated with damage, wear, and operational incidents occurring within the reverse logistics process. Based on this defective rate, Eqs. (20) and (21) determine the quantities of packaging items classified as reusable (recovered) and non-reusable (damaged), respectively.

Eq. (22) updates the output inventory of the RLP with the reusable RPIs after inspection and maintenance. These packaging items become available for shipment back to the CS, thereby initiating a new reuse cycle within the CLSC. Under regular operating conditions, recovered RPIs are shipped from the RLP to the CS every period. However, when disruptions occur, RPIs accumulate temporarily in the output inventory until reverse logistics operations resume. In contrast, damaged RPIs permanently exit the system. Eq. (23) tracks the cumulative number of damaged RPIs over each renewal cycle, which determines the periodic replenishment requirements for new RPIs. In this sense, losses are accumulated over a predefined renewal cycle (monthly or quarterly) and subsequently replenished through purchases from external suppliers.

To represent disruptions in the reverse logistics channel, Table 6

Table 5
Mathematical model of the input and output inventories at the Reverse Logistics Provider (RLP).

Variable	Difference equation	Ref.
Input inventory	${ii_t}^{rl} = {upi_{t-T_{t1}}}^{am}$	(18)
Defective rate	${dr_t}^{rl} = [y_t]^+; y \rightarrow \mathbb{N}\left(\mu_y, {\sigma_y}^2\right)$	(19)
Recovered packaging	${rp_t}^{rl} = \left(1 - {dr_t}^{rl}\right){ii_{t-T_i}}^{rl}$	(20)
Damaged packaging	${dp_t}^{rl} = {dr_t}{ii_{t-T_i}}^{rl}$	(21)
Output inventory	${oi_t}^{rl} = \begin{cases} {rp_t}^{rl}, \text{if } {ro_{t-1}}^{rl} = 1 \\ {oi_{t-1}}^{rl} + {rp_t}^{rl}, \text{otherwise} \end{cases}$	(22)
Cumulative damaged packaging	${cdp_t}^{rl} = \begin{cases} {dp_t}^{rl}, \text{if } t\%T_r = 0 \\ {dp_t}^{rl} + {cdp_{t-1}}^{rl}, \text{otherwise} \end{cases}$	(23)

Notes: From this table, a%b is the modulus operator, returning the remainder when a is divided by b.

Table 6
Mathematical model of the disruption generator module.

Variable	Difference equation	Ref.
Random number	$rn_t^{rl} = z_t; z \to \mathbb{U}(1, 10^4)$	(24)
Disruption occurrence	$do_t^{rl} = \begin{cases} 1, \text{if } rn_t^{rl} \le P_d 10^4 \\ 0, \text{otherwise} \end{cases}$	(25)
Duration of (last) disruption	$dd_t^{rl} = \begin{cases} z_t, \text{if } do_t^{rl} = 1 \\ dd_{t-1}^{rl}, \text{otherwise} \end{cases}, z \to \mathbb{U}(1, D_d)$	(26)
Time since (last) disruption	$td_t^{rl} = \begin{cases} 0, \text{if } do_t^{rl} = 1 \\ td_{t-1}^{rl} + 1, \text{otherwise} \end{cases}$	(27)
Regular operation	$ro_t^{rl} = \begin{cases} 0, \text{if } td_t^{rl} < dd_t^{rl} \\ 1, \text{otherwise} \end{cases}$	(28)

formalises a stochastic disruption-generation mechanism through Eqs. (24)–(28).

Eqs. (24) and (25) generate, at each period, a random number from a uniform distribution and compare it with a predefined disruption probability threshold. A disruption event is triggered when the generated value falls below this threshold. Here, the disruption probability P_d can be interpreted as the expected frequency of disruption occurrence. For example, $P_d = 0.02$ implies that, on average, one disruption is expected every 50 periods. Once activated, Eq. (26) determines the disruption duration within a predefined interval ranging from 1 to D_d. Eq. (27) then implements an internal counter that tracks the elapsed disruption time. Finally, Eq. (28) determines whether reverse logistics operations proceed normally or remain temporarily halted during the period, depending on the disruption status and elapsed disruption time.

4.4. Component Supplier (CS)

The CS uses returnable packaging, primarily sourced from the RLP (recovered RPIs) and occasionally from the packaging supplier (new RPIs), to fulfil the demand for parts received from the AM. To support these operations, the CS manages an inventory of packaging items ready for use, denoted as the to-be-used packaging inventory (TPI). The operational dynamics associated with this inventory are formalised in Table 7 through Eqs. (29)–(34).

Eq. (29) updates the receipts of recovered RPIs arriving from the RLP after the corresponding transportation lead time. Under regular operating conditions, RPIs are received every period. However, when disruptions occur, recovered RPIs accumulate temporarily at the RLP and are shipped to the CS once operations resume. Eq. (30) models the periodic replenishment of new RPIs purchased from the external packaging supplier to compensate for packaging losses generated within the CLSC. Consistent with the renewal policy introduced previously, these replenishment orders occur only at the end of each renewal cycle and are determined by the cumulative number of damaged RPIs tracked by the RLP. Later, Eq. (31) updates the initial position of the TPI by incorporating both recovered and newly purchased RPIs, when available.

Eq. (32) determines the quantity of parts shipped by the CS to the AM and, consequently, the quantity of packaging items (RPIs and NPIs) needed. Consistent with the assumptions introduced previously, the CS is assumed to always fully satisfy the AM demand, with RPIs constituting the preferred packaging option and NPIs being used only when the available stock of RPIs is insufficient. Finally, Eq. (33) updates the remaining stock of RPIs in the TPI, while Eq. (34) determines the quantity of NPIs temporarily used by the CS. In this way, the model explicitly captures the hybrid packaging logic observed in practice, where disposable packaging acts as a contingency mechanism that preserves material flows during periods of RPI shortage.

Table 7
Mathematical model of the to-be-used packaging inventory (TPI) at the Component Supplier (CS).

Variable	Difference equation	Ref.
Receipts of used packaging	$rup_t^{cs} = oi_{t-T_{t2}}^{rl} ro_{t-T_{t2}}^{rl}$	(29)
Receipts of new packaging	$rnp_t^{cs} = \begin{cases} cdp_{t-T_{sp}-1}^{rl}, \text{if } (t - T_{sp})\%T_r = 0 \\ 0, \text{otherwise} \end{cases}$	(30)
Initial inventory (TPI)	$ii_t^{cs} = fi_{t-1}^{cs} + rup_t^{cs} + rnp_t^{cs}$	(31)
Satisfied order	$so_t^{cs} = o_t^{am}$	(32)
Final inventory (TPI)	$fi_t^{cs} = \begin{cases} ii_t^{cs} - so_t^{cs}, \text{if } so_t^{cs} \le ii_t^{cs} \\ 0, \text{otherwise} \end{cases}$	(33)
Satisfied order – Non-returnable packaging	$\breve{so}_t^{cs} = \begin{cases} 0, \text{if } so_t^{cs} \le ii_t^{cs} \\ so_t^{cs} - ii_t^{cs}, \text{otherwise} \end{cases}$	(34)

4.5. Verification and validation

The CLSC model was implemented in a computerised simulation environment to support its analysis. The simulation horizon was fixed at $\theta = 2,000$ periods to ensure robust results. This is particularly relevant given the four stochastic elements incorporated into the model: demand (production orders), defective rate, occurrence of disruptions, and duration of disruptions.

The model underwent standard verification and validation procedures consistent with established practice in simulation (Kleijnen, 1995). Verification focused on assessing the internal consistency of the stock–flow structure, tracing intermediate outputs, and conducting boundary-condition and acceptance tests to confirm the expected model responses under predefined conditions. Validation was addressed from a purpose-oriented perspective by evaluating the plausibility of the model's structure and dynamics, using both industrial insights and prior literature (Hosoda and Disney, 2018; Ivanov, 2020; Cannella et al., 2021).

5. Operational study

This section addresses RQ1 by analysing the operational performance and dynamic behaviour of the proposed hybrid (returnable–non-returnable) packaging system under demand variability and reverse logistics disruptions. The objective is to identify the key mechanisms through which inventory-related decisions and system parameters shape service performance and packaging utilisation over time. The insights obtained in this section provide the behavioural foundation for the economic evaluation developed subsequently in Section 6.

5.1. Key performance indicators

The fundamental objective of SCs is to fulfil the needs of customers effectively and efficiently. Effectiveness refers to its ability to successfully satisfy such needs by delivering products with desired characteristics, precise quantities, and punctual timing. In contrast, efficiency centres on optimising the use of resources, which not only has important economic but also critical environmental implications. Within the framework of these complementary perspectives, we establish three metrics to gauge the performance of the examined CLSC, defined in Table 8.

In our SC context, we assess effectiveness by comparing the mean

Table 8
Key performance indicators.

Metric	Mathematical definition	Ref.
Backlog-to-Demand Ratio	$\text{BD} = \frac{\mathbb{A}[b_t^{am}]}{\mathbb{A}[po_t^{am}]}$	(35)
Returnable Packaging Inventory	$\text{RPInv} = \frac{\mathbb{A}[fi_t^{cs}]}{\mathbb{A}[so_t^{cs}]}$	(36)
Alternative Packaging Utilisation	$\text{APU} = \frac{\mathbb{A}\left[\breve{so}_t^{cs}\right]}{\mathbb{A}[so_t^{cs}]}$	(37)

Notes: $\mathbb{A}$ is the average operator.

backlog level in the AM's production system to the mean production orders that the PI must address. This relation is captured by the backlog-to-demand (BD) ratio, as presented in Eq. (35). An ideal BD ratio is 0, indicating uninterrupted production, without halts due to a lack of purchased parts.

The perspective of efficiency emphasises that careful management of resources is crucial for the overall success and sustainability of the SC. Among the various resources that a SC needs, our study focuses on packaging, which bears substantial economic and environmental costs. To this end, we quantify the returnable packaging inventory (RPInv) as the average end-of-period level of the TPI divided by the mean parts dispatched by the CS, as illustrated in Eq. (36). This metric measures the excess returnable packaging units managed within the SC, thereby indicating the overall amount of this type of packaging. Additionally, we measure the use of alternative packaging through the Alternative Packaging Utilisation (APU) metric, which represents the percentage of parts dispatched by the CS with this type of packaging, as outlined in Eq. (37).

Both RPInv and APU are metrics where lower values are preferable (as this entails lower economic and environmental costs). However, it is essential to note that a notable trade-off between them tends to arise. Minimising APU can result from an excessive investment in returnable packaging (like a high RPInv), while minimising RPInv may entail assuming a high alternative packaging utilisation (like a high APU). SC managers face the challenge of striking an appropriate balance between these metrics, considering their dependence on the various parameters (both control and physical) of the SC and their cost structure.

5.2. Design of experiments

In our research, we investigate the operational performance of the SC through statistically designed experiments. Given the limited existing knowledge in the literature regarding the dynamics of the specific SC under consideration, we conduct an exploratory study with the goal of obtaining a general understanding of the system's behaviour. In pursuit of this goal, we concentrate on five pivotal parameters, designated as our experimental factors (F1 to F5). Each is defined at two distinct levels, as detailed below.

- F1 – *Replenishment policy for the PI* (δ): We compare a push-oriented OUT policy ($\delta = 0$) with a pull-based KB rule ($\delta = 1$) to analyse the dynamics induced by alternative, industrially relevant inventory control policies adopted by the AM.
- F2 – *Renewal period* (T_r): We consider renewal cycles of $T_r = 30$ (low) and $T_r = 60$ periods (high) to examine how the frequency of replacing lost or damaged items, a managerial decision, influences system dynamics.
- F3 – *Initial stock in the TPI* (φ): This factor determines the initial level of RPIs available for use in the CLSC. We examine $\varphi = 0.5\mu$ (low) and $\varphi = \mu$ (high) to represent under- and well-provisioned initial conditions, respectively.
- F4 – *Mean defective rate* (μ_y): We analyse $\mu_y = 0\%$, an ideal scenario with no attrition of RPIs; and $\mu_y = 1\%$, representing a plausible level of losses over time.
- F5 – *Probability of disruption* (P_d): We contrast a disruption-free scenario, $P_d = 0\%$, in which the reverse logistics channel is consistently operational, with a regime characterised by occasional disruptions, where $P_d = 2\%$.

The selected factors correspond directly to the inventory-related decisions and physical parameters highlighted in RQ1. Consequently, the operational study allows us to examine how these elements influence both the dynamic behaviour of the CLSC and the trade-offs between effectiveness and packaging efficiency. In line with the exploratory nature of this study, the levels selected for the experimental factors are not intended to represent a specific industrial context, but rather to capture plausible operating ranges (for the numerical factors F2 to F5) and reasonable managerial decisions (for the categorical factor F1), consistent with industrial practice and prior research. Accordingly, these values and levels were informed by discussions with practitioners and by ranges and policies commonly adopted in the literature (Albrecht et al., 2022; Fernández-Arribas et al., 2024). This approach allows for a systematic exploration of how key parameters and policy choices affect the dynamic performance of the CLSC.

The remaining parameters are held constant to isolate the effects of interest (and avoid unnecessary complexity in the experimental design). We assign reasonable values based on a review of the literature and our industrial experience. Firstly, production orders are characterised by $\mu = 1,000$ and $\sigma = 300$, resulting in a coefficient of variation of 30%. Secondly, a coefficient of variation of 40% is always applied to the defective rate, i.e., $\sigma_y = 0.4\mu_y$ (with varying μ_y), ensuring proportional dispersion across means. Thirdly, the maximum duration of a disruption is constantly set at $D_d = 4$ periods. Fourthly, lead times are considered as $T_s = T_{sp} = T_{t1} = 2$ periods, and $T_{t2} = T_i = 1$ period. Lastly, concerning the decision parameters, SES forecasting uses a smoothing parameter of $\alpha = 0.20$, while the safety factor is established at $\gamma = 0.5$ to provide a balanced buffer against demand variability without inflating stock levels excessively.

Using a full-factorial design of experiments, we conducted simulations for all potential combinations of the five experimental factors, resulting in $2^5 = 32$ different scenarios. To ensure robust and statistically significant results, each treatment underwent thorough exploration across 10 replications, yielding a cumulative total of 320 simulation runs.

5.3. Results, operational insights, and discussion

We now analyse and discuss the results of our experiments. To assess the results across scenarios, we applied statistical tests to evaluate the significance of the five factors (F1 to F5) on the three performance metrics (BD, RPInv, APU). Specifically, we conducted fixed-effects analysis of variance (ANOVA) studies, the results of which are summarised in Table 9 through the p-values associated with each factor and metric. To complement this analysis, we also examined the relative importance of the factors for each metric by means of a Pareto analysis of standardised effects. Finally, the last row of Table 9 reports the adjusted R-squared values of the different models, showing that all models explain a large portion of the variability in the simulation results.

Before delving into a detailed discussion of the impact of each factor on every metric, it is noteworthy that the five experimental factors that we considered significantly influence the behaviour of RPInv and APU. Comparatively, F3 – *Initial stock in the TPI* (φ) emerges as the most impactful factor on these metrics (ranking 1st for RPI and APU) while F2 –

Table 9
Overview of the ANOVA results.

	BD		RPInv		APU	
	p-value	Pareto	p-value	Pareto	p-value	Pareto
F1 – $\boldsymbol{\delta}$	0.00	*****	0.00	***	0.00	***
F2 – $\boldsymbol{T_r}$	0.07	-	0.00	*	0.00	*
F3 – $\boldsymbol{\varphi}$	0.61	-	0.00	*****	0.00	*****
F4 – $\boldsymbol{\mu_y}$	0.59	-	0.00	****	0.00	**
F5 – $\boldsymbol{P_d}$	0.33	-	0.00	**	0.00	****
	$\boldsymbol{R^2}$ ***adj.***	88.04%	$\boldsymbol{R^2}$ ***adj.***	97.25%	$\boldsymbol{R^2}$ ***adj.***	96.57%

Notes: ***** denotes the highest impact of a factor on a metric; * denotes the lowest, but still significant, impact of a factor on a metric; - indicates a non-significant impact (i.e., p-value >0.05). Two-factor interaction terms are also included in the model but are not discussed here; their analysis is reported in the Supplementary Material S2.

Renewal period (T_r) has the least impact (ranking 5th for both). Notably, F1 – *Replenishment policy for the PI* (δ) is the sole factor that significantly affects BD.

5.3.1. Backlog-to-demand ratio (BD)

Fig. 2 presents the main effects plot for BD, highlighting the significant impact of factor F1 – *Replenishment policy for the PI* (δ) on this metric. Inspection of this plot reveals that the pull-oriented replenishment policy, KB, demonstrates superior performance compared to the push-oriented alternative, OUT. Specifically, simulations with the OUT-policy result in a mean backlog of 3.9% of the overall demand, and this value decreases to 2.5% with the utilisation of the KB rule, representing a substantial 36% mean reduction. Consequently, we infer that the adoption of the KB policy significantly enhances the effectiveness of our SC.

As discussed before (Table 9), the other factors do not exert a significant influence on BD. The management of returnable packaging thus does not impact the SC's effectiveness; this is due to the use of alternative, disposable packaging when returnable units are unavailable. However, it substantially affects efficiency, as we will discuss in the following subsections.

5.3.2. Returnable packaging inventory (RPInv) and alternative packaging utilisation (APU)

Figs. 3 and 4 represent the main effects plots for RPInv and APU, respectively. We analyse both metrics jointly, as there is a clear trade-off between them; alternative packaging is used when there is no returnable packaging in the TPI. Consistent with earlier discussions (based on Table 9), F3 – *Initial stock in the TPI* (φ) emerges as the most influential factor affecting these indicators. This is reasonable, since φ determines the total amount of returnable units in the system (damaged units lost are replenished through the packaging supplier). As φ grows, the investment in inventory becomes larger (RPInv grows, Fig. 3) and the need to utilise alternative packaging reduces (APU decreases, Fig. 4), which clearly underscores the aforementioned trade-off.

In contrast, F2 – *Renewal period* (T_r) has the least impact on both RPInv and APU. It is interesting to highlight that, when T_r decreases, APU experiences a slight decrease (Fig. 4), while RPInv increases (Fig. 3). This suggests that as damaged items that leave the SC are more rapidly replaced, the use of alternative packaging slightly decreases, accompanied by a growth in the average inventory of the TPI. It is also important to consider that higher T_r values may allow for economies of scale, and that inventory holding costs must remain within reasonable limits for the benefits of reducing T_r in terms of APU to outweigh its drawbacks.

At the same time, F4 – *Mean defective rate* (μ_y) has a considerable impact on both RPInv and APU. Inspection of the plots indicates that a reduction of μ_y leads to a decrease in the utilisation of alternative packaging (Fig. 4), and results in a higher mean position in the TPI (Fig. 3). This can be attributed to the delay between the departure of damaged units from the SC and the acquisition of new returnable items through the packaging supplier. However, it is important to note that while reducing μ_y increases RPInv, the overall investment in returnable packaging decreases, given that the number of items requiring replenishment is closely related to μ_y.

Examining the main effects plots of F5 – *Probability of disruption* (P_d), we observe how disruptions damage SC performance from both perspectives. As P_d grows, both RPInv (Fig. 3) and APU (Fig. 4) also increase. In highly uncertain industrial contexts characterised by frequent and/or severe disruptions, suppliers not only require a higher number of returnable packaging items but also, even with the above, resort more frequently to alternative packaging. This perspective underscores the significance of risk management in contemporary SCs. Indeed, SCs equipped with mechanisms to sustain operations during disruptive events, such as multiple sourcing or capacity and inventory buffers, possess an invaluable competitive advantage in the current business landscape.

Finally, we turn our attention to F1 – *Replenishment policy for the PI* (δ). In this sense, it is particularly relevant to highlight that the adoption of the pull-oriented replenishment rule not only enhances the effectiveness of the SC, as discussed in the previous subsection, but also makes the SC substantially more efficient by optimising the use of packaging resources. In particular, when compared to the OUT policy, KB results in a considerable reduction in the usage of the alternative packaging (approximately, APU reduces from 6% to 4%, see Fig. 4). Interestingly, this reduction occurs even when the mean position of the TPI reduces (RPInv decreases from 91% to 81%, see Fig. 3), resulting in lower investments in alternative packaging, reduced inventory expenses, and diminished environmental costs.

To assess the robustness of the operational insights reported in this section, additional analyses are provided in the Supplementary Material S2 and S3. Supplementary Material S2 examines interaction effects within the experimental design, while Supplementary Material S3 extends the analysis beyond the designed experiments through a set of scenario-based robustness checks that vary order variability, lead times, and disruption duration. Together, these additional analyses confirm that the qualitative conclusions drawn from the operational study remain stable across a broader range of operating conditions.

6. Economic study

This section addresses RQ2 by examining the economic implications of the operational dynamics identified in Section 5. Specifically, it translates the observed system behaviour into a cost-based evaluation of hybrid packaging strategies, with the objective of assessing total packaging-related costs and identifying the economically optimal

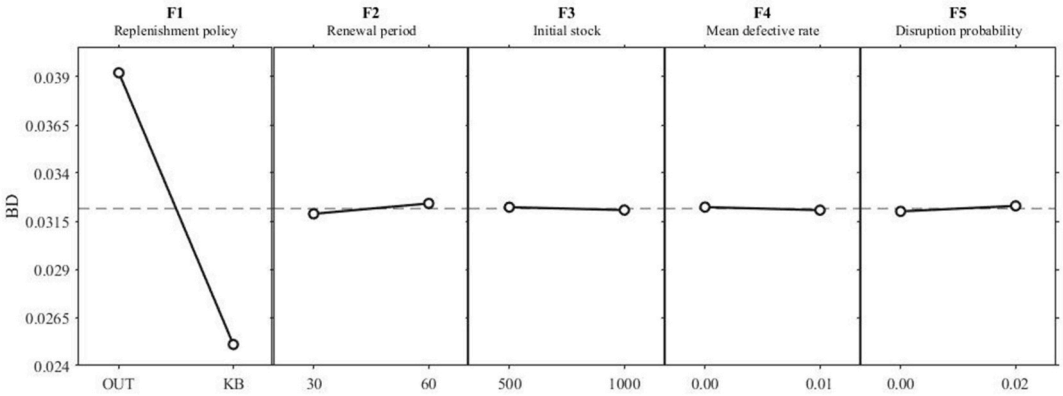


Fig. 2. Main effects plot for BD.

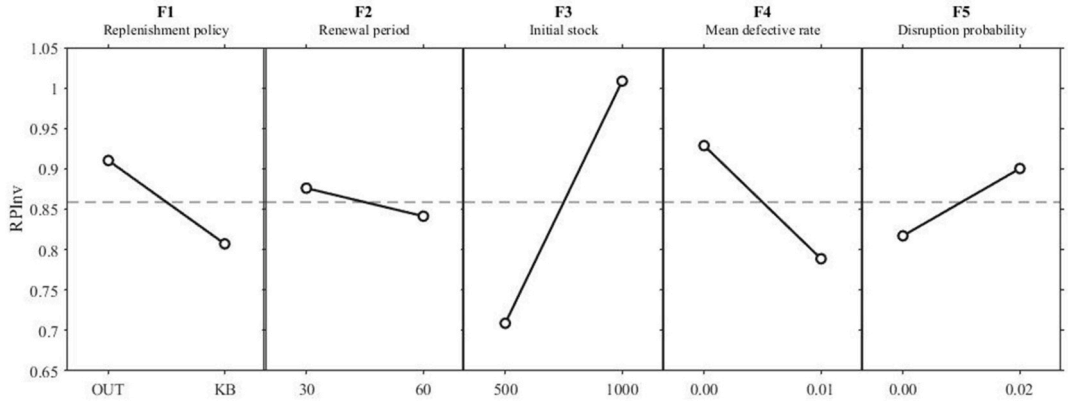


Fig. 3. Main effects plot for RPInv.

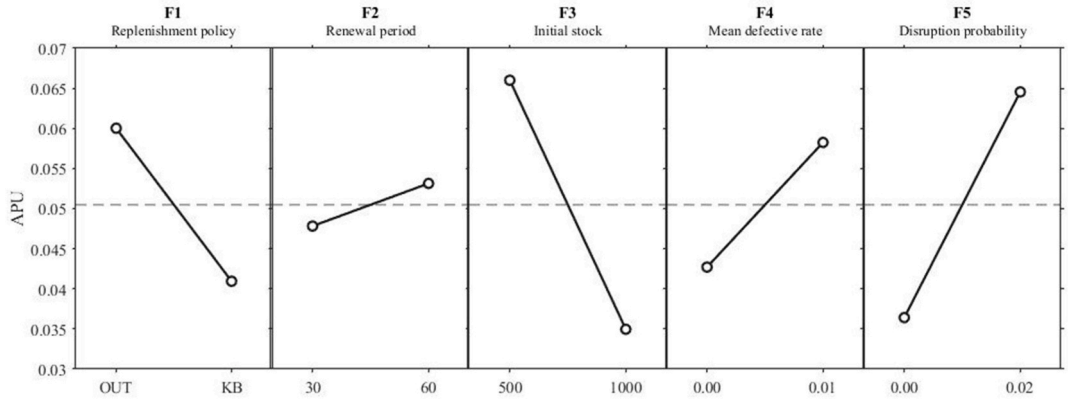


Fig. 4. Main effects plot for APU.

allocation of returnable packaging under different cost structures, disruption risks, and system parameter settings. Building on the analysis of how key system parameters affect the operations of the CLSC, we conduct an economic analysis through simulation, maintaining the same experimental conditions outlined in the preceding section.

6.1. Economic model

Drawing from our conversations with industrial actors in the automotive industry, we have formulated a cost model that captures the primary packaging-related expenses encountered by CLSCs. The model is based on seven cost components and is mathematically formalised in Table 10 (Eqs. (38)–(45)). To improve traceability, Table 10 also explicitly identifies, for each cost component, the underlying model variable it prices and its operational meaning within the CLSC. These cost components reflect the key economic dimensions of packaging management identified in the literature review (Section 2) and corroborated through the empirical study (Section 3).

First, we consider the cost of acquiring returnable packaging (*ARP*), both at the onset of the simulation and whenever they are required to replace defective items, as represented in Eq. (38), where $\kappa_{a,r}$ is the cost of purchasing one returnable unit. Second, we account for the cost associated with (re)using these units (*URP*), if they are deemed suitable after inspection, encompassing maintenance and transportation, among others. This results from multiplying the unit cost, $\kappa_{u,r}$, by the units reused throughout the entire simulation duration (Eq. (39)). Additionally, we factor in the costs of disposing of damaged packaging units (*ERP*), by multiplying the specific unit cost, $\kappa_{e,r}$, by the total number of damaged packaging units discarded (Eq. (40)). The last cost we consider for returnable packaging pertains to storing excess inventory at the TPI (*IRP*). This cost arises from multiplying the unit cost, $\kappa_{i,r}$, by the sum of returnable packaging units held in this inventory throughout the entire simulation run (Eq. (41)).

In regard to the alternative, or disposable, packaging, we also account for the costs of acquisition, usage, and disposal (*ANP*, *UNP*, and *ENP*, respectively), following the same rationale as for the returnable

Table 10
Cost model.

Cost component (Nature)	Cost source (Variable)	Mathematical definition	Ref.
ARP - Acquisition of RPIs (*availability costs*)	New RPIs purchased from external packaging suppliers (rup_t^{cs})	$ARP = \kappa_{a,r}\left[\varphi + \sum_t rup_t^{cs}\right]$	(38)
URP -Usage of RPIs (*operational costs*)	Recovered RPIs processed by the RLP and reintroduced into the CLSC (rp_t^{rl})	$URP = \kappa_{u,r}\sum_t rp_t^{rl}$	(39)
ERP - Elimination of RPIs (*disposal costs*)	Damaged RPIs removed from the CLSC after inspection (dp_t^{rl})	$ERP = \kappa_{e,r}\sum_t dp_t^{rl}$	(40)
IRP - Inventory of RPIs (*storage costs*)	Inventory of RPIs available at the CS at the end of each period (fi_t^{cs})	$IRP = \kappa_{i,r}\sum_t fi_t^{cs}$	(41)
ANP - Acquisition of NPIs (*availability costs*)	Components received by the AM in NPIs due to shortages of RPIs at the CS ($\check{r}_t^{am}$)	$ANP = \kappa_{a,a}\sum_t \check{r}_t^{am}$	(42)
UNP –Usage of NPIs (*operational costs*)	*Id.*	$UNP = \kappa_{u,a}\sum_t \check{r}_t^{am}$	(43)
ENP –Elimination of NPIs (*disposal costs*)	*Id.*	$ENP = \kappa_{e,a}\sum_t \check{r}_t^{am}$	(44)

units. However, a significant distinction arises in this scenario, as each individual alternative packaging unit is (first) acquired, (then) used, and (finally) eliminated. Consequently, unlike for the RPIs, all three costs are derived by multiplying the unit costs ($\kappa_{a,a}$, $\kappa_{u,a}$, and $\kappa_{e,a}$, respectively) by the total number of alternative packaging units utilised in the simulation, as illustrated in Eqs. (42)–(44). We do not explicitly model inventory holding costs for NPIs, as this stock is not directly managed. NPIs are treated as a short-lived substitute, accessed when returnable packaging is insufficient and removed from the CLSC after use. Their economic impact is therefore captured through the three previous cost components (Na et al., 2019).

Ultimately, the total cost is determined by summing the seven individual costs, as outlined in Eq. (45). It is important to note that this sum is divided by the simulation time horizon (θ) to provide a clearer perspective on the costs that can be attributed to managing (both returnable and disposable) packaging per period for the CLSC and the stakeholders involved.

$$\boldsymbol{TC} = \frac{(\boldsymbol{ARP} + \boldsymbol{URP} + \boldsymbol{ERP} + \boldsymbol{IRP} + \boldsymbol{ANP} + \boldsymbol{UNP} + \boldsymbol{ENP})}{\boldsymbol{\theta}} \tag{45}$$

6.2. Conditions of the simulations

As detailed below, the cost structure under consideration is based on seven-unit costs. To set these parameters for the economic analysis, we have used data provided by one of the collaborators involved in this research work. More specifically, it originates from the different costs estimated by an industrial supplier of vehicle transmissions. The returnable packaging in question is a metal cage with dividers (large multipurpose RPI) weighing 50 kg (approx.) when empty, while the alternative NPI is constructed of cardboard and weighs 5 kg (approx.) when empty.

The data obtained directly from the industrial actor establishes the baseline, referred to as *Scenario C-I*, as detailed in Table 11. As it is reasonable, acquiring reusable packaging is considerably more costly (nearly 10 times higher) than single-use packaging. Moreover, utilising this packaging (per cycle) becomes more expensive, primarily for two reasons: it entails both forward and reverse logistics operations, and its weight is considerably higher. Furthermore, disposing of this packaging is substantially more expensive due to the need for specialised processes, which often require more resources compared to single-use packaging.

Additionally, we have formulated two alternative cost scenarios to explore different real-world industrial settings. In *Scenario C-II*, we have halved the (three unit) costs of alternative packaging, reflecting a situation where reusable packaging becomes relatively more expensive (specifically, the acquisition cost of returnable packaging now increases to approximately 19 times that of single-use packaging). Conversely, in *Scenario C-III*, we have doubled the same costs, illustrating the opposite scenario (where the acquisition cost of returnable packaging is 'only' approximately five times higher than single-use packaging).

The economic study aims to examine how the key operational parameters, identified in the previous section, influence the optimal quantity (allocation) of returnable packaging units in the CLSC. Specifically, we analyse how these parameters (renewal period, T_r; mean defective rate, μ_y; and probability of disruption, P_d) affect the U-shaped relationship between the total cost (TC) and the initial stock in the CS' TPI (φ); the minimum point of this curve determines the optimal allocation (φ^*) in each specific scenario. It is important to note that we consistently employ the pull-oriented KB replenishment policy to manage the AM's inventory of parts due to its demonstrated superiority over the OUT policy in this application, as discussed in the operational study. Also, we note that the other parameters are held constant to focus on the key effects of interest, maintaining the same values as described in the previous subsection.

To accurately estimate, through simulation, the optimal allocation, φ^*, we conduct multiple simulations for each case, ranging from $\varphi = 0$ to $\varphi = 4,000$, with increments of 20 units (i.e., $\varphi = \{0; 20; 40; 60; \ldots; 4,000\}$). In this sense, each analysis (graph) presented in the following subsection results from 201 simulation runs spanning 2000 periods. Furthermore, to minimise the influence of simulation randomness and facilitate the visualisation of the curves, we employ identical stochastic seeds for all simulations conducted under the same stochastic condition.

Table 11
Different cost scenarios.

Unit cost	Scenario C-I (Baseline)	Scenario C-II (Reduced alternative packaging costs)	Scenario C-III (Increased alternative packaging costs)
$\kappa_{a,r}$	1400.00 €	1400.00 €	1400.00 €
$\kappa_{u,r}$	8.00 €	8.00 €	8.00 €
$\kappa_{e,r}$	9.00 €	9.00 €	9.00 €
$\kappa_{i,r}$	2.00 €	2.00 €	2.00 €
$\kappa_{a,a}$	150.00 €	75.00 €	300.00 €
$\kappa_{u,a}$	4.80 €	2.40 €	9.60 €
$\kappa_{e,a}$	1.00 €	0.50 €	2.00 €

6.3. Results, economic insights, and discussion

To answer RQ2, we first analyse the baseline scenario defined by $T_r = 30$ periods, $\mu_y = 1\%$, and $P_d = 2\%$, and then investigate how disruption risk, defective rates, renewal policies, and cost structures affect the economically optimal allocation of returnable packaging. Under these circumstances, Fig. 5 represents the relationship between the total cost (TC) and the initial stock of returnable packaging (φ) in the baseline cost scenario (C-I). To understand how the total cost curve emerges, we separate the costs associated with returnable packaging from those linked to alternative packaging. The former (i.e., $(ARP + URP + ERP + IRP)/\theta$) increase steadily as φ grows. In contrast, the slope of the latter (i.e., $(ANP + UNP + ENP)/\theta$) decreases considerably with φ's increase. Consequently, a U-shaped curve emerges, with the minimum (denoted by the symbol ∇) found at $\varphi^* = 1,520$ units.

The preceding analysis underscores the potential for significant reductions in the total cost of packaging (TC) through the estimation of the optimal amount of returnable units within the CLSC. Of course, this principle extends to the alternative cost scenarios C-II (reduced alternative packaging costs) and C-III (increased alternative packaging costs). These three different cost settings are represented jointly in Fig. 6. As is reasonable, the curves illustrate that as reusable packaging

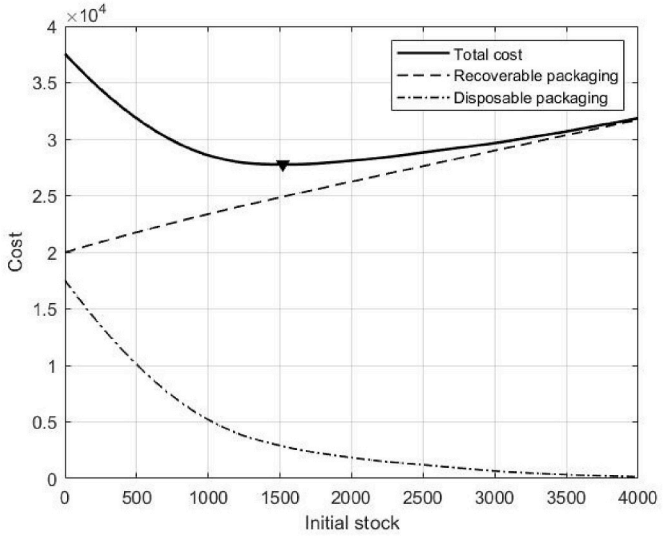


Fig. 5. Total cost of packaging, and its components, in the baseline cost scenario (C-I).

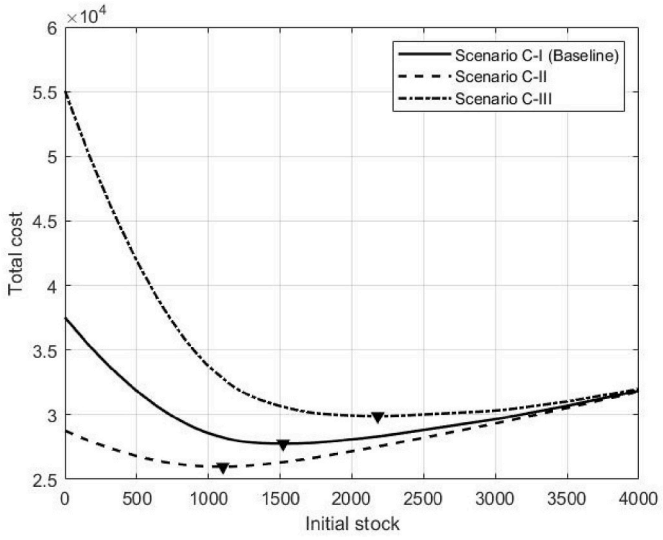


Fig. 6. Total cost of packaging in the three cost scenarios.

becomes relatively more expensive compared to single-use packaging, the optimal stock of returnable units decreases. Specifically, φ^* decreases to 1100 units in C-II, and it rises to 2180 units in C-III. Notice that the three curves converge as φ grows due to the declining use of alternative packaging.

In this context, it becomes apparent that φ^* is significantly influenced by the cost structure of the packaging system. However, it is also considerably affected by other conditions, such as the level of disruption risk within the CLSC. This is evidenced by Fig. 7, which compares, in the cost scenario C-I, the baseline case with $P_d = 2\%$ to the ideal SC operations without disruptions ($P_d = 0\%$) and a scenario with higher disruption likelihood ($P_d = 4\%$.). First, Fig. 7 illustrates that operations managers should not solely resort to alternative packaging when faced with disruptive events. In essence, they must respond to rising risks by increasing the quantity of reusable packaging in the CLSC. Particularly, φ^* increases from 1240 to 1520 units (+280) as P_d rises from 0% to 2%; furthermore, φ^* increases up to 2240 units (+1000) when P_d becomes 4%. Consequently, maintaining the quantity selected for the ideal scenario ($P_d = 0\%$) can lead to highly sub-optimal performance, particularly under frequent disruption occurrences. Additionally, it is noteworthy that Fig. 7 provides clear evidence of the (packaging) cost implications of disruptions. The minimum TC increases approximately from 25,300 to 30,400 €/period as P_d grows from 0% to 4%, representing a 20% increase.

In Fig. 8, also under scenario C-I, we make a comparison between the baseline case (with $\mu_y = 1\%$) and two additional cases: one representing the ideal scenario where returnable packaging lasts indefinitely ($\mu_y = 0\%$) and another where it has a shorter lifespan ($\mu_y = 2\%$). Beyond highlighting the significant impact of μ_y on the costs of the packaging system —higher values of μ_y necessitate increased purchases of returnable packaging units to offset losses—, Fig. 8 also elucidates how μ_y influences the optimal allocation of these units. Specifically, it is observed that φ^* increases proportionally with μ_y, although the influence of this parameter is notably smaller compared to those discussed earlier. In this regard, as returnable packaging items exit the CLSC more frequently due to damage, it becomes prudent to augment the overall allocation of such items slightly. For instance, the best-found values of φ^* are 1,440, 1,520, and 1640 for μ_y equal to 0%, 1%, and 2%, respectively.

Fig. 9 delves into the impact of the renewal period T_r, comparing $T_r = 30$ (baseline) with $T_r = 15$, $T_r = 60$, also within scenario C-I. A notable observation emerges for low values of φ, lower T_r values lead to reduced operational costs; however, for high φ values, the order of the curves is reversed, with higher levels of T_r proving more beneficial. This highlights meaningful interactions between T_r and φ that managers must discern to optimise their packaging systems. When focusing on the best strategies, it is noteworthy that the best combinations are found for $T_r = 30$. Consequently, employing intermediate values of this parameter seems reasonable, contrary to the common notion that replacing lost items as promptly as possible (if feasible) might be advantageous, but in alignment with the discussions of the operational analysis, where we identified both advantages and drawbacks of reducing/increasing T_r. When analysing the optimal values, we find that φ^* grows as T_r increases. Specifically, the best values of φ are found to be at 1,500, 1,520, and 1660 units for T_r equal to 15, 30, and 60, respectively. That is to say, as defective items are replaced more frequently, managers should operate with lower overall quantities of returnable packaging.

Lastly, we emphasise that a set of additional sensitivity and robustness checks was conducted to assess whether the economic insights reported in this section remain valid when the operating environment departs from the benchmark assumptions. The results of some of these analyses are reported in Supplementary Material S4. These indicate that, while variations in demand variability, lead times, and disruption

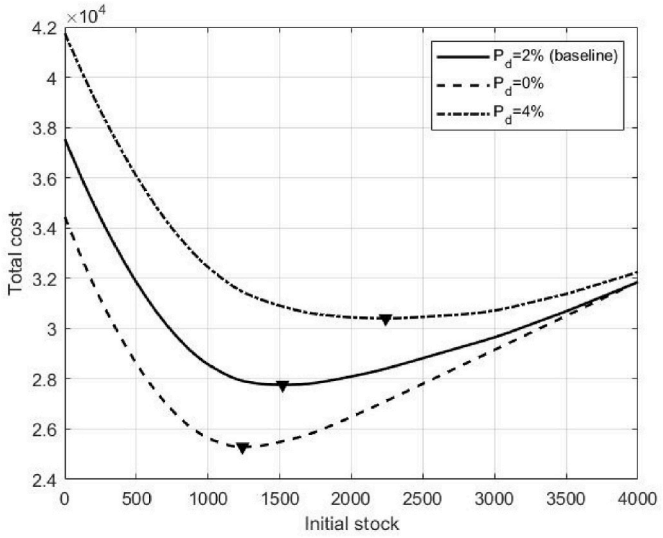


Fig. 7. Total cost of packaging for various disruption probabilities.

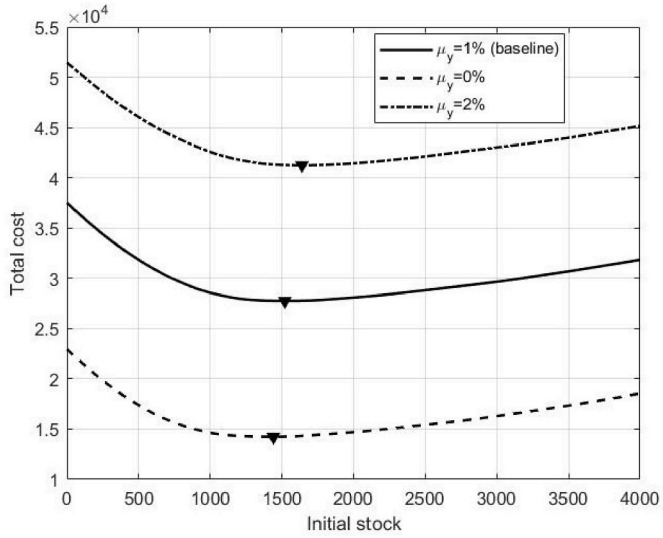


Fig. 8. Total cost of packaging for various defective rates.

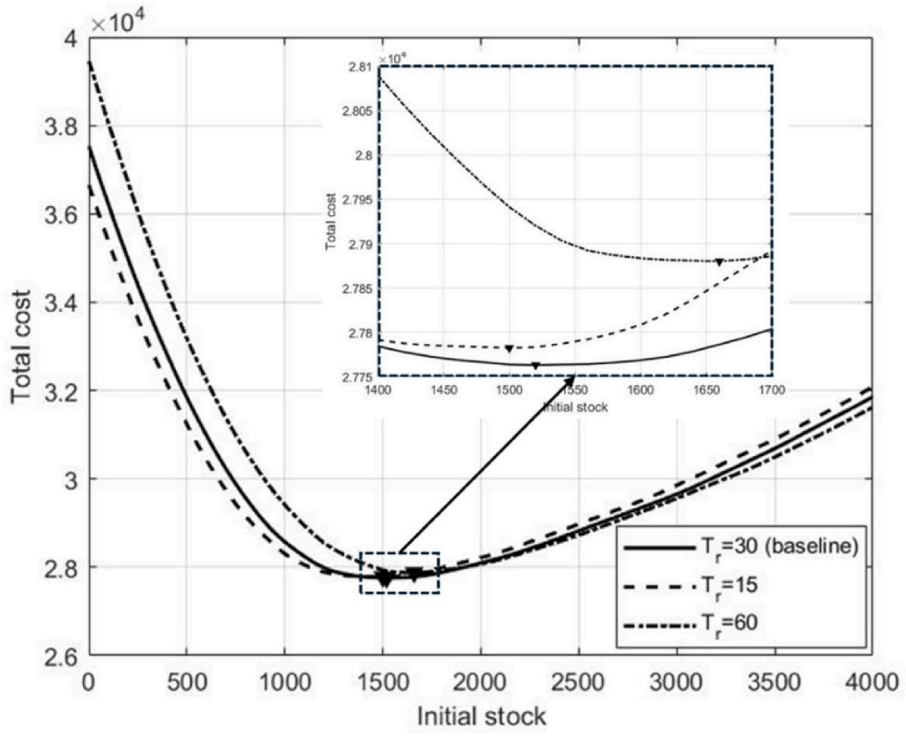


Fig. 9. Total cost of packaging for various renewal periods.

duration affect the absolute cost levels and, in some cases, the magnitude of the economic trade-offs, they do not alter the qualitative structure of the cost function or the main economic insights discussed above.

At the same time, it is important to acknowledge the considerable complexity inherent in the multidimensional parameter space underlying the model (23 parameters in total). As a result, the operational and economic dynamics of the CLSC may exhibit different or atypical behaviours at specific combinations of parameter values. A systematic exploration of this high-dimensional space lies beyond the scope of the present exploratory study, which aims to provide general economic insights into hybrid packaging systems with returnable and disposable items under disruptions. Nevertheless, investigating how the system behaviour may change under more extreme or highly specific operating conditions represents a promising avenue for future research.

6.3.1. Implications of the hybrid packaging strategy on sustainability and resilience

Although our operational analysis is framed in terms of effectiveness and efficiency, two of the performance indicators examined in this study (RPInv and APU) have clear environmental interpretations. Moreover, while the economic analysis is expressed in cost terms, its optimisation results also carry important sustainability implications. Specifically, APU represents the proportion of parts shipped using disposable packaging. Therefore, reductions in APU translate directly into lower volumes of single-use packaging waste and reduced demand for virgin packaging materials. For instance, the adoption of the KB policy reduces APU from approximately 6% to 4%, implying a one-third reduction in disposable packaging usage, which constitutes a significant improvement from an environmental sustainability perspective.

At the same time, RPInv is related to the total stock of returnable packaging circulating within the CLSC. While higher RPInv levels reduce reliance on disposable packaging, they also imply a larger pool of physical assets that must be manufactured, maintained, transported, and stored. This entails additional embedded material, energy use, and capital investment in the system. Sustainability is therefore not achieved by simply maximising RPInv or eliminating APU entirely, but by identifying a balanced configuration that minimises total resource consumption across the packaging life cycle.

Interestingly, our results reveal a structural tension between resilience and sustainability in the CLSC. As disruption probability increases, managers need more RPIs to minimise costs under higher disruption, but total costs are still higher than in the disruption-free scenario. In this sense, this resilience-oriented response (mainly, the SBV) entails maintaining a larger pool of physical assets, thereby increasing the embedded material and energy within the system. At the same time, more volatile environments also lead to higher utilisation of disposable packaging during disruption episodes. Consequently, this form of SC instability can generate a double environmental burden: greater embedded investment in returnable assets and increased disposable packaging waste.

In this sense, the hybrid packaging strategy should be interpreted as a pragmatic compromise. Rather than aiming to eliminate disposable packaging completely, which may be economically prohibitive or operationally infeasible under disruptions, managers should focus on minimising its use through appropriate inventory policies, well-calibrated RPI levels, and well-designed renewal cycles. The economic levers analysed in this study thus operate simultaneously as sustainability levers, reinforcing the alignment between production economics and circular SC design.

7. Conclusions

This study investigated how hybrid packaging systems combining RPIs and NPIs can be designed and managed within contemporary CLSCs, which are characterised by high levels of operational uncertainty and disruption risks. Building on empirical insights obtained from logistics professionals in the automotive industry and a simulation model grounded in system dynamics, we analysed the operational implications of key system (both decision and physical) parameters and their economic consequences for packaging allocation decisions.

Regarding RQ1, our findings show that hybrid packaging systems can substantially enhance the operational robustness of CLSCs by combining the efficiency advantages of RPIs with the flexibility

provided by NPIs during periods of shortage or disruption. Although RPIs generally represent the preferred solution from economic and environmental perspectives, relying exclusively on them may create vulnerabilities when reverse logistics processes are affected by disruptions, delays, packaging losses, or demand variability. In such situations, NPIs provide an effective contingency mechanism that preserves material flows and avoids disruptions to production activities. More broadly, the results reveal that inventory-related decisions and physical system characteristics jointly shape operational performance. In particular, pull-based replenishment policies, such as kanban systems, facilitate a more effective integration of both packaging types, while appropriately dimensioned RPI stocks and suitable renewal cycles reduce reliance on NPIs and improve packaging efficiency. These findings suggest that efficiency and resilience need not be conflicting objectives when hybrid packaging systems are properly designed and managed.

Regarding RQ2, the study demonstrates that determining the economically optimal allocation of RPIs is a complex decision that requires a thorough understanding of the dynamics of hybrid packaging systems. The optimal packaging pool is not determined solely by packaging acquisition costs, but rather by the interaction between packaging costs, defective rates, disruption probabilities, and renewal policies. In particular, higher disruption probabilities not only shift the optimal RPI stock upward but also entail a measurable cost penalty: in the baseline scenario, total packaging costs increase by approximately 20% as disruption probability rises from 0% to 4%. Consequently, managers should not rely exclusively on NPIs as a reactive response to disruptions, but instead proactively determine RPI stock levels and renewal frequencies that reflect the operating conditions of their CLSCs. The results also reveal important interactions between these decisions. Interestingly, while more frequent replacement of damaged RPIs reduces the amount of returnable packaging required in circulation, the results show that excessively short renewal periods do not necessarily minimise total packaging costs, as intermediate renewal cycles can outperform both extremes. This highlights the need for a balanced, integrated approach to packaging management, where renewal frequency is calibrated jointly with RPI stock levels rather than treated as an isolated operational decision.

Beyond their economic implications, the analysed decisions also have important sustainability consequences. By reducing dependence on disposable packaging while maintaining operational performance under uncertainty and disruptions, hybrid packaging systems provide a mechanism through which resilience, efficiency, and environmental objectives can be pursued simultaneously. The results therefore reinforce the idea that sustainability outcomes can be influenced not only through packaging design choices, but also through the operational configuration of packaging systems and their associated CLSCs.

From a theoretical perspective, this study contributes to the growing literature on packaging systems and CLSCs in several ways. First, it extends existing research by explicitly modelling the coexistence of RPIs and NPIs within the same CLSC. Second, it adopts a dynamic perspective that captures the interactions between inventory policies, packaging losses, disruptions, and replenishment decisions over time. Third, it responds to recent calls for simulation-based research by analysing the dynamic behaviour of packaging systems under realistic operating conditions. Finally, by combining simulation modelling with empirically grounded insights from industry, the study helps bridge the gap between conceptual modelling and practical packaging challenges.

From a managerial perspective, the study offers several practical implications. First, it encourages firms to move beyond binary decisions between RPSs and NPSs and instead consider hybrid strategies as a viable and strategically valuable alternative, particularly in environments characterised by uncertainty and disruption risks. Second, it provides a structured framework for assessing the cost and performance implications of key packaging-related decisions, including replenishment policies, RPI stock levels, and renewal frequencies. Third, it highlights the importance of aligning packaging decisions with broader CLSC characteristics, including lead times, demand variability, maintenance capabilities, and disruption exposure.

Future research could extend this work in several directions. From a sustainability perspective, integrating life cycle assessment and multi-criteria decision analysis would enable a more comprehensive evaluation of hybrid packaging strategies by jointly considering economic and environmental trade-offs. From an operational perspective, analysing multi-product systems, shared packaging pools, or coordination mechanisms among CLSC partners could provide additional insights into the returnable packaging systems. Future studies could also investigate more sophisticated disruption patterns, including correlated, persistent, or node-specific disruptions, to further improve the representation of real-world SC environments.

Disclosure statement

The authors report there are no competing interests to declare.

Funding

This work was partially funded by the Spanish State Research Agency (MCIN/AEI/10.13039/50110 0 011033)through the SPUR project (grant ref. PID2020-117021GB-I00).

CRediT authorship contribution statement

Jesús García-Arca: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. **Mar Vazquez-Noguerol:** Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Borja Ponte:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing. **J. Carlos Prado-Prado:** Funding acquisition, Project administration, Resources, Validation.

Acknowledgements

The authors express their gratitude for the collaboration and contributions of the various professionals and organisations involved in the development of this research work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijpe.2026.110149.

Data availability

The data that has been used is confidential.

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