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# Single-use or reusable? Packaging strategies for decarbonizing fresh produce distribution in Ho.Re.Ca. supply chain

G. Bartolotti [a,*], R. Accorsi [a,b], B. Guidani [a], B. Lupi [a], R. Manzini [a], M. Ricci [a], M. Ronzoni [a]

[a] *Department of Industrial Engineering, Alma Mater Studiorum, University of Bologna, Viale del Risorgimento, 2, Bologna*

[b] *CIRI –AGRO, Interdepartmental Center for Agro-Industrial Research of the University of Bologna, Via Quinto Bucci 336, 47521, Cesena, FC, Italy*

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ABSTRACT

Reducing packaging-related environmental burden has become a key priority in the agri-food sector, especially in light of regulatory pressures and sustainability goals. While reusable packaging systems are increasingly recognized as a viable alternative to single-use packaging, their implementation in the Hotel, Restaurants, and Cafe (Ho.Re.Ca.) sector remains underexplored. To understand the environmental implications resulting from different packaging and operational choices in the Ho.Re.Ca. fruit and vegetable distribution, this study quantifies carbon footprint across the entire use cycle of crates, including logistics, production, end-of-life, and washing operations, providing a comprehensive cradle-to-grave evaluation of secondary packaging strategies. Through a multi-scenario analysis, the study evaluates the influence of three key parameters (reusable crate *Breakage Probability*, reusable crate *Washing Rate*, and *Paper Share* of disposable crates) on the overall carbon emissions of the whole supply chain system. Results show that reusable systems provide the best environmental performance under low *Breakage Probability*, while hybrid configurations can outperform single-use systems under certain conditions. This study does not aim for generality but instead focuses on the unique aspects of a specific industrial case using an Operational Packaging digital Twin (OPT). This tool is developed to help practitioners assess and compare quantitative indicators of logistics performance and carbon footprint resulting from packaging choice. Findings demonstrate that packaging strategies have system-wide implications and reuse schemes require careful design, especially in fragmented and logistics-intensive sectors like Ho.Re.Ca.

## 1. Introduction and state of the art

Reducing packaging production is now a pressing priority to tackle the growing waste problem and mitigate the climate impact of multiple industrial sectors [1]. Among these, the agri-food sector stands out as one of the main packaging users, due to the short shelf-life of food products and the resulting fast-paced packaging turnover [2]. European regulations impose strict standards on the use of recycled packaging in direct contact with food, due to the potential health risks of contamination [3]. These constraints make the agri-food sector particularly critical when implementing more sustainable packaging solutions.

The European Green Deal promotes practical solutions to reduce unnecessary packaging waste, including the adoption of reusable packaging [4]. Reusable packaging represents a promising opportunity both for the creation of new sustainable businesses and for reducing the use of virgin raw materials [5]. In the agri-food sector, replacing single-use packaging with reusable alternatives is an increasingly explored and implemented strategy [6].

In recent years, reusable food packaging has received growing attention with reuse schemes being implemented across different contexts within the food sector [7,8]. A keyword search for "*reusable food packaging*" in scientific databases reveals a clear upward trend in publications, indicating a steadily rising academic interest [6]. The literature addresses reusable food packaging from multiple perspectives, recognizing that the shift from single-use to reusable systems can involve primary packaging in direct contact with food, secondary packaging, which groups multiple primary packages, and tertiary packaging [9]. Sanitary requirements vary across packaging levels, becoming progressively stricter from tertiary to secondary, and reaching their highest standards in primary packaging due to direct contact with food [10].

Life Cycle Assessment (LCA) studies confirm the environmental benefits of adopting reusable packaging systems. These studies often rely on primary data for production-related impacts, but facing transportation issues, they typically use average distances and generalized

* Corresponding author.
*E-mail address:* giorgia.bartolotti2@unibo.it (G. Bartolotti).

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**Nomenclature**

| | |
|---|---|
| EoL | End of Life |
| OPT | Operational Packaging digital Twin |
| Use cycle | The set of activities involving packaging from its release by the packaging management facility to its arrival at the final supply chain node and return back to the management system. |
| FPC | Fractional Product Crate |
| FSD | Food Service Distributor |
| RC | Reusable Crate |
| DC | Disposable Crate |
| Ho.Re.Ca. | Hotel, Restaurant, and Café sector |

assumptions. Accorsi et al [11] emphasize the importance of using primary data on the specific logistics network (i.e., actual distances between supply chain actors) since these factors significantly influence the overall environmental outcome [12]. Reuse schemes entail additional transportation procedures to collect, sanitize, and return the crates to food packagers. When reverse logistics operations are significant, the emissions from transport and washing may offset the environmental savings achieved through reduced packaging production and disposal [13]. As a result, the literature highlights the crucial role of logistics and the need to apply LCA findings to real-world scenarios using primary and case-specific data. In some cases [14], the logistics network structure leads to scenarios where single-use alternatives (paper or plastic) are preferable, leaving uncertainty about which packaging system to adopt, in which context, and with which benefits?

As stated by Yadav et al [15], research has so far focused more extensively on reusable *secondary* packaging. The literature confirms the key role of secondary packaging in protecting food during distribution operations and in optimizing transport processes [16]. Several studies have investigated secondary packaging solutions for fresh produce, focusing on applications within large-scale retail systems [17,18]. In contrast, the use of reusable crates in the Ho.Re.Ca. sector has received limited attention, and the literature on this specific application remains scarce. In particular, Di Pierro et al [19] emphasize that the Ho.Re.Ca. sector is generally structured around linear processes, where products are purchased, stored, processed, served, and consumed, with few opportunities for recirculation or circularity in the system.

The Ho.Re.Ca. sector presents distinct behaviorus compared to large-scale retail, in terms of product demand, mix variability, and order volumes. Orders in Ho.Re.Ca. are typically smaller and more fragmented, introducing additional logistical complexity. Unlike retail supply chains, where products are often transported in single-product unit loads, Ho.Re.Ca. logistics involves more mixed and partial loads, increasing operational complexities and challenges. As a result, existing studies on reusable secondary packaging cannot be directly applied to this sector and must be adapted to reflect its specific features. Reuse schemes should therefore be carefully assessed in each context, taking into account the unique characteristics and stakeholders involved in the Ho.Re.Ca. supply chain.

To address this gap, this study develops a Operational Packaging digital Twin (OPT) that leverages primary data on the network's configuration, such as facilities locations and transportation distances in between, alongside real product and package ordering profiles from and to a Food Service Distributor (FSD) operating in the Ho.Re.Ca. sector. This tool enables virtualizing the logistic operations performed within a observation time horizon (e.g., a month, a year). OPT allows for comparing the carbon footprint of reusable crates versus single-use containers (either paper- or plastic-based) for fresh products like fruits and vegetables. As required in LCA, this tool compels setting the system boundaries which typically include production, end-of-life, washing operations for reusable packaging, and transportation and distribution logistics activities, thanks to an integrated methodology. As a result, OPT quantifies logistics and carbon footprint indicators to aid objective assessment of secondary packaging choices and reuse strategies within a given industrial case, acting as a Decision Support Tool (DST) for different Ho.Re.Ca. stakeholders.

This work contributes to the growing debate on reusable packaging systems by addressing two research questions that remain unexplored in the context of Ho.Re.Ca. supply chain network:

- RQ.1 How do decisions on reusable vs. disposable packaging at the actor level influence the environmental footprint of the entire Ho.Re.Ca. distribution system?
- RQ.2 How can a DSS tailored to a given industrial case aid environmentally sustainable secondary packaging decisions?

Virtualizing the operational and logistics dynamics of a FSD, OPT supports decision-making for sustainable packaging strategies using carbon footprint assessment (i.e., crates production, washing and end-of-life) throughout specific agri-food supply chain environments. It quantifies environmental metrics and indicators based on primary data such as demand profiles, network distances, product and package flows, the facilities locations for all actors involved.

The novel contribution of this paper lies in the comparative evaluation of packaging-driven distribution systems for fresh produce in the Ho.Re.Ca. sector, comparing different packaging alternatives such as disposable, reusable, and hybrid configurations. The remainder of the paper comprises a methodological outline in Section 2, the presentation of the case study and results in Section 3. Section 4 includes discussions, while conclusions are drawn in Section 5.

## 2. Materials and method

In this study, a tool named OPT is developed in Matlab to virtualize a fresh produce supply chain and assesses the carbon footprint associated with different secondary packaging strategies. OPT enables the comparison of various packaging scenarios, including Reusable Crates (RCs), single-use options in plastic or cardboard (i.e., Disposable Crates, DCs), and mixed configurations in which some products are packed in plastic and others in cardboard, an arrangement frequently adopted by companies engaged in order picking and fresh produce distribution. In addition, the tool also allows the evaluation of mixed configurations, in which certain logistics flows are managed with reusable crates while others rely on disposable solutions, reflecting real transitioning networks from single-use to reusable packaging systems.

Packaging choice has a direct influence on the configuration of the supply chain, particularly regarding the types of actors involved, the transport routes, and the volume of goods moved along these routes. In the case of reusable packaging, the conventional linear model of production, distribution, and disposal must be restructured to incorporate reverse logistics operations.

### *2.1. Network complexities*

This study considers the perspective of a *FSD*, for which real inbound and outbound flow data are available. This enables a fully data-driven virtualization of the supply chain. Specifically, the FSD receives inbound palletized goods, where fresh produce arrives on unit loads of homogeneous secondary packaging units. These unit loads are then unpacked to aid picking operations, allowing the FSD to reassemble new units tailored to the fragmented demand of Ho.Re.Ca. clients. In the large-scale retail channel, the high sales volumes and consolidated customer demand allow outbound shipments to be organized using homogeneous secondary packaging units, each containing a single product type. In contrast, the Ho.Re.Ca. sector is characterized by smaller, highly fragmented orders that require the assembly of mixed tertiary packaging units (e.g., palletized unit loads and roll containers). These tertiary units often include products packed in different crates and mixed-product crates, also called *Fractional* Products Crates (FPC). When the requested quantity of a given product is smaller than a full crate, operators extract products from inbound homogeneous crates, weigh the exact quantity requested, and consolidate these fractional quantities into new crates specifically dedicated to this purpose, which end up containing different products in small quantities. As a result, outbound logistics units directed to Ho.Re.Ca. clients typically consist of a combination of homogeneous single-product crates and heterogeneous FPCs containing customized assortments of different items below the standard packaging thresholds.

This operational environment, which reflects the actual practices of a FSD handling fractional picking, is modelled in both reusable and single-use packaging systems. The proposed methodology differs from many literature studies, which typically apply RCs within large-scale retail distribution, where order profiles and packaging requirements are more standardized.

### 2.2. Supply chain actors

Fig. 1 illustrates the logistics network configuration, comparing the RCs network (green arrows) with the DCs network (red arrows). Single-use packaging, whether made of paper or plastic, typically involves actors operating within a linear supply chain model, characterized by a reduced number of stakeholders and processing stages compared to reusable packaging supply chains. Packaging is produced by specialized *Packaging Producers* and sent directly to *Farmers*, who fill the units with fresh product and assemble the inbound unit loads shipped to the *FSD*. The *FSD* also receives empty crates from the *Packaging Producers*, specifically intended for the assembly of fractional orders. During picking operations, the *FSD* prepares outbound flows tailored to customer demand. Given the characteristics of the Ho.Re.Ca. sector, the relatively small order volumes and daily delivery frequencies often allow the grouping of multiple customers within a single transportation route, optimizing distribution efficiency. Once delivered, single-use packaging must be disposed of, as it cannot be reused for food-grade applications.

As highlighted by green arrows in Fig. 1, when reusable packaging is adopted, supply chain complexity increases due to the integration of reverse logistics. In the modelled network, reusable crates are assumed to be already available in dedicated warehouses, reflecting a steady-state scenario in which the system is fully operational. As such, the initial production of crates is not accounted for, and the role of the Packaging Producer is limited to replacing lost or damaged units based on predefined *Breakage Probability*.

From a network perspective, RCs reach the *Farmers* from dedicated *RC Warehouses*, where previously used and sanitized units are stored and deemed suitable for new food-grade applications. Once filled with fresh produce, the crates are shipped to the *FSD*, which, as in the case of single-use packaging, unpacks them and performs picking operations to assemble heterogeneous tertiary loads tailored to Ho.Re.Ca. customer demand. These mixed loads are delivered daily via optimized distribution routes.

After delivery and once emptied of their content, the crates enter the reverse logistics loop. Typically, once per week, during scheduled delivery rounds, the trucks collect empty crates accumulated over the previous days from Ho.Re.Ca. clients. The collected units are returned to the *FSD* facility and subsequently transferred to the closest *RC Warehouse*, which oversees the reintegration of returned crates into the system.

At the *RC Warehouse*, incoming crates are inspected. Approximately 50 % are sent to *Washing Centers* before re-entering circulation, while the remaining units, if clean and undamaged, can be redistributed without further processing. During the intake process, broken crates are also identified. *Breakage Probability* can vary depending on the *Packaging Producer* and the overall management system, but typically at least 1 %

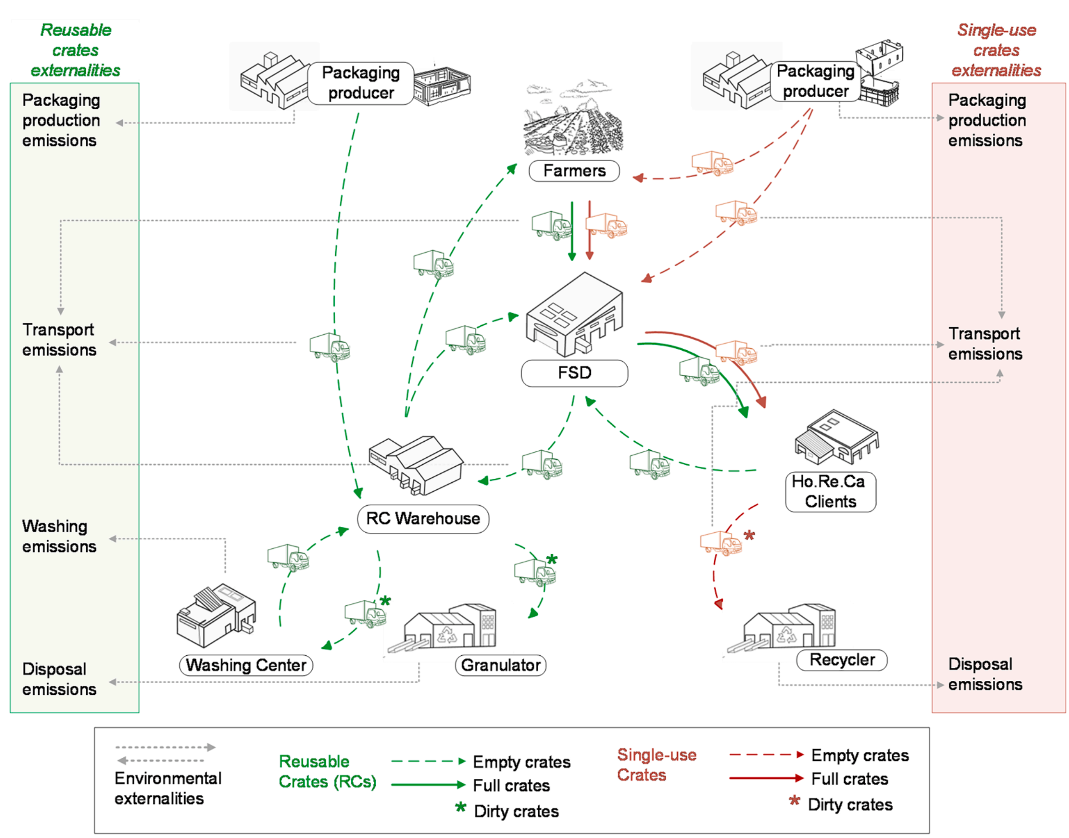


**Fig. 1.** RCs and DCs logistic connections.

of crates are returned damaged. These are sent to a *Granulator* facility, where the plastic material is recovered and reused in the production of new crates. To maintain the operational stock of RCs, damaged units are replaced with new crates supplied by the *Packaging Producer*. Once restocked, the crates are stored in the *RC Warehouse*, waiting to be redistributed to *Farmers* and other stakeholders throughout agri-food supply chains.

From an environmental perspective, each use cycle is assigned a proportional share of the impacts related to crate production, End of Life (EoL) treatment, and washing, regardless of whether the specific crate is reused, washed, or discarded after use. These impacts are calculated based on average reuse cycles and operational parameters defined by the reusable crate provider, whose logistics are optimized at a broader system level. The quantitative impact values associated with production, EoL, and washing processes for DCs and RCs are derived from commercial life cycle assessment databases. These datasets provide standardized, process-level environmental metrics. By combining these values with key operational parameters, such as crate *Breakage Probability* and *Washing Rate*, the tool evaluates the environmental footprint of supply chain operations with an integrated and scalable approach.

### 2.3. Operational packaging digital twin

Fig. 2 illustrates the logical workflow embedded in the OPT tool, which enables the modeling of daily operations under different packaging management scenarios. Users can select among three alternative configurations of the packaging-driven distribution network:

- DC-DC: Only DCs are used throughout the supply chain.
- RC-RC: Only RCs are used, with both inbound and outbound flows handled via RCs.
- DC-RC: In this mixed configuration, products arrive at the FSD in DCs but are redistributed to customers using RCs.

The third scenario holds particular relevance for real-world industrial applications, especially during the early phases of transitioning from DCs to RCs. In this context, reusable packaging is often required by Ho.Re.Ca. *Clients* for both environmental reasons and operational convenience, as these crates do not require disposal after use. However, *Farmers* and food producers face greater barriers to adopting reusable packaging due to their specific requirements (e.g., crate dimensions, load-bearing capacity), long-standing relationships with DCs suppliers, and organizational inertia. As such, the mixed scenario (DCs-RCs) also represents a plausible transitional configuration, wherein reusable packaging is first adopted for outbound flows and only later extended upstream to suppliers.

Beyond packaging type, the tool enables the user to vary key system parameters highlighted in the bottom part of Fig. 2, including:

- *RCs Breakage Probability*: This defines the probability that a RC becomes damaged during a use cycle and must be discarded (i.e., sent to the Granulator), triggering the production of a replacement unit to maintain stock balance. This rate is supposed to vary between 1 % and 5 %
- *DCs Paper Share*: Specifically, the share of cardboard versus plastic can range from 0 % to 100 %. Exploring this variable allows for environmental comparisons among different single-use packaging, depending on the crate composition.

The ultimate goal of the simulation is to generate a structured table representing daily crate flows over the simulated time period. A schematic example of this table is shown on the right side of Fig. 2. For each pair of interacting stakeholders, the table reports the number of crates (by type), the weight of crates, the weight of food transported, and the travel distance. These data serve as the basis for subsequent environmental assessment.

At the core of the simulation lies a set of input data extracted from

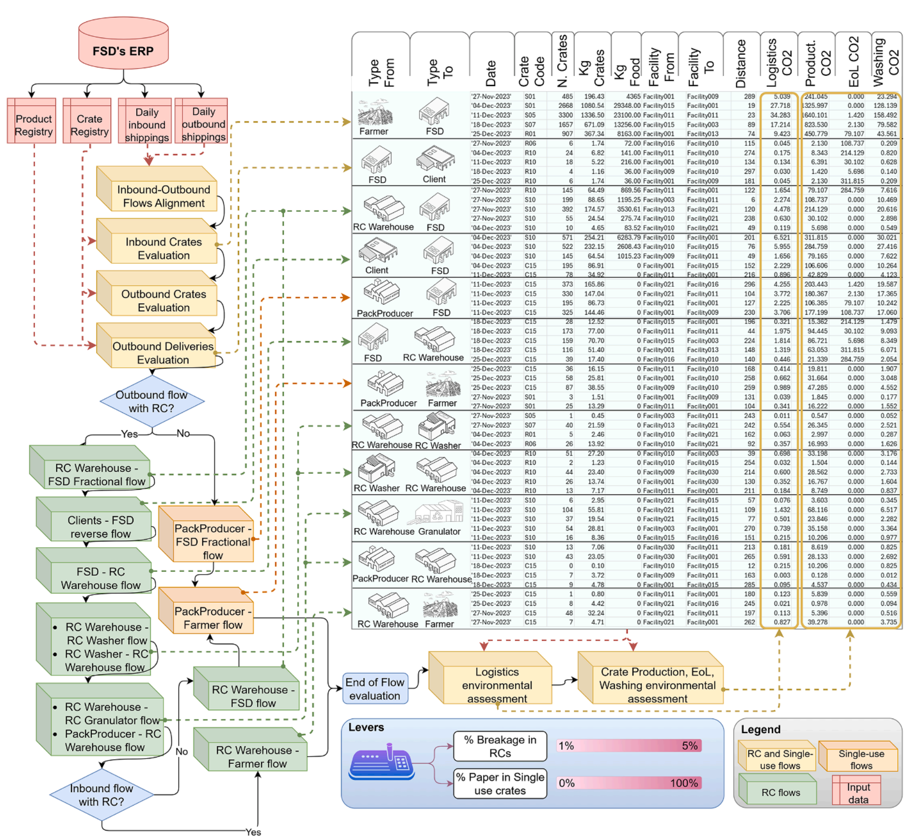


**Fig. 2.** OPT logics and data flow.

the company's Enterprise Resource Planning (ERP), highlighted in red in the top-left corner of Fig. 2. These include master data on products and packaging types (both currently in use and potentially available), as well as records of inbound and outbound flows. Inbound flows consist of batches delivered by *Farmers* to the *FSD*, typically as mono-product pallets, scheduled according to product seasonality. Outbound flows are defined by Ho.Re.Ca. orders, which consist of multiple order lines, each specifying a product and quantity. As said before, these quantities often do not correspond to full crate units, requiring FPCs management.

These data are processed in OPT tool to standardize the flows and calculate the daily volumes and weights of crates and food moved. Functional blocks presented in the scheme of Fig. 2 follow a color-coding logic: the yellow blocks contain general-purpose functions applicable to both DC and RC systems, the red blocks are specific to DCs, and the green blocks are exclusive to RCs operations.

The first function, *Inbound–Outbound Flows Alignment*, ensures consistency between incoming product batches and outgoing order lines, generating a "clean" flow dataset for subsequent calculations. Next, the *Inbound Crates Evaluation* quantifies, for each daily inbound batch, the number of crates used, their total weight, and the amount of food transported. Similarly, *Outbound Crates Evaluation* computes the same metrics for outbound flows. Outbound flows are then grouped into delivery routes by the *Outbound Deliveries Evaluation* function. At this point, the workflow diverges depending on the selected packaging configuration. If the outbound flow from FSD uses DCs, then this is the DC-DC scenario. The function *PackProducer–FSD Fractional Flow* calculates the flow of DCs needed for fractional orders, while *PackProducer–Farmer Flow* determines the number of crates required by farmers to meet inbound volumes. This ends the flow evaluation phase for the DC-DC scenario.

If RCs are used for outbound deliveries, a chain of functions is triggered to simulate the closed-loop packaging system. These include the delivery of RCs from the *RC Warehouse* to the *FSD* for fractional picking, the collection of empty crates from customers back to the FSD, and the transfer of used crates to the *RC Warehouse* where crates may be sent to *Washing Centers* or *Granulators*. Meanwhile, new crates from the *Packaging Producer* are delivered to compensate for breakage.

If RCs are used for outbound deliveries, the system further distinguishes between inbound DCs and RCs scenarios: if inbound flows are also in RCs, the tool calculates the required RCs deliveries from *RC Warehouse* to *Farmers*; If inbound flows are in DCs, the function *RC Warehouse–FSD Flow* computes the number of RCs needed at the FSD to transfer food from DCs to RCs before delivery. Meanwhile, DCs delivered to *Farmers* by the *Packaging Producer* are also quantified.

Once all crate movements (full or empty) have been quantified, the tool proceeds to the environmental evaluation phase. The *Logistics Environmental Assessment* function assesses the emissions associated with crate transport based on travel distances and flow volumes, while the *Crate Production, EoL, and Washing Environmental Assessment* function estimates the impacts of crate manufacturing, EoL treatment, and washing operations (applicable only to RCs).

## 3. Case study

The development of the OPT tool leverages real operational flow data from a *FSD*. This approach enabled an accurate modeling of the logistics processes involved in the distribution of fruits and vegetables within the Ho.Re.Ca. sector. Despite its grounding in a specific case study, the tool remains flexible and adaptable to similar contexts. The data-driven methodology allowed for the integration of key features and specificities typical of these supply chains, supporting the validation of the OPT through a real-world application. The presented case study illustrates how data guided the tool's development, demonstrating its practical implementation, benefits, and achievable outcomes.

The FSD, whose operational inbound and outbound flow data were used in this study, is located in Bologna, and the majority of its Ho.Re.Ca. customers are concentrated in the Emilia-Romagna region. This is illustrated in Fig. 3, which shows the geographic distribution of clients and a heatmap of demand intensity across the network area. The FSD supplies 302 customers with a total demand covering 289 product codes.

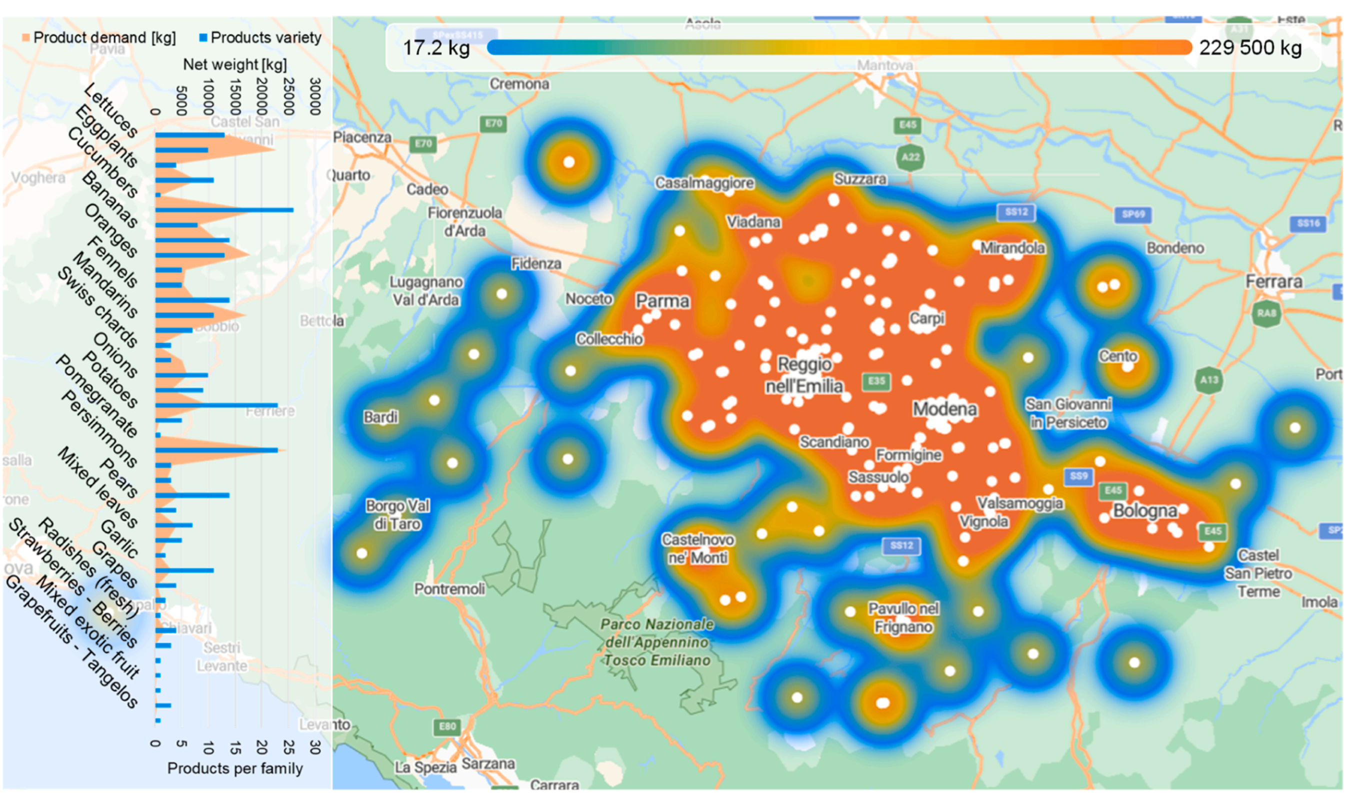


**Fig. 3.** Client distribution and Fresh produce demand. Demand time horizon: 27/11/2023 – 01/01/2024.

These product codes are grouped into 40 product families, each consisting of multiple individual items. On the left side of Fig. 3, the area chart illustrates the demand volume for each product family over the case study period, which spans approximately the month of December 2023, while the accompanying bar chart indicates the variety of products within each family, measured by the number of distinct product codes.

While product demand from customers is concentrated in the Emilia-Romagna region, supply from farmers is distributed across the entire country. The availability of each product is influenced by the climatic conditions specific to each region. Fig. 4 shows the locations of 88 farmers. On the bottom-left, it displays the supply of oranges, mandarins, lemons, apples, and pears, with bubble size indicating the monthly quantity (in kg) shipped to the foodservice distributor. As expected, the production of oranges, mandarins, and lemons is predominantly located in Southern Italy, while the production of apples and pears is concentrated in the Northern regions due to climate-related factors. Fig. 4 (right) shows the daily shipment flows from *Farmers* to the *FSD*. The visualization highlights the operational dynamics modeled within the system: shipment volumes vary across days, reflecting fluctuations in demand from Ho.Re.Ca. customers.

Currently, fresh produce is handled using DCs, which follow a linear logistics model (red flows in Fig. 1). The company's ERP system was analyzed to identify the DCs currently in use. This system monitors the operations of the foodservice distributor, including inbound shipments from farmers. However, it only tracks volumetric information related to the crates, without recording their *Paper Share*. To address this limitation, crate weights for both paper and plastic versions were estimated for each crate type based on field measurements. As a result, each specific crate exists in both paper and plastic versions. This assumption increases the flexibility of the tool, allowing users to define the proportion of crates made of paper versus plastic. This feature reflects real-world conditions, as the dominance of paper or plastic crates tends to be case-specific and varies across different FSDs. This assumption is implemented as a user-defined parameter in the simulation tool.

Table 1 provides a complete list of the DCs, their best RC counterpart (selected from Table 2), and details on their external dimensions (width, depth, height). The DC-RC matching is based on volume similarity, to ensure that the selected RC can accommodate a comparable amount of product.

Thanks to the availability of data from the company’s ERP system, it is possible to access the outbound delivery routes assigned to a single transport vehicle. Under a set of specific assumptions, this allows the reconstruction of the reverse logistics loop for reusable crates. The following assumptions are adopted to model the reverse flow:

- RCs are collected from clients once per week. Specifically, during Monday deliveries, the logistics operator also collects the crates used by clients during the previous week and returns them to the FSD.
- The FSD ships the collected reusable crates to the *RC Warehouse* once per month. The *RC Warehouse* is then responsible for RCs management, including sorting for washing, damage, or storage. Under the responsibility of the RC managing company, RCs operations benefit from the economies of scale of such a broader system.
- It is assumed that, due to economies of scale, the RC operator can consolidate shipping from multiple facilities into full truckloads. Therefore, only a share of the total shipping carbon footprint is attributable to the *FSD*.
- It is assumed that all flows managed by the RC operator (*RC Warehouse* to *Washing Center*, RC *Warehouse* to *Granulator*, and *Washing Center* to *RC Warehouse*) are carried out on the same day the *FSD* sends crates to the *RC Warehouse*. These flows are included in the model to quantify the overall logistical and washing impacts, although their operational execution is not the responsibility of the *FSD*.

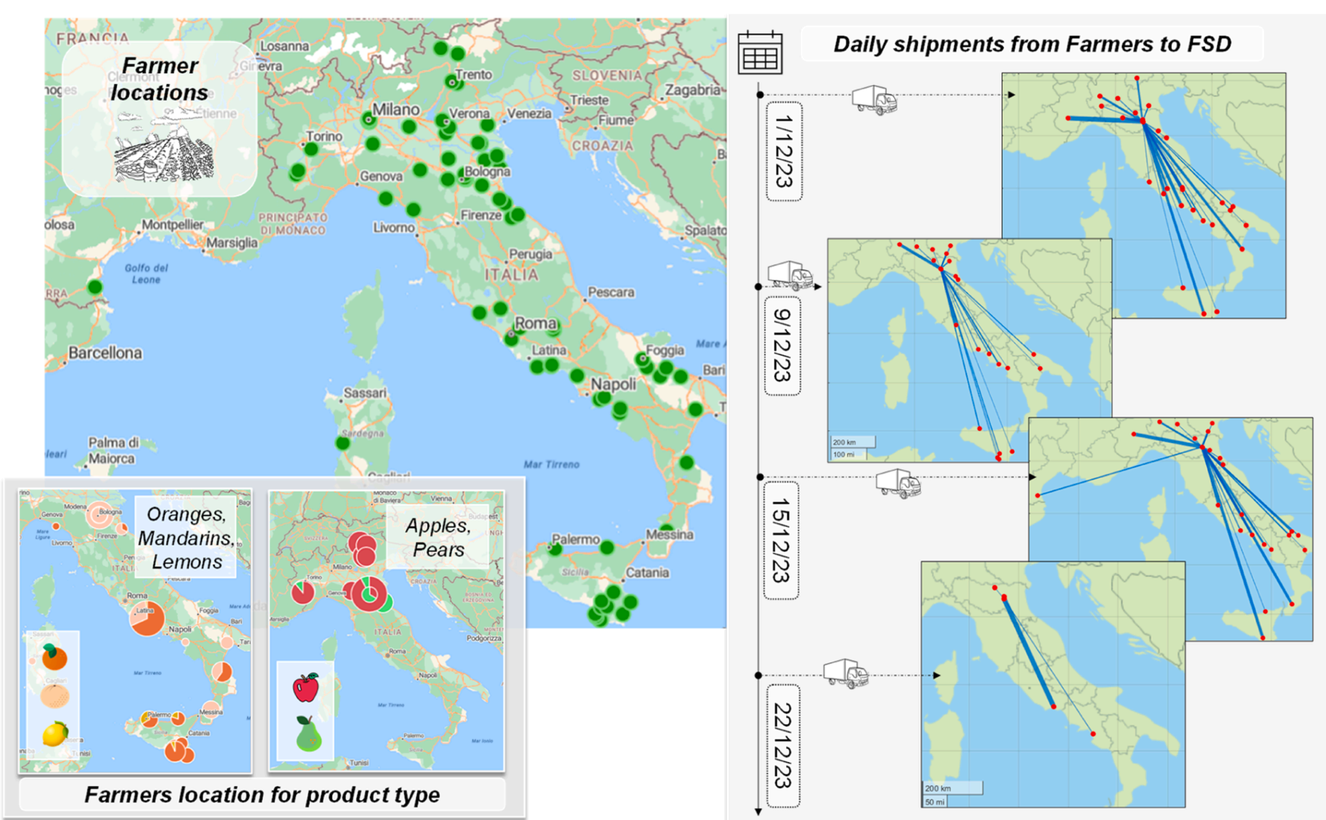


**Fig. 4.** Examples of supplier distribution in space and time.

**Table 1**
Disposable crates properties.

| Disposable crates (DCs) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| ID Crate Single use | ID Crate Associate Reusable Crate | Length [mm] | Width [mm] | Height [mm] | ID Crate Single use | ID Crate Associate Reusable Crate | Length [mm] | Width [mm] | Height [mm] |
| *SC_01* | *RC_06* | 400 | 300 | 100 | *SC_28* | *RC_06* | 300 | 250 | 90 |
| *SC_02* | *RC_04* | 400 | 300 | 160 | *SC_29* | *RC_06* | 400 | 250 | 90 |
| *SC_03* | *RC_05* | 330 | 270 | 170 | *SC_30* | *RC_06* | 400 | 300 | 90 |
| *SC_04* | *RC_06* | 390 | 280 | 70 | *SC_31* | *RC_05* | 500 | 300 | 90 |
| *SC_05* | *RC_06* | 360 | 240 | 120 | *SC_32* | *RC_04* | 600 | 400 | 90 |
| *SC_06* | *RC_06* | 400 | 300 | 80 | *SC_33* | *RC_05* | 250 | 250 | 250 |
| *SC_07* | *RC_06* | 400 | 300 | 100 | *SC_34* | *RC_06* | 200 | 200 | 200 |
| *SC_08* | *RC_06* | 240 | 240 | 130 | *SC_35* | *RC_03* | 600 | 400 | 120 |
| *SC_09* | *RC_01* | 1200 | 1200 | 750 | *SC_36* | *RC_06* | 250 | 300 | 160 |
| *SC_10* | *RC_01* | 1000 | 1200 | 550 | *SC_37* | *RC_05* | 400 | 250 | 150 |
| *SC_11* | *RC_06* | 300 | 200 | 210 | *SC_38* | *RC_04* | 300 | 400 | 170 |
| *SC_12* | *RC_05* | 400 | 200 | 210 | *SC_39* | *RC_05* | 350 | 300 | 150 |
| *SC_13* | *RC_04* | 300 | 300 | 210 | *SC_40* | *RC_06* | 200 | 300 | 160 |
| *SC_14* | *RC_04* | 400 | 300 | 210 | *SC_41* | *RC_06* | 250 | 150 | 160 |
| *SC_15* | *RC_03* | 500 | 300 | 210 | *SC_42* | *RC_04* | 500 | 300 | 150 |
| *SC_16* | *RC_01* | 500 | 400 | 210 | *SC_43* | *RC_03* | 500 | 400 | 150 |
| *SC_17* | *RC_06* | 200 | 200 | 250 | *SC_44* | *RC_02* | 600 | 400 | 160 |
| *SC_18* | *RC_01* | 600 | 400 | 180 | *SC_45* | *RC_06* | 200 | 200 | 250 |
| *SC_19* | *RC_01* | 600 | 400 | 210 | *SC_46* | *RC_05* | 300 | 500 | 100 |
| *SC_20* | *RC_01* | 600 | 400 | 180 | *SC_47* | *RC_05* | 300 | 500 | 100 |
| *SC_21* | *RC_03* | 600 | 400 | 120 | *SC_48* | *RC_05* | 500 | 300 | 90 |
| *SC_22* | *RC_04* | 400 | 300 | 180 | *SC_49* | *RC_05* | 500 | 300 | 90 |
| *SC_23* | *RC_02* | 600 | 400 | 160 | *SC_50* | *RC_04* | 300 | 500 | 160 |
| *SC_24* | *RC_04* | 400 | 300 | 160 | *SC_51* | *RC_02* | 600 | 400 | 160 |
| *SC_25* | *RC_06* | 300 | 300 | 100 | *SC_52* | *RC_02* | 600 | 400 | 160 |
| *SC_26* | *RC_06* | 300 | 200 | 90 | *SC_53* | *RC_06* | 300 | 200 | 130 |
| *SC_27* | *RC_06* | 400 | 200 | 90 | | | | | |

**Table 2**
Reusable crates properties.

| Reusable crates (RCs) | | | | | |
|---|---|---|---|---|---|
| *ID Crate Reusable* | Length [mm] | Width [mm] | Height [mm] | *Unit weight [kg]* | *# of associations with single-use crates* |
| RC_01 | 600 | 400 | 227 | 1.83 | 6 |
| RC_02 | 600 | 400 | 176 | 1.66 | 4 |
| RC_03 | 600 | 400 | 160 | 1.5 | 4 |
| RC_04 | 600 | 400 | 115 | 1.38 | 9 |
| RC_05 | 400 | 300 | 176 | 1.07 | 10 |
| RC_06 | 400 | 300 | 115 | 0.85 | 20 |

- The shipment of clean and empty RCs for filling purposes takes place once per week. These shipments include the *RC Warehouse-Farmers* flow and the *RC Warehouse-FSD* (intended for the filling of FPCs)

The OPT tool enables the integration of environmental data from LCA studies, databases, and scientific literature. In this case, the entire analysis draws upon the dataset provided by [11]., which includes emission factors for the production, washing, and end-of-life stages. This study allowed for the estimation of emissions per use cycle for RCs, including production, washing, and disposal, as well as emissions related to the production and EoL of DCs made of paper and plastic. The RCs considered in this study are composed of raw materials sourced according to a specific formulation: 59 % virgin polymer, 39 % secondary (recycled) material, and 2 % coloring masterbatch. These percentages reflect actual production practices adopted by stakeholders in the sector.

Transport emission data are obtained from EcoTransIT World's emission calculation tool [20], which is certified according to the new ISO 14083 standard, and supported by [21] report.

The OPT allows for the simulation of the three packaging configurations previously described: RC–RC, DC–DC, and DC–RC. Two key parameters varied to account for more realistic operational conditions. The *Breakage Probability* of RC was tested at three levels: 1 %, 3 %, and 5 %, while the *Paper Share* of DCs was adjusted across five scenarios: 100 % paper, 75 % paper - 25 % plastic, 50 % paper - 50 % plastic, 25 % paper - 75 % plastic, and 0 % paper (fully plastic). Additionally, based on industry input, it was assumed that 50 % of RCs are washed after each use, corresponding to one cleaning cycle every two rotations, on average. A complete list of the simulated scenarios and the corresponding variable settings is presented in Table 3.

**Table 3**
List of variable settings for the simulated scenarios.

| Packaging Configuration | RCs *Breakage Probability* ( %) | DCs *Paper Share* ( %) |
|---|---|---|
| RC-RC | 1 % | / |
| RC-RC | 3 % | / |
| RC-RC | 5 % | / |
| DC-DC | / | 100 % |
| DC-DC | / | 75 % |
| DC-DC | / | 50 % |
| DC-DC | / | 25 % |
| DC-DC | / | 0 % |
| DC-RC | 1 % | 100 % |
| DC-RC | 1 % | 75 % |
| DC-RC | 1 % | 50 % |
| DC-RC | 1 % | 25 % |
| DC-RC | 1 % | 0 % |
| DC-RC | 3 % | 100 % |
| DC-RC | 3 % | 75 % |
| DC-RC | 3 % | 50 % |
| DC-RC | 3 % | 25 % |
| DC-RC | 3 % | 0 % |
| DC-RC | 5 % | 100 % |
| DC-RC | 5 % | 75 % |
| DC-RC | 5 % | 50 % |
| DC-RC | 5 % | 25 % |
| DC-RC | 5 % | 0 % |

## 4. Results

The analysis enables comparing how different packaging types influence the total number of crates required and the total kilograms transported to meet customer demand, with particular attention to the handling of fractioned products. Subsequently, the focus shifts to evaluating operational and logistics performance under varying packaging selections system levers (i.e., the *Breakage Probability* of RCs and the share of paper crates within the total number of DCs).

### 4.1. Crate volume and weight dynamics across packaging configurations

The OPT enables virtualizing the daily transport flows based on inbound and outbound data extracted from the company's ERP system. Depending on the scenario (DC-DC, DC-RC, RC-RC), the tool calculates the number of crates handled per day. A key element incorporated into the simulation is the management of FPCs, which requires additional handling steps and leads to a higher number of crates needed by the *FSD* to satisfy clients' demand. Thus, the system accounts for both the inbound crate used for product reception and the additional crate needed to accommodate small product quantities in FPCs. FPCs are supplied to the *FSD* either by the *Packaging Producer* (for DCs) or by the *RC Warehouse* (for RCs). This supply flow is managed on a weekly basis and is fully modeled within the simulation environment.

Fig. 5 illustrates the number of crates handled across the supply chain to meet food demand. The purple line represents the quantity of food (in kilograms) shipped daily from farmers to the *FSD* in response to customer demand. The bar chart in the upper part of the Fig. shows the number of crates handled in the network, according to the three different scenarios. The bar chart in the middle part displays the total weight (in kilograms) of crates moved throughout the system.

The graphs reveal that the overall crate volume remains relatively stable across the RC-RC and DC-DC configurations, despite the different nature of the flows. In contrast, the mixed DC-RC configuration results in a marked increase in the total number of crates circulating in the system. This is due to the coexistence of inbound disposable and outbound reusable flows, which do not offset each other but rather accumulate. All scenarios exhibit recurring weekly peaks associated with the scheduled delivery of crates for FPC handling. However, in the mixed configuration, these peaks are substantially amplified because, unlike the other configurations, the system must receive not only the crates for FPC but also an additional set of RCs to repack all outbound products that arrive in DCs.

While the number of crates handled in the disposable and fully reusable scenarios is comparable, this is not true for the total transported weight. Reusable crates are engineered for durability and extended life cycles, which entails more robust structures and a higher use of raw materials. As illustrated in the central bar chart, scenarios involving RCs result in a significantly higher transported weight compared to those based solely on disposable alternatives.

The line chart in the lower part of the Fig. illustrates the daily greenhouse gas emissions resulting from logistics, expressed in *kgCO₂eq*. This chart clearly shows that the higher weight of RCs results in greater daily transport-related emissions. In contrast, scenarios using only DCs exhibit the lowest transport-related environmental burdenLogistics emissions are modeled on a daily basis and computed using actual distances and real-world network configurations, rather than relying on average values. This allows companies to monitor their carbon footprint with high temporal and spatial granularity and to implement effective mitigation strategies.

The following analyses investigate whether this additional transported weight can be offset by the environmental benefits achieved through a lower per-use impact in the production and EoL phases of RCs.

### 4.2. Crate logistics in alternative packaging scenarios

This section analyzes the movement of crates among supply chain actors under three representative packaging scenarios. The analysis is

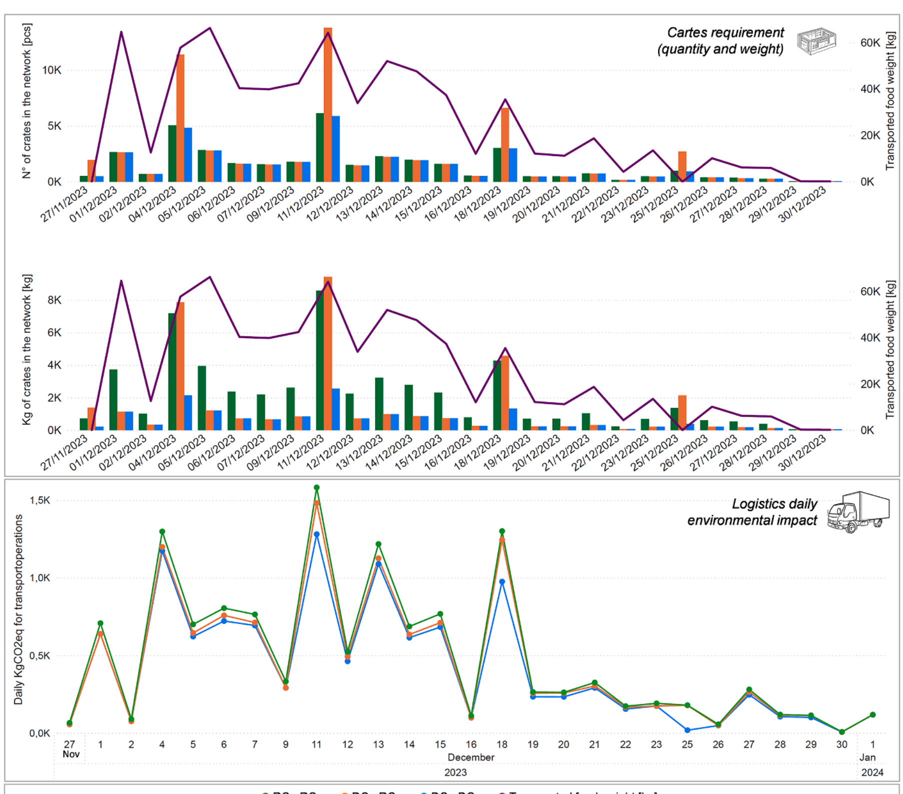


**Fig. 5.** Crates' requirement (N. of crates), required crates' weight (kg), and daily logistics impact (KgCO2eq).Time horizon: 27/11/2023-1/01/2024.

based on the configuration of flows shown in Fig. 6 and the data summarized in Table 4. The simulation was conducted over a one-month period (December 2023), involving 302 customers and 289 distinct product codes.

Fig. 6 presents a set of Sankey diagrams that visualize the crate flows in each scenario. Linear diagrams represent the direct outbound logistics of crates from the *Packaging Producer* (for DCs) or from the *RC Warehouse* (for RCs) to *Ho.Re.Ca. clients*. A circular Sankey diagram illustrates the complete reverse logistics loop in the RC–RC scenario, showing both inbound and outbound movements.

The three scenarios examined are:

- DC–DC: 25 % cardboard and 75 % plastic single-use crates;
- DC–RC: The same inbound composition as above, with outbound flows in reusable crates (1 % *Breakage Probability*);
- RC–RC: Fully reusable configuration with a 1 % *Breakage Probability*.

The values for crate composition and breakage reflect realistic, business-as-usual conditions. For clarity, each linear Sankey diagram is normalized so that the *FSD* always handles 100 % of the crate volume. Flows among other actors are scaled accordingly. Table 4 shows that, while outbound volumes remain similar across all scenarios (around 30,000 crates), the number of crates entering the *FSD* varies significantly depending on the packaging strategy. The DC–RC scenario requires handling 57.4 % more inbound crates than DC–DC, and 53.3 % more than RC–RC.

The diagrams also reveal how the system handles FPCs assembled at the *FSD*. In the DC–DC scenario, FPCs account for about 9,000 units, roughly 30 % of outbound crates, while the remaining 70 % are homogeneous (single-product) crates. These FPCs are created by unpacking approximately 7,000 inbound crates, which are then redistributed into mixed units. In the RC–RC scenario, by contrast, FPCs are preassembled and delivered directly from the *RC Warehouse* to the *FSD*. They represent 28 % of total outbound crates, while 72 % are routed directly to clients without repacking.

**Table 4**
Logistics crates flow (Number of moved crates).

| | DC - DC | DC – RC | RC – RC |
|---|---|---|---|
| *FSD* input (N° of crates) | 37.1 K | 58.4 K | 38.1 K |
| *FSD* output (N° of crates) | 29.9 K | 30.4 K | 30.4 K |
| FPC* *Total N° of RCs in the system in the DCs-RCs scenario* | 9.0 K | 30.3 K* | 9.5 K |

The circular Sankey diagram illustrates this added complexity of RCs logistics. It shows the RC–RC loop in a balanced structure, with the upper half depicting outbound flows from each node and the lower half representing inbound flows. Each actor is split into input and output components, and the two halves are perfectly balanced, as total inbound flows equal total outbound flows over the considered time horizon.

### 4.3. Environmental logistic comparison among scenarios

Fig. 7 presents the percentage breakdown of the logistics-related carbon emissions profile across the three representative packaging scenarios introduced earlier. Each pie chart illustrates the contribution of different transportation flows within the supply chain, categorized by the type of actor pair involved (e.g., *Farmer* to *FSD, FSD* to *Client*). While

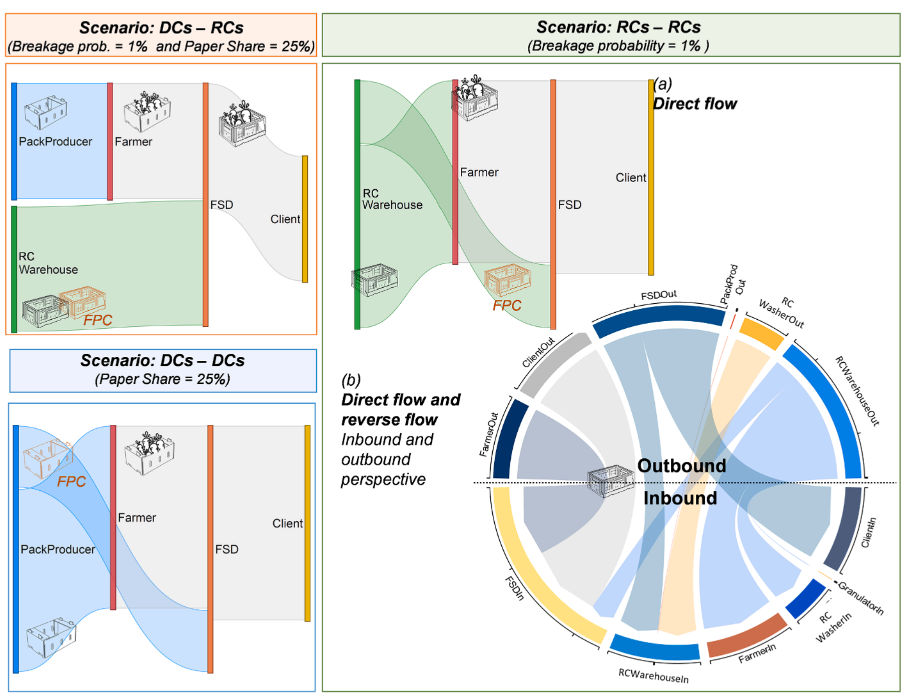


**Fig. 6.** Crates' volume flows in different packaging configurations.

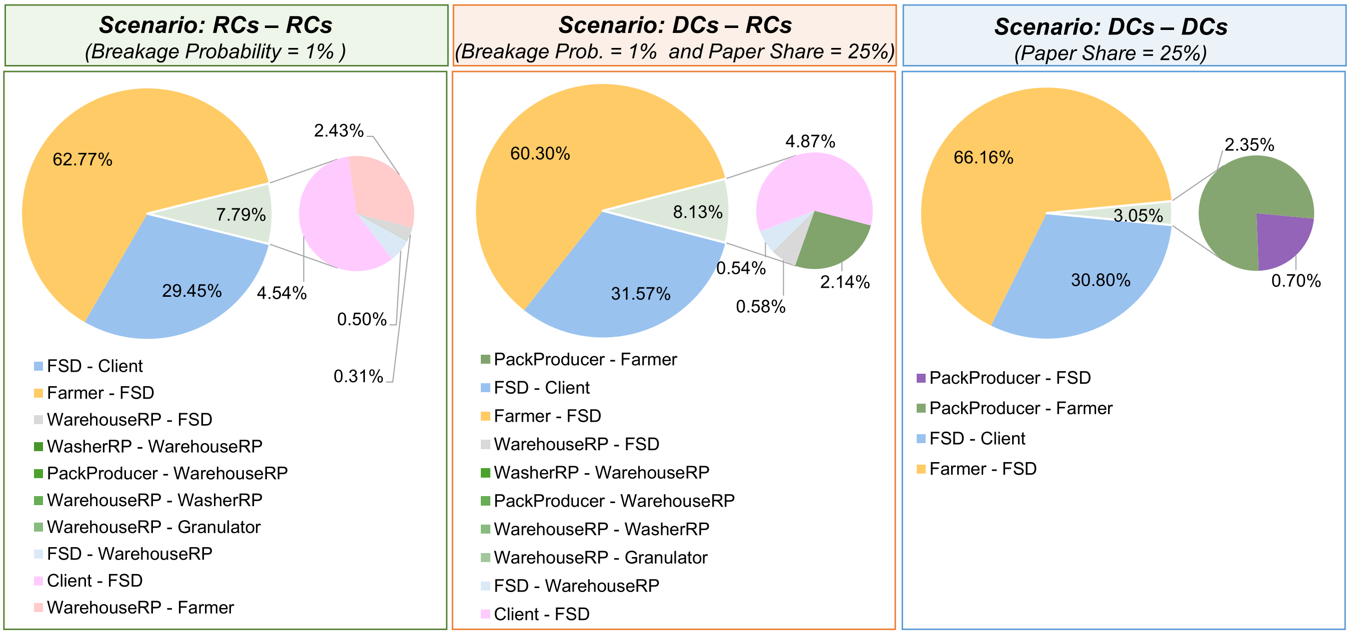


**Fig. 7.** Logistic carbon footprint components of three scenarios.

**Table 5**
From-to table of logistics impact (kgCO2eq) in the RCs-RCs scenario. Time horizon: 27/11/2023 – 01/01/2024.

| RCs-RCs (Washing Rate = 50 % and Breakage probability=1 %) | | | | | | | |
|---|---|---|---|---|---|---|---|
| | *Clients* | *Farmers* | *FSD* | *Granulator* | *RC Warehouse* | *WasherRP* | *Total* |
| *Clients* | | | 591.75 | | | | *591.75* |
| *Farmers* | | | 8180.98 | | | | *8180.98* |
| *FSD* | 3838.05 | | | | 65.32 | | *3903.37* |
| *PackProducer* | | | | | 0.03 | | *0.03* |
| *RC Warehouse* | | 316.79 | 41.03 | 0.11 | | 0 | *357.92* |
| *WasherRP* | | | | | 0 | | *0* |
| *Total* | *3838.05* | *316.79* | *8813.76* | *0.11* | *65.35* | *0* | *13034.06* |

**Table 6**
From-to table of logistics impact (kgCO2eq) in the DCs-DCs scenario. Time horizon: 27/11/2023 – 01/01/2024.

| DCs – DCs (Paper Share = 25 %) | | | | |
|---|---|---|---|---|
| | *Clients* | *Farmers* | *FSD* | *Total* |
| *Farmers* | | | 7329.72 | *7329.72* |
| *FSD* | 3412.09 | | | *3412.09* |
| *PackProducer* | | 260.27 | 77.15 | *337.43* |
| *Total* | *3412.09* | *260.27* | *7406.87* | *11079.23* |

these charts provide a relative distribution, the corresponding absolute impact values can be found in Table 5, Table 6, and Table 7, which also report total impacts per stakeholder and per scenario.

It is important to note that, although the pie charts are normalized, the total absolute impact varies significantly across scenarios. As shown in the tables, the RC–RC scenario is the most logistically impactful, whereas the DC–DC scenario results in the lowest emissions. This difference is primarily due to the additional reverse logistics activities required for reusable crates, which involve more stakeholders, additional trips, and longer transportation distances. Furthermore, RCs are heavier than single-use alternatives, leading to higher emissions per kilometer transported.

The dominant contributors to logistics-related impacts across all scenarios are the *Farmer*-to-*FSD* routes (accounting for 60–66 % of total impact) and the *FSD*-to-*Client* routes (29–32 %). These flows involve the transportation of full crates containing fresh produce, resulting in higher overall weights and greater emissions. Additionally, these routes involve a high number of geographically dispersed actors, particularly on the supplier side. As shown earlier (Fig. 4), suppliers are spread across the

**Table 7**
From-to table of logistics impact (kgCO2eq) in the DCs-RCs scenario. Time horizon: 27/11/2023 – 01/01/2024.

| DCs – RCs (Washing Rate = 50 %, Breakage Probability=1 % and Paper Share = 25 %) | | | | | | | |
|---|---|---|---|---|---|---|---|
| | *Clients* | *Farmers* | *FSD* | *Granulator* | *RC Warehouse* | *WasherRP* | *Total* |
| *Clients* | | | 591.75 | | | | *591.75* |
| *Farmers* | | | 7329.72 | | | | *7329.72* |
| *FSD* | 3838.05 | | | | 65.32 | | *3903.37* |
| *PackProducer* | | 260.27 | | | 0.03 | | *260.30* |
| *RC Warehouse* | | | 70.43 | 0.11 | | 0 | *70.54* |
| *WasherRP* | | | | | 0 | | *0* |
| *Total* | *3838.05* | *260.27* | *7991.90* | *0.11* | *65.35* | *0* | *12155.69* |

entire Italian territory, and their shipments of full crates to the *FSD* contribute significantly to total emissions due to the long distances involved.

In the RC–RC scenario, the outbound flow of RCs is followed by a reverse flow from *Clients* back to the *RC Warehouse*. Although these return flows involve empty crates, they still contribute nearly 5 % of total logistics emissions, as they require dedicated trips over medium distances. In contrast, in the DC–DC scenario, reverse logistics is absent: only about 3 % of the total logistics impact is associated with the transportation of empty DCs from the *Packaging Producer* to supply chain nodes. In this case, 97 % of the logistics impact is directly linked to core supply chain operations (i.e., transporting filled crates from *Farmers* to *Clients,* routed through the *FSD*) since single-use crates are disposed of after delivery to the end user. By comparison, in scenarios involving RCs, reverse logistics operations (e.g., collection, washing, storage, redistribution, regranulation) can account for more than 8 % of the total logistics impact. These findings highlight how system complexity and crate design choices influence not only material impacts but also transportation-related emissions.

### 4.4. Multi-scenario analysis of alternative packaging systems

This section presents and discusses the multi-scenario analysis conducted on the configurations listed in Table 3. The goal is to evaluate how the system's environmental performance changes across the three packaging strategies (DC-DC, RC-RC, and DC-RC) as a function of two key parameters: the *Breakage Probability* of RCs and the *Paper Share* of DCs, defined by the share of paper versus plastic.

#### 4.4.1. Comparative environmental analysis

Fig. 8 (left) shows a scatter plot where each point corresponds to one simulated scenario. The vertical axis represents the total greenhouse gas emissions, while the two horizontal axes capture the variation in RC *Breakage Probability* and paper content in DCs. The results clearly indicate that RC-RC scenarios (in yellow) consistently provide the best environmental performance, with lower emissions than all other configurations across the entire parameter space. In contrast, DC-DC scenarios (in blue) always result in the highest environmental burden. The hybrid DC-RC configuration generally performs in between, though its performance is much closer to DC-DC than to RC-RC. Notably, the advantage of DC-RC over DC-DC is not uniform. It depends strongly on the scenario conditions: when the share of paper in single-use crates is very high and the RC *Breakage Probability* reaches 5 %, the environmental difference between the two becomes minimal. This highlights the sensitivity of the system's relative performance to both variables.

All three configuration types exhibit clear linear trends. As expected, DC-DC scenarios show a linear relationship with paper share. RC-RC scenarios behave oppositely, showing linear sensitivity to *Breakage Probability*. In contrast, DC-RC scenarios are influenced linearly by both parameters. To further investigate these dynamics, interpolated planes were generated for each configuration group and are shown in the right panel of Fig. 8. These surfaces make it possible to identify the boundaries in the parameter space where the environmental performance of different configurations becomes equivalent.

Interestingly, the RC–RC configuration remains the most sustainable option across a wide range of conditions, but this advantage erodes as the *Breakage Probability* increases. Equation (1) formalizes this threshold by representing the intersection line between the RC–RC and DC–DC planes. It provides a decision-support reference for determining, given any specific paper–plastic composition of DCs, the maximum RC *Breakage Probability* under which reusable solutions remain environmentally advantageous.

$$Break\ \%_{RC} = -0.1213 * Paper\ \%_{DC} + 0.2432 \quad (1)$$

For example, with a full-paper DC hypothesis ($Paper\ \%_{DC} = 100\ \%$), the threshold for the *Breakage Probability* results in 12.2 %. This means the DC-DC scenario is favorable when DC are 100 % paper-made and RC *Breakage Probability* is greater than 12.2 %, which corresponds to an average of 8.33 use cycles per crate.

It should be emphasized that this result is context-specific and cannot be generalized. The findings are directly shaped by the characteristics of the case study, including the structure of the logistics network, the operational requirements of Ho.Re.Ca. clients, and the specific types of crates available in this industrial setting.

#### 4.4.2. Analysis of environmental burden by life cycle stage

Fig. 9 presents a matrix of bar charts illustrating the environmental performance of each scenario, broken down by impact category: production, EoL, washing, and logistics. Each column represents a different level of DCs Paper Share, while each row corresponds to a specific RCs *Breakage Probability*. The Fig. reveals that two components are predominant across scenarios. The first is logistics, which, although variable across configurations as shown in the Results section, remains a consistently significant contributor in all scenarios. The second is the impact associated with crate production, which dominates in scenarios involving single-use crates (i.e., DC–DC and DC–RC). This observation supports the results discussed in Fig. 8, where RC–RC configurations consistently achieved the lowest overall emissions. Despite their higher logistical footprint, the advantage of RC–RC scenarios clearly stems from the markedly lower impact attributed to crate production.

While RCs are, in absolute terms, more environmentally intensive to manufacture than DCs, their extended reuse over multiple cycles significantly dilutes this impact. The share of production impact allocated to each usage cycle is proportional to the *Breakage Probability*. For instance, with a *Breakage Probability* of 1 %, a crate is expected to be used 100 times before disposal. As a result, each use carries only one-hundredth of the production and end-of-life impact, while the impact of washing depends on the *Washing Rate*, which was set at 50 % for all

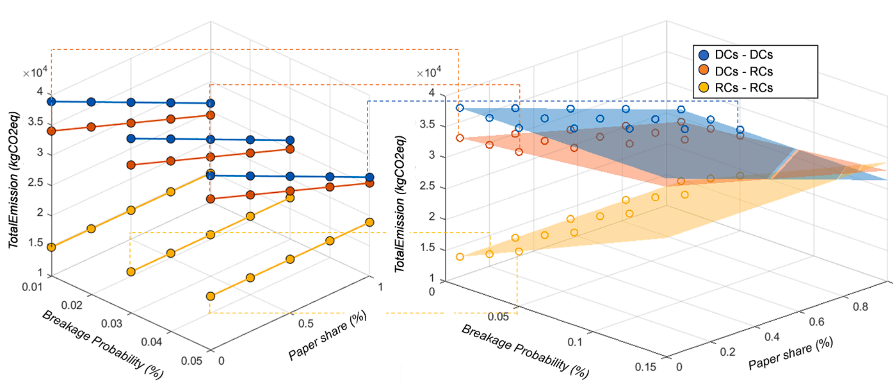


**Fig. 8.** Total emissions scenarios' comparison.

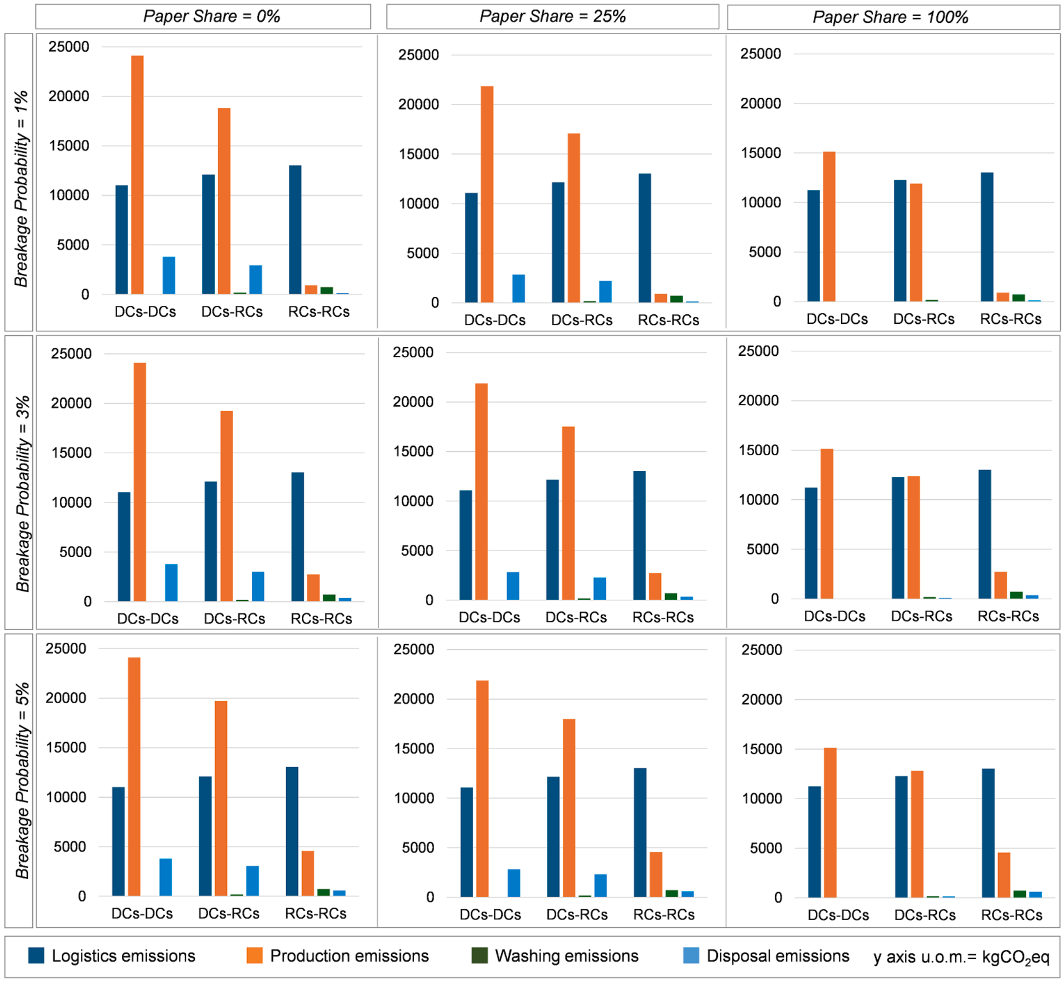


**Fig. 9.** Emission components for different scenarios.

scenarios shown in Fig. 9, meaning only half of the returned crates are washed after each use.

The Fig. also confirms that, as RC *Breakage Probability* increases, RC–RC scenarios show higher impacts in both the production and end-of-life categories. Conversely, increasing the share of paper in DCs leads to a clear reduction in the production-related impacts of scenarios involving single-use crates, indicating that paper represents a more sustainable alternative to plastic in disposable applications. However, this substitution is not universally viable due to material constraints, particularly in relation to weight and mechanical resistance requirements for certain products.

#### 4.4.3. Carbon footprint assessment under full reuse scenario

Fig. 10 presents the overall environmental burden analysis for the RC–RC scenario, in which all crates used in the supply chain are reusable. The red dots represent the total impact values of simulated

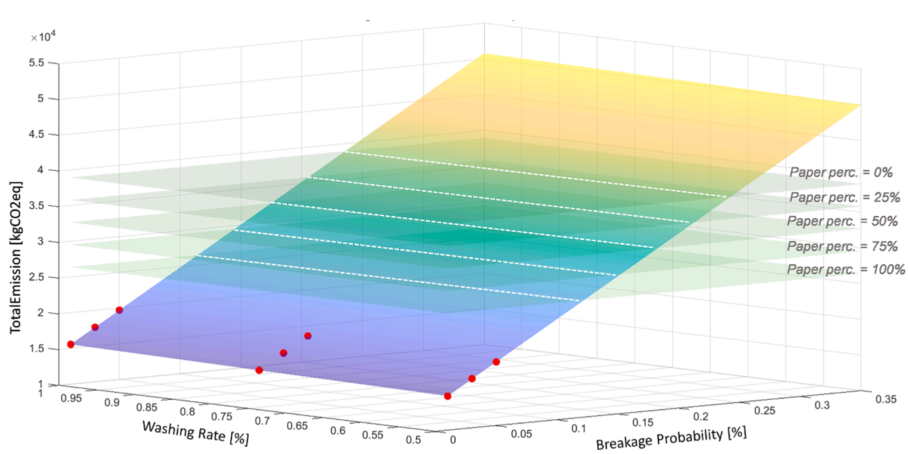


**Fig. 10.** RC-RC environmental impact as a function of washing rate and breakage probability.

scenarios under varying assumptions for crate *Breakage Probability* and *Washing Rate*. A multicolored plane interpolates these points, showing how the total impact evolves across the parameter space. Superimposed on this surface are five horizontal planes, each corresponding to the total carbon footprint of the DC–DC scenario at different levels of paper content in single-use crates (0 %, 25 %, 50 %, 75 %, and 100 %).

The visualization highlights two key findings. First, the *Breakage Probability* has a much stronger influence on the total impact of the RC–RC system than the *Washing Rate*, which has a comparatively limited effect. Second, even under the most favorable conditions for single-use crates (i.e., 100 % paper content), the DC–DC scenario never outperforms the RC–RC system in terms of environmental performance. These results indicate that, within the specific case study analyzed, the RC–RC configuration is clearly the most environmentally advantageous option, provided that the system ensures a sufficiently low *Breakage Probability*. The plane equation is the following:

$$KgCO_{2\ eq} = 103428.712 \cdot Break\ \%_{RC} + 1527.057 \cdot Washing\ \%_{RC} + 13009.917 \quad (2)$$

Its intersection with the DC-DC scenario plane at 100 % paper content results in the following line:

$$Break\ \%_{RC} = -1.4769e^{-2} * Washing\ \%_{RC} + 1.2931e^{-1} \quad (3)$$

With $Washing\ \%_{RC} = 100$ %, the resulting $Break\ \%_{RC}$ threshold is 12.93 %, while for $Washing\ \%_{RC} = 50$ %, $Break\ \%_{RC} = 12.19$ %. This result is consistent with Eq. (1), which was derived under the assumption of 50 % *Washing Rate* and indicated a threshold *Breakage Probability* of 12.19 % for the RC-RC configuration to remain preferable over the best DC-DC scenario (i.e., 100 % paper content). Comparing the two threshold values computed at the extreme ends of the *Washing Rate* spectrum reveals only minimal variation, confirming the relatively limited influence of *Washing Rate* operations on the system's overall environmental impact. Thus, this analysis reinforces the previously identified threshold of approximately nine reuse cycles for RCs to be environmentally advantageous when compared to the most favorable single-use configuration.

## 5. Discussions

In this section, RQs are examined to discuss how the development of the OPT tool, its application, and the resulting analyses contribute to addressing each question and supporting informed decision-making.

*RQ1. How do decisions on reusable vs. disposable packaging at the actor level influence the environmental footprint of the entire Ho.Re.Ca. distribution system?*

The multi-scenario simulation results demonstrate that packaging decisions made at the actor level have a substantial effect on the environmental performance of the entire supply chain. Among the three packaging configurations analyzed (DC–DC, RC–RC, DC–RC), the RC–RC scenario consistently achieves the lowest total emissions, provided that the system maintains a sufficiently low *Breakage Probability*. The DC–DC scenario, in contrast, is the most environmentally burdensome due to its reliance on production and EoL processes for each use cycle.

The hybrid DC-RC scenario offers intermediate performance but tends to align more closely with DC-DC in most conditions. Conceptually, it would appear to be the least favorable option, as it combines the drawbacks of both systems, relying on disposable crates upstream and managing reusable flows downstream. However, within the specific conditions of the Ho.Re.Ca. sector analyzed, this is not necessarily the case. The presence of FPCs, which require the *FSD* to purchase and manage a certain number of crates regardless of upstream decisions, partially offsets the burden of mixing crate types. As a result, under certain parameter combinations, DC-RC scenarios outperform DC-DC ones in environmental terms.

*Breakage Probability* and *Paper Share* are critical levers: as RC *Breakage Probability* increases, the advantage of reuse diminishes, with the RC–RC scenario becoming less favorable beyond a threshold of approximately 12 % *Breakage Probability*. Conversely, increasing the share of paper in DCs improves the environmental performance of disposable solutions, although even a 100 % paper-based configuration does not outperform RC-RC when reuse conditions are favorable.

These effects are particularly relevant in the fresh produce Ho.Re.Ca. sector. Although the adoption of RCs generates additional return flows and increases the weight of transported packaging, the analysis shows that the logistics impact is consistently dominated by the transportation of filled crates (i.e., direct flows), namely the *Farmer-FSD* and FSD-*Client* routes. These two flows alone account for over 90 % of logistics emissions. The *Farmer-FSD* segment is especially impactful, contributing nearly twice the emissions of the *FSD-Client* segment due to both longer distances and the absence of consolidated delivery rounds. This underlines the importance of considering the specific structure of each supply chain when evaluating packaging strategies.

The environmental benefits of reusable solutions are primarily driven by the reduction in per-use production and EoL impacts, which are made possible by distributing these burdens across many usage cycles. By integrating all these logistics and operational variables, the OPT provides a holistic view of the system and allows decision-makers to understand how packaging decisions influence the performance of the entire supply chain.

*RQ.2 How can a DSS tailored to an actual logistic network aid environmentally sustainable secondary packaging decisions?*

The OPT tool provides practical support for secondary packaging strategies for environmental care in the Ho.Re.Ca sector. By leveraging primary data on actual product flows and actor locations, the OPT enables the mirroring of operational dynamics with high temporal and spatial accuracy. It allows decision-makers to evaluate the carbon footprint of different packaging scenarios under realistic conditions, reflecting the logistics network's specificity.

Unlike traditional LCA models that rely on average distances and generic assumptions, the OPT tool integrates case-specific parameters such as crate weights, real delivery routes, and customizable operational levers, including the RC *Breakage Probability*, the RC *Washing Rate*, and the DCs *Paper Share*. The tool also enables the simulation of hybrid DC-RC configurations, which are particularly relevant in transitional phases where the *FSD* starts using RCs downstream while continuing to receive disposable packaging from upstream suppliers. This feature makes the OPT particularly valuable in contexts where actors only partially control the supply chain. For example, the tool shows how small adjustments to the variable parameters can shift the environmental balance across scenarios. Moreover, by modeling the operational flows day by day, this tool can reveal logistical bottlenecks and peaks, or unnecessary complexity introduced by mixed packaging strategies, enabling more targeted and informed interventions. In doing so, it acts as a Decision Support System capable of translating operational conditions into actionable sustainability insights tailored to the real configuration of the supply chain.

### 5.1. Alignment with related studies

A comparison with related research helps position this study within the broader literature on packaging and environmental assessment in food supply chains, while also highlighting the methodological challenges inherent in such analyses. The quantification of environmental impacts per crate is highly sensitive to packaging properties (weight and volume), logistics assumptions, and network structure (supply chain organization, number of stages, and geographical density), making cross-study comparisons non-trivial. Under geographically dispersed networks, logistics-related emissions may offset the benefits associated with production and end-of-life stages of reusable packaging systems [22,26]. For this reason, several studies emphasize the importance of

**Table 8**
Comparison of kgCO2eq/crate*rotation across reusable packaging networks in fresh produce supply chains.

| | Rerence crate [dm3] | | | | Network | | |
|---|---|---|---|---|---|---|---|
| Paper | Ext. vol. | Weight | Rotations | Coeff | Type | Avg. Traveled Km | kgCO2eq/crate*rot |
| [11] | 28,56 | 1,4 | 100 | 0,0490 | Retail | 1300 | 0,951 |
| [16] | 48 | 1,9 | 140 | 0,0396 | Retail | 840 | 0,530 |
| This paper | 26,6 | 1,38 | 100 | 0,0519 | HoReCa | 831 | 0,860 |

using real distances in LCA, as opposed to average secondary transport data [23,24]. Packaging-properties-focused assessments further underscore the strong interaction between material characteristics and logistics choices [25]. Accordingly, when comparing LCA results across the literature, it is essential to account for boundary conditions rather than relying solely on the comparison of final numerical values.

We compared the results of our study (RCs–RCs scenario focusing on the RC_03 format) with existing literature assessing the environmental benefits that stem from the adoption of reusable crates in fresh produce supply chains. The selected studies [11,16] focus on retailer-based distribution networks rather than the Ho.Re.Ca. sector considered in this paper. Table 8 summarizes some of the boundary conditions involved in the analysis and the numerical results obtained.

Since these studies adopt different functional units, we normalized the results rescaling them to kg CO2eq per crate per rotation to ensure comparability using the information available in each paper. This harmonization relies on a set of assumptions, which are outlined below.

In Accorsi et al [11], the functional unit is defined as a fully loaded pallet of RCs distributed from growers to retailers over a 10-year time horizon within a nationwide retail network. The study accounts for both fixed and variable transport emissions as well as the pallet carbon footprint contribution. An average number of crates per pallet is derived through a distance-weighted approach that distinguishes between open and closed crate logistics. The logistics carbon footprint calculation relies on primary traveled distances data (approximately 1,300–1,500 km per cycle).

Rasines et al [16] define the functional unit as the transport of 1 kg of fresh fruit or vegetables to the retailer. Assuming a load of 15 kg per crate, the reported impacts were scaled accordingly to obtain a per-crate, per-cycle value.

After normalization, the results exhibit a consistent level of comparability across studies. In particular, the values reported by Accorsi et al [11] and those obtained in this study are closely aligned (with estimated impacts of 0.95 and 0.86 kg $CO_2$-eq per crate per use cycle, respectively), despite differences in system boundaries and supply chain configurations. By contrast, Rasines et al [16] report a lower value (0.53 kg $CO_2$-eq per crate per cycle), which can be mainly attributed to the use of lighter crates for an equivalent volume of transported product. Moreover, although both Accorsi et al [11] and Rasines et al [16] refer to retail supply chains, the former is characterized by a more geographically dispersed network, as reflected by the higher average distance traveled by a crate over a single use cycle.

Overall, while the normalization enables a meaningful cross-study comparison at the crate level, the observed differences confirm the strong sensitivity of environmental results to boundary conditions (packaging properties and network structure).

### *5.2. Managerial implications*

A key managerial implication of this study relates to the limited generalizability of its findings beyond the specific network examined. The heterogeneity of operational contexts within the fragmented Ho.Re. Ca. sector constrains the derivation of universal benchmarks and limits the applicability of single-index metrics for evaluating optimal packaging strategies. The variability observed across comparable case studies discourages a “one-size-fits-all” approach and instead underscores the OPT’s role, designed to capture the specific features of each network.

By modelling detailed logistics flows based on real distances and actor configurations, the OPT enables a more accurate assessment of the environmental trade-offs among packaging systems. Its flexibility allows companies and policymakers to tailor the analysis to their supply chain structure and operational conditions, leading to informed and context-specific decisions.

Building on this perspective, the following points represent *decisional hotspots* that is, critical aspects, drivers, and warnings that should be carefully examined in every operational setting, as they can substantially influence environmental performance:

- Prioritize reuse under controlled breakage: In the analyzed network, reusable crates outperform all alternatives provided that breakage remains below 12 %. Therefore, managerial practices that extend crate life (such as operator training, improved handling, and investment in more robust designs) are essential.
- Recognize the limits of hybrids: In the industrial case analyzed, hybrid DC–RC configurations outperform fully disposable systems mainly because the large number of crates required for FPCs is managed through reuse. Although reverse logistics slightly increases impacts compared to DC–DC systems, the reduction in production and end-of-life burdens associated with disposables more than compensates for this. However, this outcome is strongly dependent on the specific business structure and the high fragmentation of demand, and should not be assumed to hold in other contexts.
- Paper share matters, but does not replace reuse: Increasing the paper fraction in disposable crates can lower emissions relative to plastic, yet even fully paper-based systems do not outperform reuse when crates circulate beyond nine cycles. Paper should therefore be regarded as a mitigation measure rather than a substitute for reuse.

## 6. Conclusion

This study evaluates the environmental performance of secondary packaging strategies in the fresh produce Ho.Re.Ca sector through a developed tool named Operational Packaging digital Twin (OPT). This tool provides a context-specific environmental assessment that accounts for both direct and reverse logistics, as well as production, EoL, and reusable crates’ washing processes.

The OPT integrates enterprise-specific data, including actual distances, crate types, and delivery patterns, enabling a highly contextualized environmental assessment. Through a multi-scenario analysis, the study evaluates the influence of two key parameters for RCs (*Breakage Probability* and *Washing Rate*) and one key parameter for DCs (material composition as *Paper Share*) on the overall greenhouse gas emissions of the supply chain.

In the evaluated case study, the analysis confirmed that fully reusable configurations consistently offer the lowest greenhouse gas emissions, provided that crate *Breakage Probability* remains low. Hybrid configurations (reusable crates introduced downstream while disposable ones are used upstream) represent a viable transitional solution and can outperform fully disposable systems under certain conditions. This results from the peculiar features of the Ho.Re.Ca. sector, where a significant share of orders requires the preparation of Fractional Product Crates (FPCs). To fulfill this demand, the *FSD* must manage a dedicated inbound flow of empty crates, regardless of the upstream packaging configuration. As a result, even when inbound flows are composed of disposable crates that must be discarded after use, replacing all outbound DCs with reusable ones can lead to a net environmental benefit. In this case, the additional reverse logistics burden required to recover and manage RCs downstream is offset by the *FSD* inbound flow of RCs for FPC assembly, which are less impactful than DCs ones. This context-specific condition explains why the DC–RC configuration may, under certain scenarios, perform better than the fully disposable DC–DC option, despite appearing counterintuitive. It highlights the importance of accounting for node-specific operations and internal repacking dynamics when evaluating the environmental performance of packaging systems in real-world supply chains.

The study addresses two research questions: (1) how actor-level decisions on packaging type influence the environmental footprint of the Ho.Re.Ca. distribution system, and (2) how a tailored DSS can guide environmentally informed choices. The findings demonstrate that packaging strategies have system-wide implications and that reuse schemes require careful design, especially in fragmented and logistics-intensive sectors like Ho.Re.Ca.

## CRediT authorship contribution statement

**G. Bartolotti:** Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **R. Accorsi:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **B. Guidani:** Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **B. Lupi:** Writing – review & editing, Software, Investigation, Data curation, Conceptualization. **R. Manzini:** Writing – review & editing, Software, Methodology, Conceptualization. **M. Ricci:** Writing – review & editing, Methodology, Data curation, Conceptualization. **M. Ronzoni:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

## Declaration of competing interest

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

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## Data availability

Data will be made available on request.

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