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A decision support system for the environmental assessment of fruit and vegetables packaging and distribution systems

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Abstract. This study introduces a novel decision support system (DSS) framework to model and assess three alternative material-driven logistics networks for secondary packaging systems (SPSs) in the fruit and vegetable supply chain. These SPSs cover reusable plastic containers (RPCs), single-use plastic containers (SPCs), and corrugated cardboard boxes (CCBs). By integrating primary data from enterprise resource planning systems with Geographic Information Systems, the DSS offers high-resolution insights into transportation flows, payloads, and environmental emissions. The framework captures key lifecycle stages of packaging and distribution systems, from the production and use to end-of-life management, enabling a robust comparative analysis of environmental performance. The proposed tool further assists the supply chain's stakeholders in preparing environmental reports that account for the impacts generated by their annual logistics flows and enables the forecasting of future impacts by incorporating estimated flows. Applied to a large-scale logistics network of an Italian retailer, the DSS revealed significant trade-offs between reusable and single-use SPSs. The findings underscore the importance of data-driven tools for optimizing sustainability in food supply chain logistics and suggest avenues for future research to enhance the scalability and applicability of DSS frameworks in complex supply chains.

Keywords. *Environmental decision support systems; sustainability; food supply chain; supply logistics; packaging systems; reusability.*

1. INTRODUCTION

In an increasingly interconnected and resource-conscious world, the way goods are produced, transported, and delivered has become a focal point for industries aiming to balance efficiency with environmental responsibility. In particular, the food sector faces mounting pressure to address sustainability challenges within its supply chains, as these systems often involve significant material flows and environmental impacts. Supply chains, broadly defined, encompass the intricate network of activities and stakeholders required to move goods from production to the end consumer. Within this context, logistics emerge as a cornerstone for ensuring both operational effectiveness and ecological stewardship.

A key area in sustainable food supply chain is the management of reusable packaging, such as crates for fresh fruits and vegetables. These crates offer a circular alternative to single-use packages but require careful coordination among various actors, including producers, distributors, retailers, and logistics providers, to optimize activities such as transportation, storage, and reverse logistics processes. Efficient recovery, cleaning, and redistribution depend on seamless collaboration across the supply chain. An accurate modeling of these logistical flows is essential for optimizing their use and quantifying environmental benefits. To achieve this, leveraging primary data is pivotal for capturing the dynamic and complex realities of crate movements within the food supply chain. Existing literature has extensively examined the environmental impacts of secondary packaging in food supply chains, with reusable containers often highlighted as a sustainable alternative to single-use packages as corrugated cardboard boxes. Studies demonstrate that while reusable packaging reduces waste and reliances on virgin materials (Singh et al. 2006; Albrecht et al. 2013), their environmental benefits depend heavily on the efficiency of their logistics (Yadav et al., 2024). Transport distances, payloads, and reverse logistics operations, such as crate collection and washing, significantly influence the sustainability of these systems (Koskela et al., 2014; Abejon et al., 2020). Optimization techniques often serve as a decision-support tool to efficiently manage reverse flows and reusable crates inventories (Accorsi et al., 2022a), rather than to identify environmental and cost trade-offs (Ronzoni et la., 2022a,b). However, many studies rely on secondary or averaged data, limiting their ability to capture the complexity and variability of real-world logistics networks. Recent research has emphasized the importance of integrating primary data—such as detailed transportation routes, payload utilization, and fuel consumption—to improve the resolution and reliability of Life Cycle Assessments (LCAs). Moreover, methodologies augmented with Geographic Information Systems (GIS), decision support systems and digital twins have shown promise in modeling large-scale networks, offering granular insights into transportation emissions and optimizing logistical flows (Accorsi et al., 2022b; Lupi et al., 2024; Lee and Fan 2024). Despite these advancements, the literature still lacks comprehensive assessments that fully integrate real-world data and logistical implications, underscoring the need for more

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robust and data-driven approaches to model and compare secondary packaging systems (SPSs) flows and networks.

This study introduces a decision support system (DSS) for three alternative logistics networks dedicated to different material's SPSs for the fresh fruits and vegetables supply chain. By virtualizing real-world transportation flows and leveraging primary data from enterprise resource planning (ERP) systems, the DSS captures detailed information about shipment routes, payloads, fuel consumption, and logistical operations, including storage, washing, and network's inventory balancing. Integrated with GIS, it enhances spatial resolution by mapping the production and logistic network and optimizing routes, providing a more accurate representation of network dynamics. The aim is to quantify key environmental impact metrics such as traveled distance or fuel consumption for each lifecycle phase, offering insights into trade-offs between reusable and single-use SPSs. The stakeholders, such as retailers and distribution actors, can use the tool to evaluate current logistical flows, predict the effects of future configurations, and make informed decisions to optimize operations. Applied to a countrywide food supply chain with hundreds of actors and over a multi-year period, the proposed DSS supports the optimization of complex logistics networks, demonstrating its potential as a powerful tool for enhancing sustainability and resilience in real-world food supply chains.

The remainder of this paper is the following: Section 2 illustrates the four-stages methodological approach which involves the definition of the main logistic actors, the format of the packages (i.e., crates), transportation vehicles, and logistical flow data. Then, Section 3 applies the proposed DSS to analyze the logistics flow data of a major Italian retailer in the food sector. Finally, Section 4 summarizes the main contribution of this study and presents some outlines for further research.

2. METHODOLOGY

This section illustrates the methodological approach which is based on a four-stage framework shown in Figure 1. Each step addresses a critical aspect of the logistics network, from identifying actors (stage 1), packaging formats (stage 2), and transportation vehicles (stage 3) to integrating real-world data and simulating comparative scenarios (stage 4). This systematic approach ensures that the complexities of reusable and single-use SPSs in food supply chains are accurately captured and analyzed.

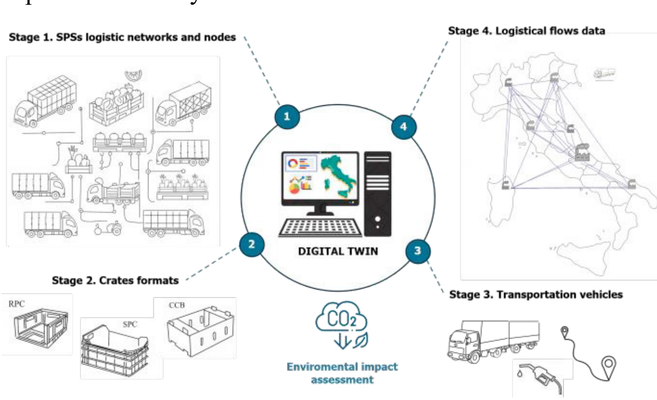

Figure 1. Methodological framework

The first stage focuses on defining the logistics network actors involved in the food supply chain, with particular attention given to three types of SPSs used for handling fresh fruit and vegetables: Reusable Plastic Containers (RPCs), Single-use Plastic Containers (SPCs), and Corrugated Cardboard Boxes (CCBs). These SPSs are made of a crate size and vary according to the material and the associated material-driven network, size, payload, and End of Life (EOL) treatments. Figure 2 provides a detailed schematic of the alternative logistics network for SPSs, illustrating the flow of crates across various stages—raw material production, package production, package use, and EOL. The color-coded arrows trace the movements of crates, emphasizing the circularity of reusable systems and the processes required for sustainable lifecycle management.

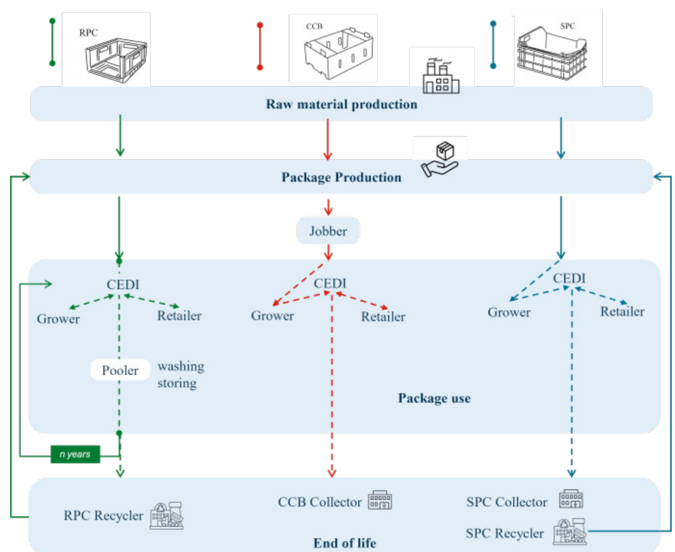

Figure 2. SPSs material-driven networks

In the Raw Material Production stage, virgin materials are processed based on specific recipes, shared by all packaging systems. At the Package Production stage, RPCs and SPCs integrate virgin, secondary, and auxiliary materials, whereas CCBs rely solely on virgin materials. During the Package Use stage, all crates are delivered to growers, food processors, or packers, filled with products, and sent to retailers' distribution centers before reaching retail stores. However, CCBs require an additional actor - the Jobber - who shapes them into ready-to-fill boxes. Uniquely, the RPCs network incorporates a pooler responsible for collecting and washing used containers, which are cleaned after every two rotations. A rotation refers to the full cycle of a crate from its initial dispatch (e.g., being filled with products) to its return after use. This includes delivery to retailers, use for product display or transportation, and subsequent collection for cleaning. In the EoL stage, treatment processes differ. RPCs are collected by the pooler for recycling, while SPCs undergo reverse flows managed by retailers' distribution centers. In contrast, CCBs are processed by collector facilities but do not involve secondary material reuse due to regulatory restrictions. These varying network structures reveal complex environmental trade-offs, emphasizing the need for a detailed sustainability analysis.

The user of the proposed DSS is required to input all nodes representing the actors within the three networks, e.g., producers, recyclers, washing facilities, and reverse logistics providers. Each node is characterized by a unique identification code (Node ID) and geographic coordinates (latitude and longitude). GIS is employed to accurately determine the location of each actor within the network, facilitating the mapping of their spatial distribution and enabling the visualization of logistical flows. Table 1 provides an example of three nodes within the RPC network designated for crate' washing.

Table 1. Logistic nodes for washing in the RPC network.

Network	Node type	Node ID	Latitude	Longitude
RPC	Washing	W01	43.770	11.112
RPC	Washing	W02	44.731	11.552
RPC	Washing	W03	45.007	8.9268

Once established, the logistic network is saved in a comprehensive database containing information on nodes and distances. The users retain the ability to modify the nodes by adding or removing actors to investigate new scenarios. This flexibility supports the ongoing adaptation and refinement of the model, ensuring its applicability to evolve real-world dynamics.

The second stage focuses on defining the crates' format. Figure 3 illustrates the graphical user interface (GUI) adopted for managing and modifying these data.

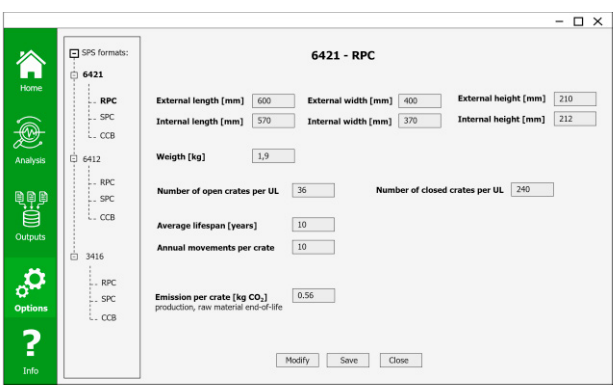

Figure 3. GUI for crates formats.

The data associated with each format encompasses a range of parameters that influence both logistical and environmental performance. These parameters include the external and internal dimensions—length (L), width (W), and height (H), measured in millimeters—the unit weight (M) of the crate in kilograms, and the stacking capacity, defined as the number of closed (#closed) or open (#open) crates that can be loaded onto a single unit load (UL). Furthermore, the tool incorporates the average operational lifespan of the crate, expressed in years, as well as the annual movements, representing its frequency of use within a year. A critical parameter is the environmental impact (E). This impact, expressed in kilograms of CO_2 equivalent (kg CO_2 eq) per crate, accounts for several key lifecycle stages, including production, raw material procurement, and end-of-life processing (e.g., recycling and disposal). Notably, this parameter, along with the others, may vary depending on whether the crate is adopted as a RPC, SPC, or CCB. For example, RPCs include additional environmental considerations related to the washing process, which depends on the average number of rotations a crate undergoes annually and its total lifespan. For each crate format, the tool requires the user to define these dimensional attributes for each SPS, thereby ensuring consistency across various packaging systems to facilitate multi-scenario analysis. Users are provided with the flexibility to view and edit these parameters as well as to add new formats to the system.

The third stage involves defining the key operational parameters of transportation vehicles involved in the logistics networks. Assuming that transportation is exclusively road-based, the user must specify several critical attributes that significantly affect the system's efficiency and environmental impact. These parameters include the number of palletized unit loads (pallets) each vehicle can accommodate, which determines transportation capacity, and the average vehicle filling degree, expressed as a percentage, indicating the typical utilization rate of the available space. Additionally, the user is required to input the unit fuel consumption, measured in liters per kilometer, as a crucial metric for evaluating operational costs. To comprehensively assess the environmental impact of transportation, emissions data for both empty and fully loaded vehicles must also be provided, expressed in grams of CO_2 eq per kilometer. These environmental metrics are evaluated based on the Finnish Lipasto database (VVT, 2009).

By incorporating these parameters, the simulation accounts for the variability in transportation performance and its contribution to the overall impact accounted for the logistic network. This detailed approach ensures the model's accuracy in capturing operational dynamics and environmental considerations.

In the fourth and final stage of the DSS framework, the user (e.g., retailer, distribution center) provides the logistical flows for each hub involved in the network object of the analysis. If the analysis involves a more complex flow, such as one that spans multiple retailers, the user can include the hubs of each retailer. Figure 4 shows the tool's GUI designed for uploading logistical flow data and provides an overview of the imported records.

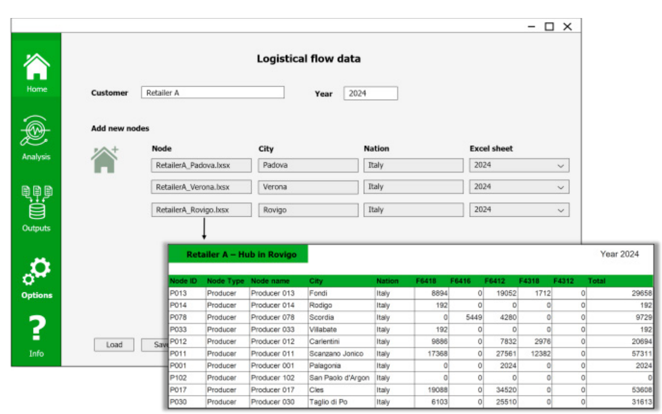

Figure 4. GUI for logistical flows.

This process involves submitting data either through a Microsoft Excel data sheet or via a direct connection to a database. The uploaded dataset typically contains historical annual records of the crates received, along with details about their formats and the city where both the origin and destination hubs are located. In the exemplification reported in Figure 4 the user "Retailer A" has three hubs located in Padova, Verona and Rovigo. For each node, the retailer uploads the data sheet containing all the fruit and vegetable crates shipped from various producers to the retailer hub, as the one shown in Figure 4 for the hub located in Rovigo. Each row represents a producer or a distribution center, identified by a unique Node ID, Type, Name, City, and Nation, providing details about its location and role. The other columns indicate specific crate formats (e.g., F6418, F6416), with quantities showing the number of crates shipped by each producer to the retailer. The "Total" column aggregates these values. For example, Producer 013 from Fondi, Italy, delivered 29,658 crates in 2024, including 8,894 crates of format F6418 and 19,052 crates of format F6412. This stage not only allows for the evaluation of historical logistical flows but also facilitates the forecasting of future flows by incorporating estimated data.

Once the network configuration is finalized, the DSS automatically introduces additional balancing flows for a comprehensive picture of the logistics network analyzed. These flows are generated in response to the user-provided data and are designed to account for the return, washing, redistribution, and recycling of crates within the logistics network according to the crates' material and reusability. In the previous example, these flows involve the return of empty crates from the retail hubs back to the distribution centers or other hubs, and the shipment of empty crates from the hubs to producers who need to fill them with fruit and vegetables.

The balancing flows vary according to the SPS included in the analysis. A brief recap of these flows is here reported:

- For RPCs, empty crates are sent from a warehouse facility to growers, processors, or packers for filling. After use, they are returned from retailers to a washing center managed by the pooler, then redeployed to the pooler's hub ready to be reused. Once the maximum rotations are reached (Figure 3), RPCs are sent to recycling facilities, where the materials are processed into secondary raw materials for new RPC production.
- For SPCs, new crates are distributed from package producers to growers or packers for filling. Used SPCs are then transported from retailers to distribution centers for reverse logistics and recycling. The recycled materials are reprocessed into new SPCs.
- For CCBs, flattened boxes are shaped into ready-to-fill forms by a jobber and sent to growers or packers. After use, the boxes are collected from retailers and sent to processing facilities, typically for recycling or energy recovery.

The hubs involved by these balancing flows are selected from those defined in Stage 1, using a proximity-based allocation strategy. This strategy prioritizes the nearest hub capable of providing the required services, such as washing, pooling, storing, or recycling, thereby optimizing the logistical network and minimizing associated transportation impacts.

In conclusion, the tool generates a detailed multi-scenario report that compares the environmental impacts of the flows established in the previous stage under the three alternative network configurations (i.e., using only RPC, SPC, or CCB). A visual dashboard collects five key environmental metrics which refer to packaging waste (kg), fuel consumption (l), cumulative distance (km), total emissions (kg CO_2 eq), and emissions specifically due to transport (kg CO_2 eq). These metrics provide valuable insights to support informed decision-making, enabling stakeholders to evaluate trade-offs and optimize logistical and sustainability outcomes.

3. CASE STUDY APPLICATION

This section presents a case study showcasing the application of the proposed DSS to evaluate the environmental impacts of the logistics network of a major Italian food retailer. By simulating logistics flows, transportation emissions, and crate usage over a 10-year period, the results delve into the trade-offs between reusable and single-use packaging systems. Figure 5 illustrates the geographical distribution of the nodes involved in the Italian logistics networks of the RPC, SPC, and CCB included in this case study (stage 1).

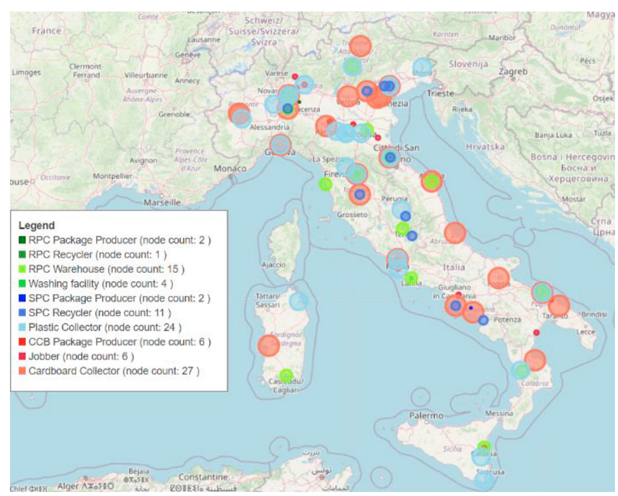

Figure 5. Case study: the actors of the three alternative SPSs material-driven networks.

Each node type is color-coded, with the size of the bubbles representing the number of nodes of that type. RPC nodes, shown in green, include warehouses and washing facilities, with RPC Warehouses being the most common (15 nodes). SPC nodes, in blue, consist of plastic collectors (24 nodes) and recyclers (11 nodes), while CCB nodes, in red, are mostly cardboard collectors (27 nodes). The map illustrates the nationwide distribution of the nodes, with concentrations around industrial and logistical hubs, reflecting the supply chain organization for these packaging systems.

Table 2 provides the dimensional attributes of the crates' formats adopted in the logistics flows of the retailer object of this analysis (stage 2). Seven different formats are described. For each format the external dimensions (length, width, height in mm), weight (kg), stackability, and environmental emissions associated with production, washing, and EOL treatments are reported. Regarding the environmental emission E [kg CO_2], the value for the formats 6410 and 6412, were illustrated in details by Lupi et al. (2024). For the others, emissions were estimated through a conversion based on the crate's weight and internal volume, allowing for a proportional estimation of their environmental impact. Table 2 shows the values referred to the RPC distribution network. Equivalent data are provided for the SPC and CCB networks to enable the comparative analysis of the sustainability and efficiency of the different packaging systems within the network.

Table 2. Case study: crates formats.

Format	L	W	H	M [kg]	#open	#closed	E [kg CO_2]
3416	300	400	180	1.10	96	480	6.6322
6423	600	400	227	1.83	36	288	6.7526
6418	600	400	176	1.66	48	288	5.9803
6416	600	400	160	1.50	56	288	5.7380
6412	600	400	115	1.38	72	288	5.0566
4318	400	300	176	1.07	96	576	4.6477
4312	400	300	115	0.85	144	576	4.1859

The transportation of crates within the logistics network involves vehicles with specific operational and environmental characteristics (stage 3). These vehicles are designed to accommodate up to 33 palletized unit loads, with an average vehicle filling degree of 75%, which represents typical utilization of available space. Fuel consumption is set at 0.371 liters per kilometer. The emission data for these vehicles vary depending on their load status: 630 g CO_2 eq/km when the vehicle is empty and 962 g CO_2 eq/km when fully loaded.

Finally, the logistical flows included in this analysis (stage 4) involve ten distribution hubs strategically located across four Italian regions. These hubs manage an annual flow of around 50.6 million crates, utilizing seven different crates formats. Table 3 exemplifies the data uploaded for the year 2023, with values expressed in units of hundreds (*10^2).

Table 3. Case study: crates flow (*10^2) over the year 2023.

Hub	3416	6423	6418	6416	6412	4318	4312
R0TO	6	1	53232	30	41027	15386	0
R0VI	14	0	0	877	219	0	0
R0TE	6	426	23516	98	18747	3519	89
R0BA	0	0	64	2	19	0	0
R0RE	165	2	34208	634	25320	9730	0
R0SA	54	0	16418	291	13290	6108	2
R0FO	154	1	34792	535	25540	11761	0
R0R	3	0	3866	422	2006	460	0
R0FI	3871	907	0	6540	5295	0	0
R0SC	18346	3711	0	67348	57389	0	0

The formats 6418 and 6412 rule the total flow, underlining their critical role in the retailer's supply chain. Specifically, R0SC, the most active hub, handles high volumes of 6416 (673,480 crates) and 6412 (573,890 crates), indicating its central role in managing large-scale distribution operations. Other hubs, such as R0VI and R0BA, show lower volumes, suggesting they either handle specialized operations or serve smaller geographical areas.

The DSS models the retailer's logistics network through the four stages defined in the methodology section and generates a geographical distribution of the nodes involved in the logistics network along with the vehicle flows. Figure 6 visually highlights the retailer's distribution hubs, represented in orange, alongside producers' facilities in violet and other relevant nodes introduced during the estimation of balancing flows for the RPC network. The bubble's size is proportional to the number of vehicles entering and leaving each node during the period of analysis, offering valuable insights into transportation dynamics and node-level activity.

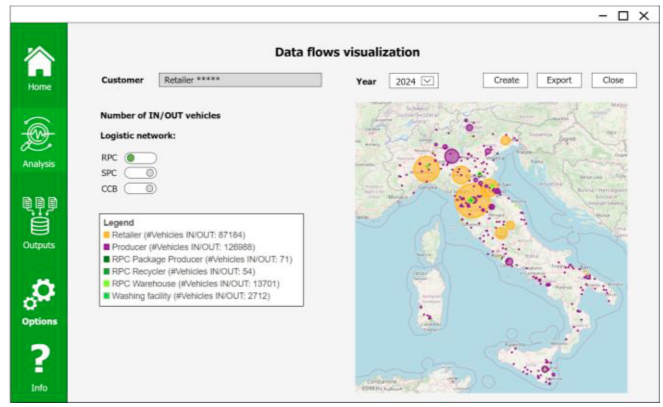

Figure 6. Case study: the nodes involved in the RPC network.

The environmental impacts generated by the annual flows shown in the previous map are detailed in a report. This report consists of a visual dashboard, illustrated in the GUI reported in Figure 7, which exploits the previously defined environmental metrics through five comparative histograms.

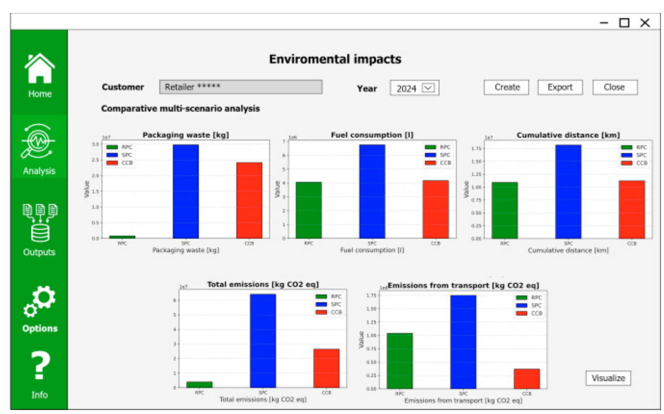

Figure 7. Case study: report GUI.

These histograms compare the environmental impacts resulting from the analysis of the retailers' flows across the three alternative packaging systems: RPC, SPC, and CCB. The results highlight significant differences among them. RPC is the most sustainable option, consistently showing lower values across key impact categories, including waste generation, fuel consumption, and emissions. Total emissions for SPC are 64.1 million kg CO_2 equivalent, more than 16 times higher than RPC (3.96 million kg CO_2 eq) and nearly 2.5 times higher than CCB (26.4 million kg CO_2 eq). This aligns with the inherent advantages of RPC's reusability and durability, which significantly reduce resource use and environmental footprint.

A closer look at transport-related emissions reveals that they represent a significant portion of total emissions for all three distribution systems. In particular, for RPC, transport emissions account for approximately 26% of total emissions (1,03 out of 3,96 million kg CO_2 eq). In the case of SPC, transport emissions contribute a substantial 27% (17,5 out of 64,1 million kg CO_2 eq). For CCB, transport emissions form an even larger share, around 14% (3,6 out of 26,4 million kg CO_2 eq). These percentages reveal the critical role of logistics optimization in reducing the environmental impact of SPS logistic networks.

In this case study, the ability to reference and detail the flows revealed critical insights, such as the significant share of transport emissions in overall impacts (e.g., 26% for RPC, 27% for SPC, and 14% for CCB). Without this level of granularity, the interplay between logistics, packaging design, and emissions might have been overlooked, leading to less informed decisions. These findings underscore the importance of adopting a rigorous, data-driven approach to evaluate the environmental impacts of packaging and distribution systems.

4. CONCLUSION

This study presents a novel DSS framework designed to assess the environmental impact of secondary packaging and distribution systems within the fresh fruit and vegetable supply chain. It addresses key gaps in the literature, particularly the reliance on secondary or average data in previous studies. By integrating primary data from ERP systems with GIS, the DSS enables a comprehensive life cycle assessment (LCA) that captures the dynamic complexity of large-scale logistics networks. The tool includes a high-resolution comparative analysis of the logistical and environmental performance associated with the adoption of three alternative secondary packaging containers: RPCs, SPCs, and CCBs. The application to an Italian case study underscores the pivotal role of RPCs in advancing supply chain sustainability, demonstrating significant reductions in greenhouse gas emissions, waste generation, and resource use over a ten-year horizon. This novel tool further assists users in preparing environmental reports that account for the impacts generated by their annual logistics flows and enables the forecasting of future impacts by incorporating estimated flows.

Future research could expand on this study to:

- Explore alternative flow-balancing strategies that go beyond proximity, incorporating hub capacity, or operational costs.
- Integrate intermodal transportation modes, such as shipping, air freight, or rail, could provide insights into optimizing efficiency, sustainability, and network resilience.
- Extend the framework to other supply chains with logistical challenges similar to perishable products' packaging and distribution systems.

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