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Design Support Tool for Reusable Packaging Sustainability Assessment in the Food Industry

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Abstract: Embracing reusable and sustainable packaging is an opportunity to reduce the environmental burdens across agri-food supply chains in alignment with the European Green Deal goals. This paper introduces a visual dashboard as a decision-support tool for Reusable Packaging Circular Supply Chains (RPSCs) within the agri-food sector. The dashboard integrates key operational parameters as levers, including material composition, production processes, reuse cycles, and logistical network configurations. The dashboard enables stakeholders to assess environmental and economic trade-offs in real time. As a computerized-aided design tool, the developed interface relies on data architecture and scripts hidden from the final users. A proof-of-concept application within an international food retailer's logistics network demonstrates the tool's practical utility, confirming the reductions in production and disposal emissions of reusable packaging compared to single-use. However, challenges persist in adopting reusable packaging, including a significant reliance on the logistical infrastructure, the impact of washing processes, and the enhanced costs linked to increased complexity. This paper underscores the importance of accessible operative tools in facilitating cross-functional collaboration toward a shared common goal, contributing to a more sustainable agri-food sector.

Keywords: Reusable primary packaging; Circular supply chain; Food systems; Visualization dashboard; Decision support system; Circular economy.

1. INTRODUCTION

Addressing packaging waste generation has become a priority in the government's and industries' agenda, and improvement pathways are already targeted in protocols such as the EU Green Deal (Giganti et al., 2024). Without proactive intervention, packaging waste levels are projected to rise further (European Commission, 2022a). Among other manufacturing sectors, the agri-food industry relies heavily on packaging for product protection, extending shelf life, and ensuring safety during transportation and logistics operations (Paiva and Ugaya, 2024). Additionally, the high turnover of many food items results in the production of packaging waste at a faster pace compared to other sectors (Mielinger and Weinrich, 2024). In response to these challenges, the EU Green Deal provides clear guidelines for transitioning the packaging sector towards climate neutrality. One of the primary strategies within the Green Deal framework is recycling, requiring that all packaging in the European market be recyclable in a sustainable and economically viable way by 2030. Another key strategy is to reduce the overall packaging volume by promoting reusable and refillable options. Although reusable packaging has been explored in the agri-food sector, the literature focuses on returnable transport items (RTI) (Sarkar et al., 2019; Zhang et al., 2024) and secondary packaging (e.g., Reusable Plastic Containers - RPCs). Reusable primary packaging research is limited, and most studies tend to be case-specific (Mahmoudi and Parviziomran, 2020). Adopting reusable primary packaging requires a major adjustment in the agri-food supply chain, engaging mass distribution networks, retail nodes, and consumers (Meherishi et al., 2019). This shift requires moving away from the traditional linear business model towards circular networks and operations.

In reusable packaging circular supply chains (RPCS), the consumer triggers the reverse flow. The system's reliance on consumer (or end-users) behavior adds to the operational complexity, highlighting the need for coordinated efforts (Greenwood et al. 2021, Accorsi et al., 2022). Consequently, guiding the transition toward reusable primary packaging in the food industry calls for a holistic approach. Life Cycle Assessment (LCA) studies in literature confirmed the reusable packaging environmental benefits (Accorsi et al., 2022a, 2022b; Hitt et al., 2023; Yadav et al., 2024). However, these analyses frequently overlook the economic feasibility of more sustainable alternatives. Quantitative tools that help manage the trade-offs between minimizing environmental impact and reducing costs facilitate the transition to RPSCs (Michele Ronzoni et al., 2022; M. Ronzoni et al., 2022). The literature focuses on strategic studies with a long-term perspective. Moreover, LCA studies offer static and case-specific data. Therefore, this paper addresses the need for user-friendly tools that deliver results and metrics within timeframes that align with daily operational requirements, offering concrete managerial application. In RPSCs, one actor's decisions inherently impact other stakeholders, highlighting the importance of cross-functional collaboration toward a shared

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objective (Bartolotti et al., 2025). This article introduces a computer-aided design tool intended for life-cycle scenario simulation, which provides key performance indicators (KPIs) and metrics to early drive designers, practitioners, and users. This tool implements a set of design and operational levers, enabling the users to evaluate the economic and environmental trade-offs associated with alternative packaging configurations and uses. The design support tool enables users to quickly evaluate operational decisions by addressing important questions, such as:

- *Q1.* What are the environmental and economic impacts of packaging production when different manufacturing processes are used, and how does material composition affect these impacts?
- *Q2.* How does the environmental impact of reusable packaging change as the number of reuse cycles increases?

Leveraging specific parameters allows users to quantify the impact of individual decisions on the entire supply chain, facilitating the development of vertical and horizontal collaborations among actors and stakeholders. Developing accessible, shared tools for all actors within the RPSCs ensures the alignment toward common sustainability goals. Section 2 describes the steps of the methodology used to build our decision support tool. Section 3 presents and discusses how the tool can be applied to a real case study, while Section 4 draws conclusions.

2. MATERIALS AND METHOD

The transition to reusable packaging involves a shift from a linear model (produce–use–dispose) to a circular supply chain, where forward flows are integrated with reverse flows. This change requires consumers to return used packaging to designated collection points, called Reverse Vending Machines (RVM).

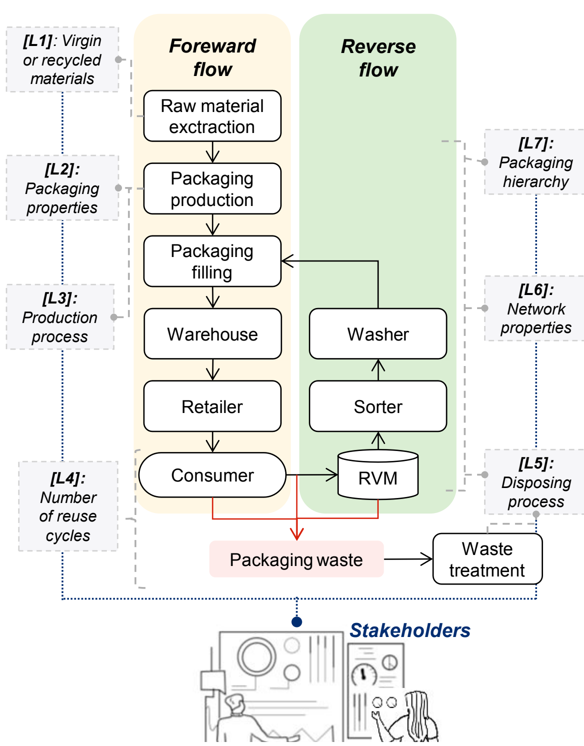

Figure 1. RPSC flows and key strategic parameters.

Figure 1 showcases the actors involved in the RPSCs and the material flow. Packaging production facilities exploit virgin raw materials to manufacture reusable packaging, which is then sent to filling locations for product packaging. Once filled, the packages move through storage and distribution channels to retailers. After consumption, citizens can return the packaging to RVMs. The packaging is then sorted to create a homogeneous unit load and sent for washing before reuse. However, reverse flows often differ from forward flows due to transport breakage and incomplete consumer returns.

In RPSCs, key strategic and operational parameters shape overall performance, making some options more advantageous than others. The visualization dashboard integrates such parameters as adjustable *levers*, allowing users to simulate the system's expected outcomes. Moving the levers enables an impact assessment of the supply chain through metrics and KPIs quantification. Figure 1 highlights the seven strategic levers incorporated into the dashboard design [*L.1-7*]. The packaging composition [L.1], defined as a mix of virgin and recycled materials, and its properties [L.2] (e.g., weight, volume, material) must be optimized as a trade-off between costs and emissions. Packaging can be produced using various manufacturing processes with differing environmental impacts and costs [L.3], which also affect the mechanical and chemical properties of the materials. Some packaging types are more durable than others, making them suitable for adoption in RPCSs as they support a greater number of Reuse Cycles (RCs - i.e., the total times it can be used in a specific logistic network before disposal or recycling). The number of RCs [L.4] depends not only on the packaging's physical and chemical characteristics but also on return rates from consumers and breakage levels. Furthermore, the environmental impact is significantly influenced by the waste management strategy [L.5] used for packaging not reintegrated into the supply chain. Key logistical factors include the selection and geographic placement of production nodes and the distances between them, which define the supply chain structure [L.6]. Additionally, the unit load configuration [L.7] is critical to enhance the overall logistics efficiency. By optimizing secondary and tertiary packaging and maximizing load utilization, volumetric efficiency in transport operations can be significantly improved. Designers or other users looking to extract information can act on these levers [L.1-7] to obtain metrics and KPIs that aid in the decision-making process.

2.2 Interface organization and design

As a computerized-aided design tool, the developed interface relies on two layers, as depicted in Figure 2. The first layer is a static, non-visible data warehouse. The data warehouse gathers information about reusable packaging, its properties, and available unit load configurations. Environmental data is derived from LCA analyses, while economic data can be provided by companies managing reusable packaging. The proposed interface utilizes a relational database as a data source, with the fields detailed in Appendix A. The levers L1-7, representing the key variability parameters, are integrated into the interface developed in Microsoft Power BI through *objects* that can assume different values. Table 1 outlines the strategic levers of the network, the corresponding dashboard objects, and the variability ranges or potential values that these parameters can assume.

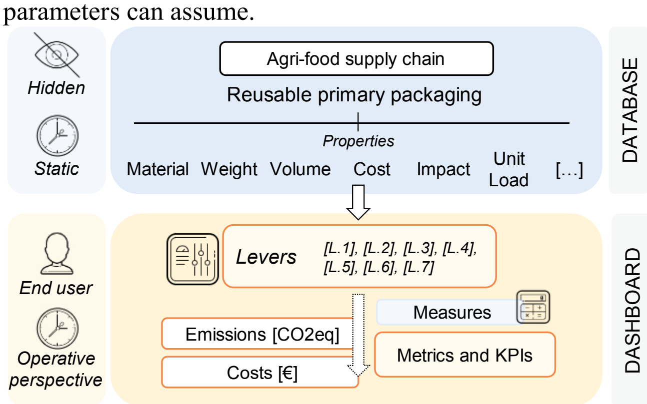

Figure 2. Interface design structure.

Scripts written in Data Analysis Expressions (DAX) language are embedded within the system, enabling dynamic calculations of the indicators that adjust as lever values change. The computation of these DAX measures is automated and hidden from the user. End users can immediately assess the impacts of parameter variations through visual tools that provide at-a-glance views of environmental and economic KPIs.

Table 1: Inc=Incineration, Lan= Landfill, Rec= Recycling, CS= Case-Specific

Lever	*Dashboard objects*	*Values*
[L.1]	Parameter for the selection of the percentage of recycled material	*0 – 100 [%]*
[L.2]	Selection of different materials, volume, and packaging type	*CS*
[L.3]	Selection of alternative disposing process	*CS*
[L.4]	Parameter for the selection of variable reuse cycles (RCs)	*0 – 20 [cycles]*
[L.5]	Selection of alternative disposing process	*[%] Inc, [%] Lan, [%]Rec*
[L.6]	Parameter for the selection of average distances between nodes	*[Km]*
[L.7]	Selection of the available secondary and tertiary packaging	*CS*

3. PROOF OF CONCEPT

The application of the visualization dashboard within a food packaging reuse network underscores the tool's benefits as a proof of concept in a real-world application. This analysis adopts a holistic approach, employing the tool during the design phase to facilitate the adoption of reusable packaging into the supply chains of two major French retailers.

The visualization interface helps select reusable packaging from 47 suitable alternatives based on their chemical and mechanical properties. The environmental data is derived from LCA analyses using SimaPro 7.3.3 software, while the economic data is based on project assumptions and input from companies involved in the reuse network. These companies, acting as industrial partners, oversee the production of packaging, filling operations, and retail distribution and manage the nodes dedicated to washing and sorting operations. The maximum number of tested Reuse Cycles (RCs) is 20. However, the actual number of safe RCs may depend on the type of food, usage conditions, and the washing system employed. The tests that assessed the maximum number of RCs evaluated chemical migration, sensory tests, and the physical properties of the packaging.

A preliminary analysis compares packaging options with equal volume capacities, making them interchangeable alternatives. This process enables the identification of the best configuration of packaging material and size, production methods, and disposal techniques to reduce emissions. Figure 3 provides an analysis comparing packaging options with a capacity of 1000 ml through a three-dimensional scatter plot. The x-axis contains the disposal process alternatives, while the y-axis outlines the corresponding production processes. The height represents the unitary emissions of each packaging option identified by colors, measured in CO_2 equivalents. The sphere's size indicates the weight of the packaging, confirming that lighter packaging generally has a lower environmental impact despite variations in production processes and disposal scenarios. The comparative analysis outlines the PKG_34, produced through the thermoforming process (PR_03) and using recycling as a waste management strategy (D_04), results as the solution with the lowest emissions, measured in CO_2 equivalent. Such preliminary analysis enables defining a subset of packaging options on which to focus further evaluations.

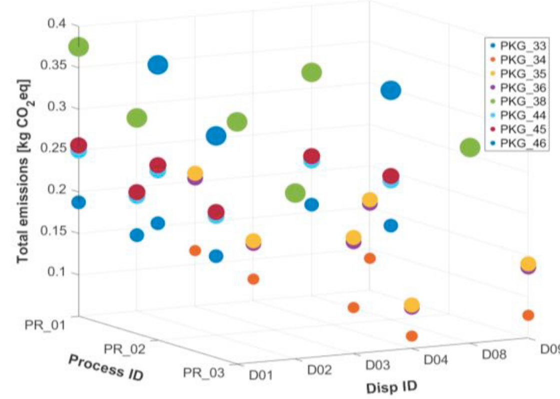

Figure 3: Comparative Analysis of Packaging Options (*1000 ml*).

An in-depth analysis explores how packaging fits into a complex supply chain. Optimal environmental solutions are not always feasible due to infrastructural and economic constraints. Boundary conditions may hinder the economic and environmental viability of adopting reusable. Figure 4 presents the interface of the developed tool. The gray panel on the left allows users to select a specific packaging type [L.2] for a detailed assessment and adjust key strategic levers. Once a specific packaging option is selected, the dashboard enables users to investigate alternative production processes [L.3] and define a mix of disposal methods in percentage terms [L.5]. This feature is relevant for assessing waste management strategies, where a single unified approach to recycling is not always possible because of restrictions on recycling all waste generated by packaging. Users can also adjust the number of RCs [L.4] and the material composition of the packaging, specifying the ratio of virgin and recycled raw materials [L.1].

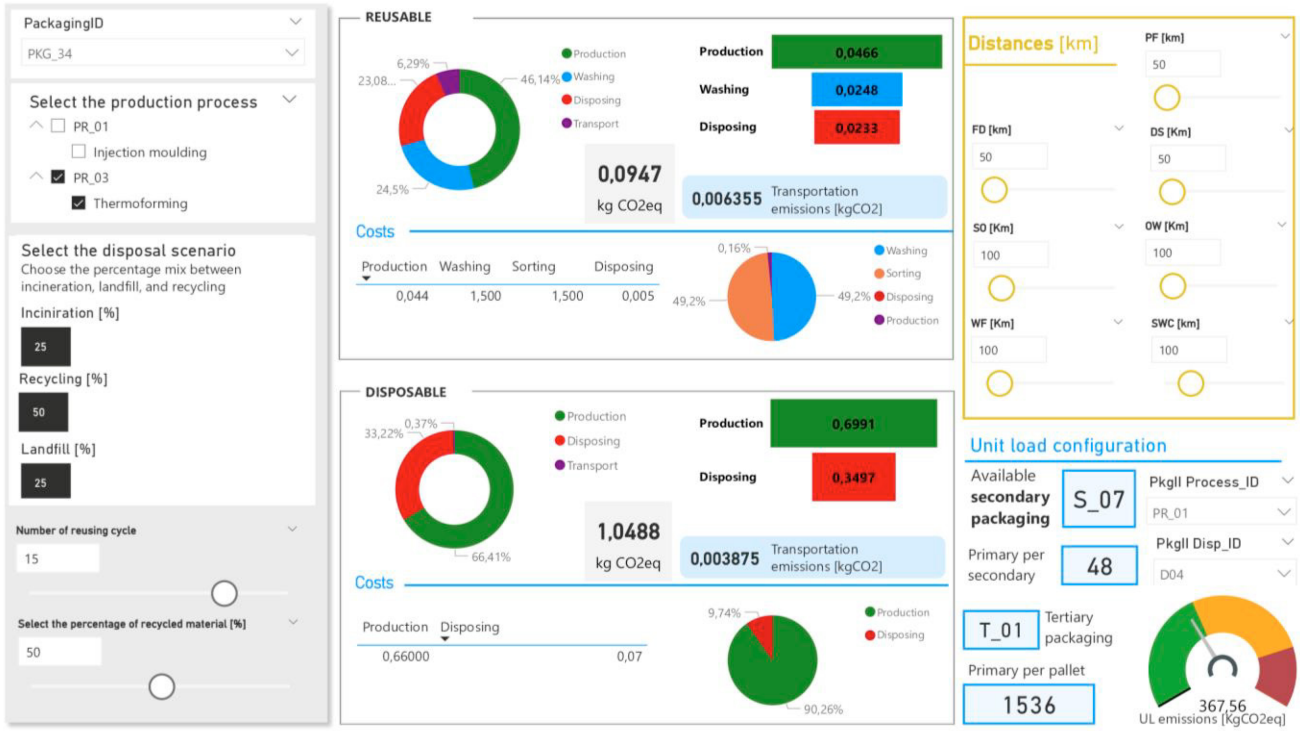

Figure 4. The developed interface. Legend: Packaging producer- Food packager, FD= Food packager – Distribution Center, DS = Distribution center – store, SO= Store – Sorter, OW=Sorter – Washer, WF= Washer – Food Packager, SWC= Store – Waste Center.

The upper-right panel highlights the infrastructural properties of the network [L.6] and enables users to adjust the average distances between supply chain actors. Modifying these parameters directly impacts costs and emissions, which are dynamically represented in the central part of the dashboard. Through real-time data visualizations powered by DAX scripts, users receive immediate insights into environmental and economic impacts. The dashboard also facilitates a comparative analysis of reusable packaging versus single-use scenarios. In a single-use scenario, only the production, filling, distribution to the retailer, and disposal at a waste center stage are considered, assuming that consumers are located in proximity to the stores. When analyzing reusable packaging, used containers can be reintroduced into the supply chain for a number of n RCs; therefore, the packaging is produced and disposed of only once, while sorting and washing operations are performed n times. In contrast, the single-use scenario would require the production and disposal of n units of packaging to achieve the same level of service.

Although reusable packaging entails additional stages, the environmental burdens associated with production and disposal are reduced. This comparative analysis underscores the relevance of the network's infrastructural and logistical configuration. Long transportation distances can undermine the environmental benefits of reduced production and disposal. This issue becomes more significant as n increases, highlighting logistics' role in shaping the overall sustainability of reusable packaging systems. In the bottom-right section, information about the configuration of the unit load is provided. This includes the number of primary units per secondary unit and the total number of primary units per pallet. These details enable adjustments to the characteristics of the secondary packaging [L.7] and aid in calculating the overall emissions associated with transporting the unit load along the supply chain.

4. RESULTS AND DISCUSSIONS

A first proof-of-concept entailed assessing the impact of various production process alternatives and material composition (percentage of recycled material used) on emissions and costs (*Q1*). The results are shown in Figure 5, where the production emission values for packaging PKG_34 are represented as green bars in the histogram, and orange circles indicate the associated production costs for each scenario. Production costs and emissions include the production process and the raw material used.

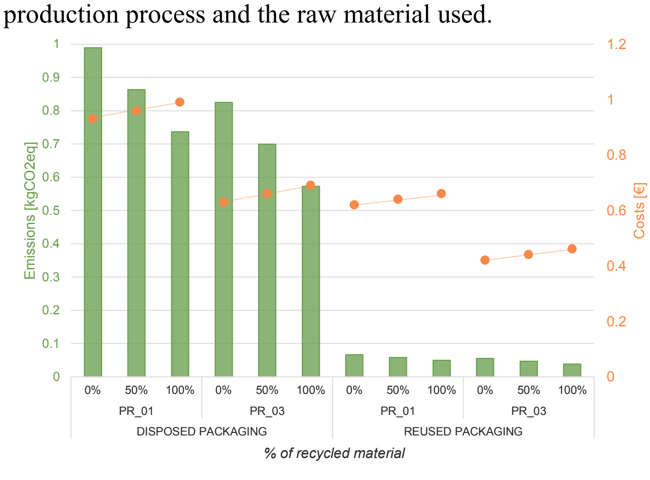

Figure 5. Impacts of material composition and production process variation on production emissions and costs.

The analysis assumes 15 Reuse Cycles (RCs), with a disposal scenario consisting of 25% incineration, 25% landfill, and 50% recycling. Average distances of 100 km are considered at each stage of the supply chain. The study examined variations in material composition, adjusting the proportion of recycled material from 0% to 50% and 100%, testing two types of production processes (PR01= Injection molding, PR03= Thermoforming) [L.1-L.3]. This evaluation is applied to both scenarios, whether the packaging is disposed of or reused. The plot clearly indicates that the costs and emissions associated with production (production process and raw materials) are significantly higher when the packaging is disposed of. Each use of disposable packaging requires the production of new materials, leading to increased consumption of raw materials. In contrast, costs rise proportionately with the amount of recycled virgin material utilized, as noted in Shamsuyeva and Endres, 2021.This occurs primarily because European regulations (European Commission 2022) impose severe safety standards on food packaging, which necessitate specific processing and treatment procedures that enhance costs. This highlights the need to bolster economic incentives for food packaging recycling, making this process viable.

Adjusting the dashboard slices based on the number of RCs [L.4] allows for determining how many cycles are required for reusable packaging to ensure lower carbon emissions compared to single-use packaging. Under the studied conditions and specified distances, just two RCs are enough to observe the environmental benefits of reuse. However, the tool provides key insights by assessing the required number of RCs for specific supply chains, leveraging the ability to set and model average distances between stakeholders. Shorter reverse logistics distances can further support the transition to reusable packaging. Considering the disposal scenario and average distances between actors of the previous analysis, it is possible to quantify the emissions from production (including the production process and raw material), washing, transportation, and disposal change as the number of RCs increases (*Q2*). In Figure 6, the number of cycles was varied from 0 to 20 in step 5, and the results are presented in the histogram below. The histograms represent the emissions for packaging use (i.e., each time the packaging is selected to contain food) as the number of times it is reintroduced into the supply chain varies (RCs). The histograms compare the four reuse scenarios with the case in which the packaging is disposed of after a single use.

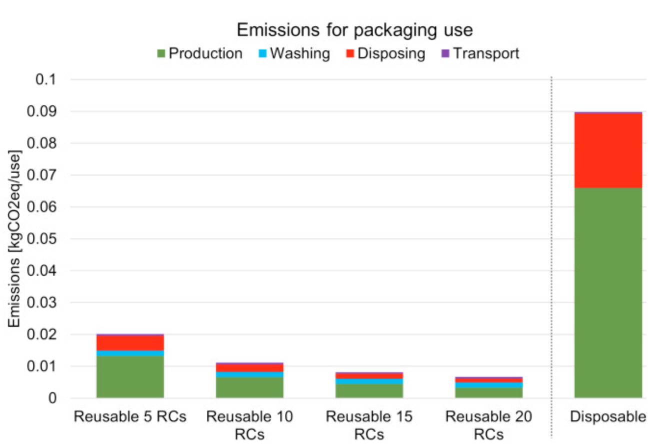

Figure 6. Total emissions per packaging use

The results show that, for reusable packaging, emissions for use decrease with the number of RCs, demonstrating the environmental benefit of maximizing reuse. In the scenario in which packaging is discarded after each use, emissions are generated solely by production and disposal. In contrast, reusable packaging involves emissions from washing and additional transportation for each cycle, but these are offset by the decreasing impact of production and disposal as the number of UCs grows. This analysis highlights the importance of increasing RCs and optimizing washing and transportation processes to enhance the sustainability of reusable packaging systems.

5. CONCLUSIONS

This paper highlights the transformative potential of reusable primary packaging in the agri-food sector, offering a clear pathway toward reducing environmental burdens and advancing climate neutrality goals. Circular supply chains for primary packaging are inherently more complex due to the number of stages involved and the presence of multiple actors with different roles. Addressing these challenges requires a collaborative framework that aligns stakeholder interests and supports informed decision-making. The design-support tool developed in this study aims to enable stakeholders to understand the impact of their decisions on the broader supply chain and to make choices that balance environmental and economic objectives. This dashboard integrates critical strategic levers of reusable packaging supply chains, including packaging characteristics, production and disposal processes, and logistical network parameters such as infrastructure and transport configurations. By dynamically adjusting these parameters, stakeholders can model and analyze trade-offs, fostering a more sustainable approach to packaging management. The tool assists stakeholders in developing operational strategies by providing intuitive metrics for industry managers and decision-makers, facilitating the adoption of reusable packaging. The proof-of-concept application demonstrates the environmental benefits of reusable packaging in reducing emissions from production and disposal and describes how the tool can be concretely applied in industries. The analysis delineates the pathways and future strategies for the integration of reusable packaging within the food industry. These findings highlight the importance of identifying key cost drivers and improving consumer awareness to maximize the number of reuse cycles. Educating consumers about the advantages of reusable packaging is crucial for extending its life cycle and minimizing its environmental impact. Ultimately, promoting collaboration among supply chain participants and leveraging shared expertise is essential to address the challenges associated with reusable packaging systems. The analysis of the results also reveals challenges for the future, such as increased costs and the complexities introduced by sorting and washing processes. In future developments, the design-support tool could play a role in shaping policies and defining incentives, aiding companies and retailers in the transition toward reusable packaging. By tackling these barriers and encouraging systemic change, reusable packaging has the potential to enhance sustainability in the agri-food sector.

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Appendix A. DATA SOURCE STRUCTURE

Table	***Attributes***
Primary Packaging	***PkgI_ID***, *Material, Weight, Volume, Dim1, Dim2, Dim3*
Secondary Packaging	***PkgII_ID***, *Material, Weight, Volume, Dim1, Dim2, Dim3, MaxWeight, Reusable*
Tertiary Packaging	***PkgIII_ID***, *Material, Weight, Volume, Dim1, Dim2, Dim3, MaxWeight, Reusable*
UnitLoad	***PkgI_ID, PkgII_ID, PkgIII_ID***, *Stackable, PrimaryPerSecondary, SecondaryPerTertiary, PrimaryPerUL, UL_weight*
Production Process	***Process_ID***, *ProcessName, ProcessType, Description*
Disposing Process	***Disp_ID***, *DispName, Disp_Material, Description*
Join_Primary_ Process_Disp	***PkgI_ID, Process_ID, Disp_ID,*** *Process_std, VMat_emissions1, Process_emissions, VRmat_emissions2, Washing_emissions, Disposal_emissions, Emissions_udm, LCA_indicator, Energy_matproc, Energy_disp, Energy_udm, VMatprocess_emissions1, RMatprocess_emissions2, VTot_emissions, RTot_emissions, Cost_prod, Cost_disposing, Cost_RMaterialV, Cost_RmaterialR, Cost_wash, Cost_sort*
Join_Secondary _ Process_Disp	***PkgII_ID, Process_ID, Disp_ID,*** *Mat_emissions, Process_emissions, Disposal_emissions, Emissions_udm, LCA_indicator, Energy_process, Energy_disposal, Energy_udm, Tot_emissions*
Join_UL_ Process_Disp	***PkgI_ID, Process_ID_p, Disp_ID_p, PkgII_ID, Process_ID_s, Disp_ID_s, PkgIII_ID***, *Stackable, Secondary_tot_emissions, Tertiary_tot_emissions*