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Data architecture framework for reverse logistics management in reusable food packaging networks

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Abstract

Managing agri-food supply chains requires the concurrent consideration of raw food and packaging materials flows. Unfortunately, packaging contributes to waste generation despite its vital role in ensuring safe distribution. To tackle this issue, the European Union fosters the adoption of reusable primary packaging and the introduction of sustainable closed-loop systems over the traditional based on single-use. Creating closed-loop packaging systems is achievable only through collaborative relationships among actors, stakeholders, and policymakers. Tailored data architectures facilitate the efficiency of such partnerships and collaboration, encouraging the adoption of sustainable paradigms. This paper proposes a data architecture framework that supports high-quality primary data collection for reusable primary packaging supply chains. Furthermore, the data framework aids decision-making processes within circular primary packaging systems, providing economic and environmental metrics. A flexible user interface facilitates the creation of customized output that impels the adoption of sustainability paradigms within the agri-food sector.

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Keywords: Circular network; Food supply chain; Reusable primary packaging; Packaging waste.

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1. Introduction and state of the art

Tracking and understanding raw food and packaging materials flow simultaneously is essential in managing and designing agri-food supply chains. Such interrelated streams couple in producing and delivering packaged food to end consumers. The importance of packaging in preventing food losses [1] is said to have caused the associated waste to become an issue for supply chain actors, policymakers, and stakeholders. In the European Union, packaging accounts for 36% of municipal solid waste [2]. Moreover, 40% of plastic polymers and 50% of paper fiber in Europe are devoted to packaging production, underlining the urgent need for a more sustainable and fair exploitation of raw materials [3].

The literature analysis provides solutions addressing the problem from different perspectives. On one hand, the strategic selection of packaging materials, such as compostable biomaterials or bioplastics [4], can reduce the environmental burden. On the other hand, consumer behavior plays a role in reducing packaging waste [5] under the assumption that an aware consumer would opt for more sustainable packaging choices. This paradigm finds particular resonance in the reusable packaging system. To reduce packaging waste, reusing food containers should be the primary goal of a sustainable food industry [4]. Previous studies have examined the economic and environmental impact of reusable secondary packaging [6]. Less attention is paid to reusable food primary packaging [7] despite the European Green Deal [8] suggests reuse as the prior strategy. Reuse imposes reverse networks and operations enabled by collaborative connections and partnerships among actors under the circular economy paradigm [9]. To build and facilitate such connections, data visibility sharing and communication are essential [10].

Literature highlights the need for tailored data architectures to support data visibility throughout the supply chains encompassing reverse flows [11]. Traceability systems are employed in Returnable Transport Items (RTIs) to overview multiple usage phases/cycles [12]. Radio Frequency Identification (RFID) technologies may track reusable containers across the supply chain processes. Furthermore, the development of digital passports under the Internet-of-Things paradigm communicates operational information to the stakeholders [13].

Despite the relevance of data architectures, there is currently no evidence of a data framework designed for primary packaging in the food industry. Reusable primary packaging exhibits inherent complexity and a multitude of attributes to be addressed [14]. When it comes to food products, traceability is guaranteed by sources like companies' IT management software (Enterprise Resource Planning software), resource-embedded sensors, and other secondary data repositories. Unfortunately, the same options are not often viable for packaging and containers. To conclude, the literature agrees that high-quality primary data is crucial for managing and performance monitoring of reusable systems [15], especially when coping with economic and environmental (e.g., LCA) drivers [16].

This study introduces a novel Data Architecture Framework (DAF) explicitly tailored for reusable primary packaging aimed at integrating and standardizing all relevant information concerning actors and closed-loop supply chain operations intended for a circular food packaging industry. This DAF aids decision-making in circular packaging systems, providing hierarchical inputs for optimization problems and quantifying Key Performance Indicators (KPIs) into multi-dimensional (i.e., economic and environmental) dashboards to drive sustainability targets.

2. Material and methods

Effective Reusable Packaging Supply Chain (RPSC) management is crucial in the agri-food industry. This requires coordination among different actors with distinct roles, as shown in Fig. 1. Reusable packaging networks manage two types of logistic flows - the product-packaging forward flow and the used packaging reverse flow. The forward flow starts with manufacturing new containers at the packaging producer facility. The containers are then filled with food at the food packager's facility, and homogeneous unit loads of a specific product-packaging configuration are built. The product is then dispatched to distribution centers for stocking and picking operations before reaching the store to fulfill demand. The reverse flow is triggered when dirty packaging is collected in Reverse Vending Machines (RVMs), which are located near stores or in highly populated urban areas. Consumers can return the packaging and get a deposit. RVMs send the containers to collection and sorting centers before they are sanitized at specific washing facilities. Once cleaned, the reusable packaging is returned to food packagers for a new use cycle, closing the logistic loop. Integrating such forward and reverse operations helps minimize the need for virgin raw materials for packaging.

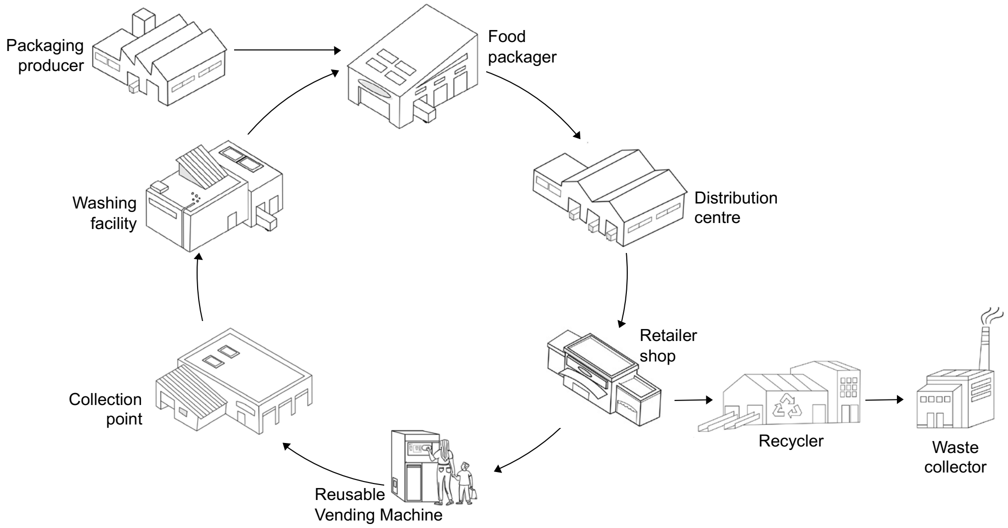

Fig. 1. Reusable packaging supply chain network

Although the framework prioritizes reusable packaging, recycling is considered for broken containers and manufacturing scraps. Reusable packaging leaves the circular network, whether broken or not returned by the consumer.

The proposed DAF consists of two layers: the first is a relational database for RPSC data warehousing; the second aids practitioners with a multi-dimensional dashboard of performance indicators. Such indicators are quantified to respond to queries in natural language, which drive the formulation of data tables, features, and relationships.

In Table 1, the competency questions have a two-fold outlook: the behavior of infrastructures, nodes, and facilities and the overall RPSC circular system. The two layers are closely connected. The first layer is the data architecture designed for data gathering. This layer enables the computation of customized queries and KPIs defined through the user interface, which compose the second layer of the DAF.

Table 1. Competency questions

Specific node competency questions	RPSC competency questions
• *What is the additional cost per node for adopting a reusable policy?* • *How many RVMs should be installed in a specific store to collect all used containers efficiently?* • *By how much should the number of washing lines increase to meet the needs arising from the adoption of reusable packaging?* • *How much should the storage capacity of collection points increase to manage and carry out used container sorting operations effectively?*	• *What is the impact in terms of total travel distance to meet the network demand due to the adoption of reusable packaging? (**Q.1**)* • *What is the impact of packaging hierarchy configuration on logistic efficiency? (**Q.2**)* • *What is the total amount of waste generated when adopting the reusable policy compared to the original case, and how does the selection of packaging impact this?* • *How does the system performance change with variations in consumer behavior related to container return?* • *What is the impact of GHG emissions generated by adopting the reusable policy?*

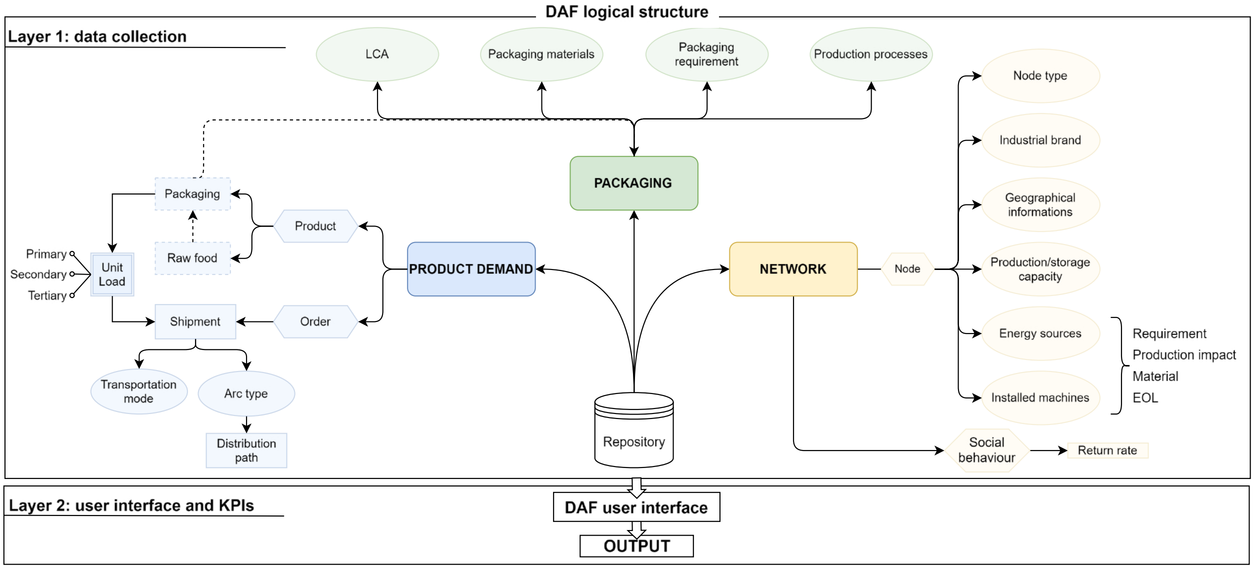

Fig. 2. General data architecture structure

2.1. DAF logical structure

A relational database is the first layer of the DAF. Fig.2 illustrates the data architecture that drives the design of tables and relationships organized through three domains.

The first domain is concerned with geographical data related to the logistics network's infrastructure capabilities. It collects information on the production and storage capacities of nodes, which are impacted by the machinery and systems installed. The domain also considers the environmental footprint of actors' energy sources and machinery. Additionally, it gathers information on citizens' attitudes towards reusable packaging returns since customers are an essential part of the RPSC.

The second domain focuses on the packaging system and collects information about the materials used, production processes, and packaging requirements. The domain also evaluates the sustainability of reusable packaging compared to single-use options by considering both economic and environmental factors.

The third domain outlines data on product demand within the RPSC. Retailers' food product demand drives production and distribution flows, creating orders within the RPSC. These orders are represented as a graph's arcs, with each arc defined by its origin, destination, quantity of product/packaging, and transportation mode. A sequence of arcs defines a possible distribution path. The coupling of raw food with primary packaging and the unit load configuration (i.e., the combination of primary, secondary, and tertiary layers) for the shipment are also considered. Such decisions directly impact the logistic efficiency and environmental performance of a distribution path.

2.2. DAF Entity-Relationship diagram

The database shown in Fig. 3 consists of 48 tables that are connected through foreign keys (FK). These keys establish relationships by referencing primary keys (PK) in other tables.

The tables are divided into three clusters based on their data domains. The yellow tables are related to the logistic network and include facility-oriented data describing geographical and infrastructural properties. The connection between the 'Node' and 'Machine' tables describes the intra-facility technologies and energy sources, which helps quantify air and water emissions and consumption. The network domain also encompasses tables such as

‘ReusabilityParameters’ to gather records of consumer attitudes and behaviors regarding reusable packaging return in the RPSC. The table ‘RVMLocations’ identifies the location of the container collection systems across the network. The light blue tables are designated for the product demand domain.

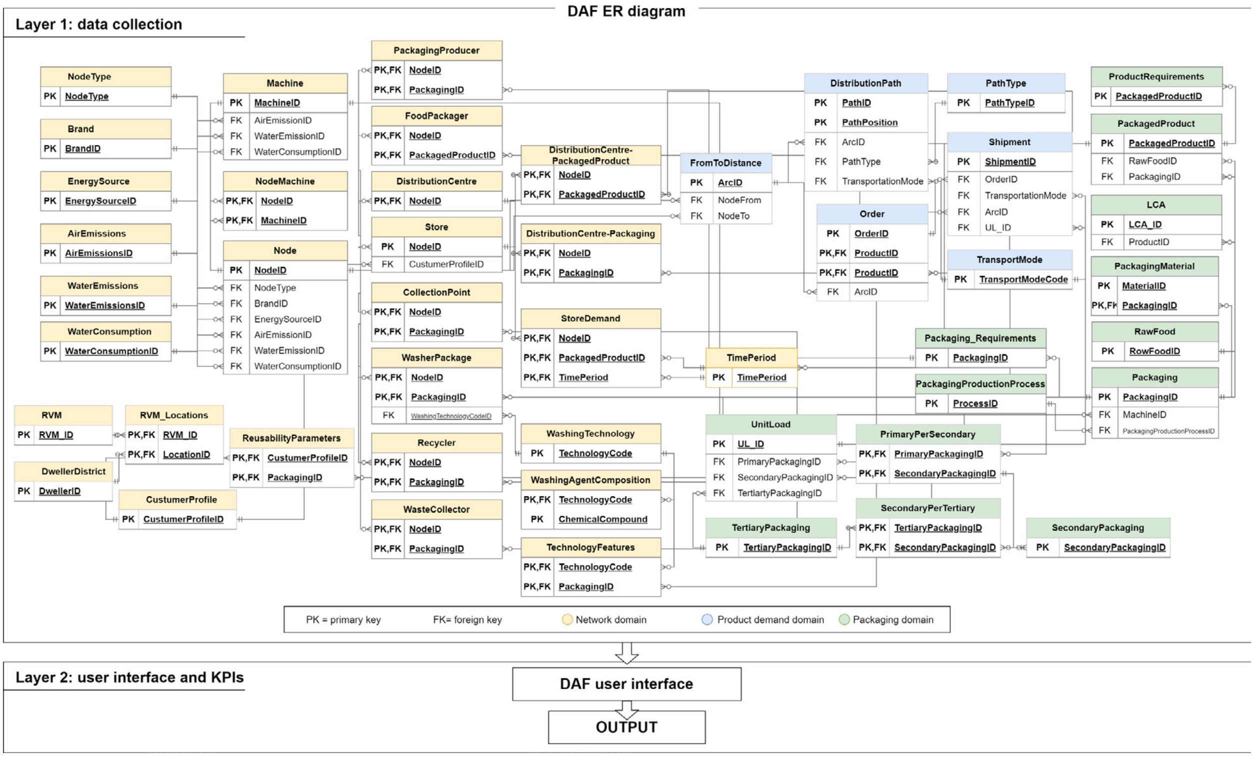

Fig. 3. Database Entity Relationship Diagram

The ‘Order’ table can collect data regarding product and packaging orders between nodes. The relationship between the ‘Order’, ‘Shipment’, and ‘FromToDistance’ tables can be used to trace node connection and product/packaging flows. The ‘DistributionPath’ table collects the sequence of available connections between nodes, which allows for comparing the sustainable performance of different logistic choices.

The green tables refer to the packaging domain. The ‘UnitLoad’ table describes the possible combinations between primary, secondary, and tertiary packaging. The green tables also focus on primary packaging characteristics such as ‘LCA’ and ‘PackagingMaterial’ and their coupling with the raw food items such as ‘PackagedProduct’.

2.3. DAF user interface

The second layer of the system provides support for decision-making with quantified performance indicators, as shown in Fig. 4. These indicators are derived from SQL queries that are constructed and executed by the DAF. The system also allows users to customize the RPSC network through an intuitive user interface, as shown in Fig. 4. Users can narrow down geographical areas and system boundaries by selecting a subset of nodes, transport modes, products, or primary packaging. Using the parameters leverage feature, users can compare multiple scenarios' environmental performance and cost through sensitivity analysis. Users who want to query the database interact with the interface to specify the reference system from which they gain information. Finally, the system extracts the KPIs relevant to the chosen network to address the user's inquiry.

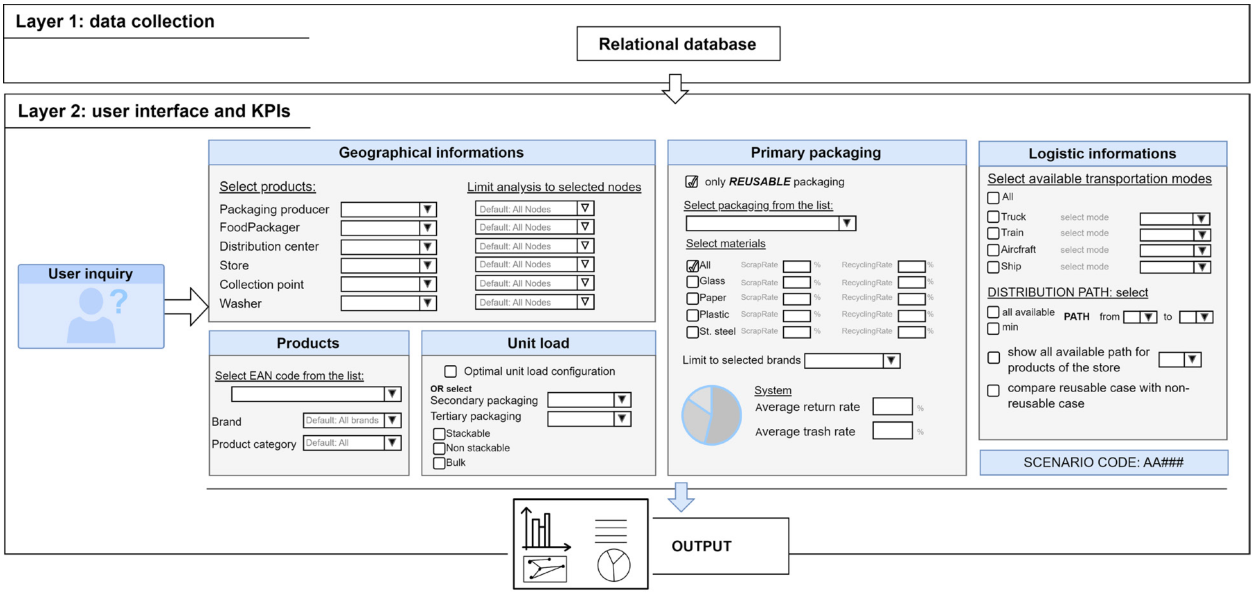

Fig. 4. User inquiry process

3. Application and discussion

The study conducted in a French retailer network showcases the benefits of the proposed DAF. The network consists of 518 nodes, as described in Table 2, and deals with 59 food products that could be combined with 51 different primary packaging types based on product and packaging requirements. The evaluation is conducted over a monthly demand profile and focuses on a single type of RVM and transportation mode. Primary data (i.e., products' demand, node locations, storage capacities, etc.) is gathered through interviews with industries. Secondary data are derived from literature and project assumptions.

Table 2. Case study network nodes

Number of node type			
Packaging producer	110	Collection point	154
Food packager	55	Washer	51
Distribution center	153	Recycler	1
Store	148	Waste node	1

3.1. Waste assessment for packaging selection

A first proof-of-concept entailed assessing the impact of different packaging alternatives on waste production and examining the implications of a reuse policy compared to disposal. In Fig.5, the flow chart illustrates the expected output and the logical pathway for its quantification through the DAF.

We assume food products are wrapped in reusable or disposable packages, and we want to calculate the packaging material waste in both solutions. Customer preferences and attitudes affect the likelihood of choosing one packaging or the other. This justifies the link between the customer profile and the packaging selection in the database, along with the corresponding lever in the user interface. A tailored query (Q.1) gets the geographic boundaries (i.e., North-East of France), the subset of facilities connected to a subset of stores, and distinct product EAN codes to fulfill. The packaging recycling rates are gathered from the EUROSTAT [17] database. Q.1's results, summarized in Table 3, underline a quantitative comparison between reuse and single-use packages in terms of raw material waste. The proposed analysis entails pre-established associations between food products and specific primary packaging, as shown in Table 3.

Table 3. Query for waste assessment for packaging selection

Product ID	Demand [pcs]	Packaging ID	Material ID	Recycled waste [kg]	Non-recycled waste [kg]	Case
P1	80	PKG_28	PP	19.0	31.0	REUSE
P2	222	PKG_28	PP	52.8	86.1	
P3	578	PKG_39	PP	405.8	662.1	
P4	562	PKG_47	Glass	6409.5	1602.4	
P1	80	PKG_A	PP	608.0	992.0	DISPOSE
P2	222	PKG_B	PP	2196.4	3586.6	
P3	578	PKG_C	PP	1687.2	2752.8	
P4	562	PKG_D	HDPE	12813.6	20906.4	

The dashboard resulting from the analysis includes a bar chart, which can be seen in Fig.5. The histogram represents the weight of waste in kilograms for different materials and compares the amount of waste generated by various alternative packaging solutions. The waste from reuse category includes packaging that consumers do not return, the scraps generated during reverse logistics operations, and various washing processes. The waste is divided into two categories based on the average material recycling rate. These categories are potentially treatable waste, indicated in the bar chart with green coloring, and untreated waste, shown in red coloring.

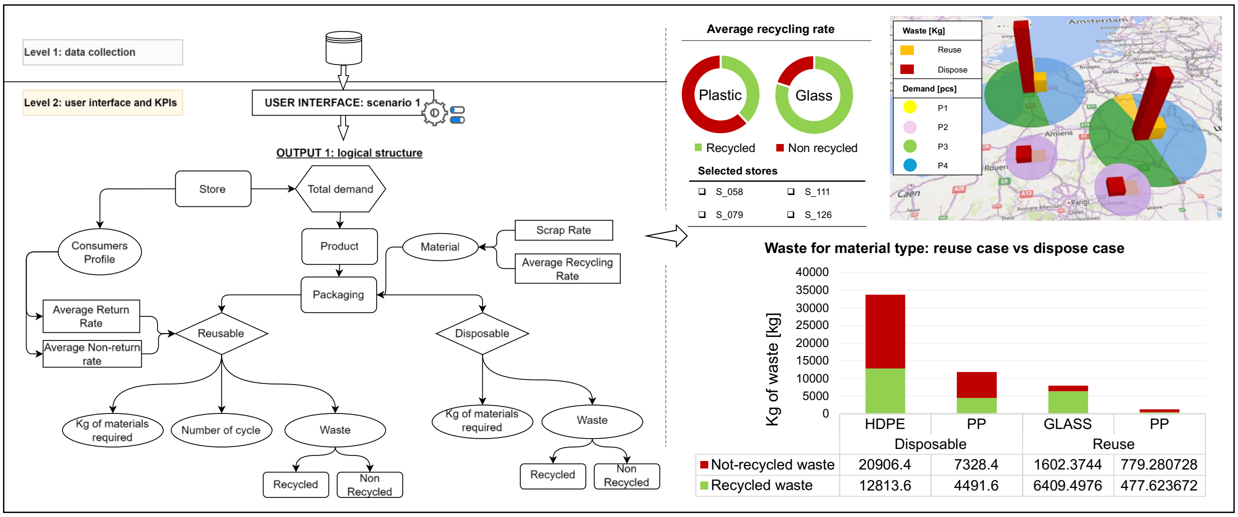

Fig. 5. Output of query for waste assessment for packaging selection

3.2. Logistic performance from the packaging hierarchy

Reusable packaging transportation involves two phases. Firstly, packaged food is delivered from food packagers to retailer's shops via a logistic center. Then, the empty packaging is sent back to the food packagers using reverse logistic operations. This empty packaging facilitates higher stackability than in the forward distribution containers, reducing the volume occupied on a palletized unit load. The selection of primary containers impacts logistic efficiency since packaging stackability depends on material and shape. Logistic efficiency involves maximizing the number of units on a pallet, improving volume saturation rates, and reducing the number of shipments. By optimizing transport operations, RPSC emissions and costs can be decreased. In addition, logistic efficiency can be enhanced through the packaging hierarchy configuration, where DAF helps select the proper primary, secondary, and tertiary combination to maximize the number of containers in a unit load. Another query (Q.2) provides a dashboard to assess the impact of secondary packaging choices through KPI quantification. Q.2 examines different unit load configurations tailored to a specific network narrowed through user interface settings. The proposed application focuses on optimizing the packaging configuration of a primary package called "PKG_28" on an ISO1 pallet by evaluating the allocation of four secondary containers. Solving the Manufacturer Pallet Loading (MPL) optimization problem determines the optimal configuration of secondary containers on a pallet [18].

The logic behind Q.2 is integrated into the DAF, which is shown in the flowchart of Fig. 6. The dashboard provides information on the optimal secondary container to maximize the number of packaged food items (case 1) and empty packaging (case 2) within the palletized load. The DAF quantifies the number of primary packaging per shipment and the resulting loaded weight, given the pallet loading capacity of the transportation vehicle (e.g., 33 pallets). The first case concerning the forward distribution computes the gross weight of the unit load for a specific product, while the second, as for the reverse operations, accounts for the weight of the packaging. This analysis helps compare different packaging configurations in terms of logistic performance and assess transportation costs per unit.

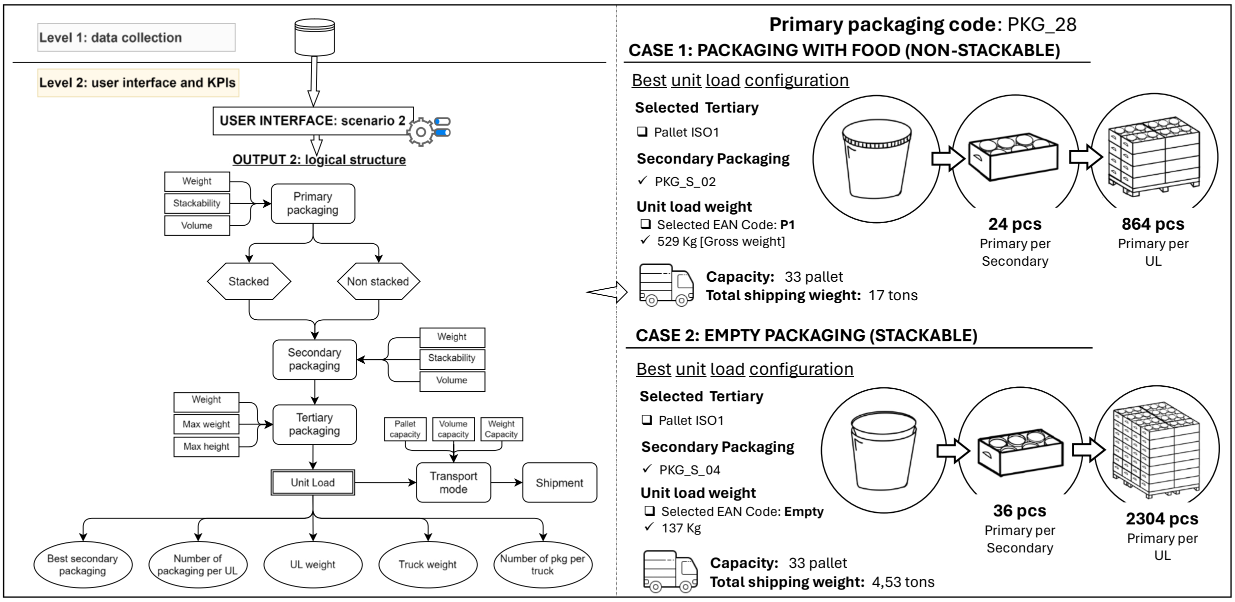

Fig. 6. Packaging hierarchy logistic impact

4. Conclusions

European policies suggest that using reusable primary packaging effectively promotes sustainability in agri-food supply chains. However, implementing sustainable practices in these networks requires a data architecture framework supporting data collection and visibility. While food traceability is guaranteed, this is not the case for packaging. To address this issue, this paper illustrates a flexible Data Architecture Framework (DAF) with a two-fold purpose. Firstly, the DAF facilitates data standardization and warehousing through a specialized database for reusable primary packaging. Secondly, the DAF provides dashboards with KPIs that can assist in decision-making for adopting sustainable practices in the agri-food supply chain. The DAF also provides a user interface that allows the creation of different circular network scenarios that can be compared in terms of economic and environmental performance. The proof-of-concept presented in the article demonstrates the benefits of the DAF in assessing the impact of packaging on waste production and logistic efficiency. In the future, the DAF can be used as an input for decision optimization models aiding strategic and tactical closed-loop package supply chain network design and planning.

The main goal of the DAF is to establish closed-loop networks for a more sustainable agri-food supply chain. By promoting the use of reusable primary packaging, the DAF aims to reduce waste production and raw materials consumption, ensuring economic and environmental sustainability achievements in the field of the food industry.

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