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A Data Architecture to aid Life Cycle Assessment in closed-loop Reusable Plastic Container networks

Baruffaldi G.[a*] , Accorsi R.[b], Volpe L.[b], Manzini R.[b]

a Department of Management and Engineering, University of Padua, Stradella San Nicola 3, 36100, Vicenza, Italy
b Department of Industrial Engineering, University of Bologna – Alma Mater Studiorum, Viale Risorgimento 2, 40136, Bologna, Italy

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Abstract

Returnable container networks have caught the eye of those companies that aim to reduce waste generation and environmental impact. The literature already includes studies on the environmental impact (i.e. Life Cycle Assessment, LCA) of these networks. However, the major part is based on secondary data since the collection of primary data is complex and time-intensive. This paper proposes an object-relational database dedicated to the storage of data from a closed-loop reusable plastic crates (RPC) networks for fruits and vegetables. The goal is supporting scholars and managers during the LCA through a user-friendly data architecture, while suggesting structured guidelines for the primary data collection. Each node of the RPC network is characterized by a similar set of entity types, such as machines, which allows to process the RPCs with respect to specific cycles. Each entity, process and cycle are therefore reflected in the database by objects that are connected with relations.

Keywords: Reusable plastic crates; LCA; closed-loop supply chain; object-oriented database; database architecture.

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[*] Giulia Baruffaldi. Tel.: +39-051-2093405.
E-mail address: giulia.baruffaldi2@unibo.it

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1. Introduction

The key role of reusable packaging in the prevention of waste generation and in the reduction of the energy consumption is recognized by scholars and practitioners alike [1]. Reusable packaging networks entail the implementation of the so-called closed-loop systems, which exploit the reuse of entire products or of some of their parts to maximize the process of value creation over the entire products life-cycle [2] [3]. Closed-loop reusable packaging networks result in reducing the processing of virgin material, contributing to lower the high environmental impact of the package sector. It is worth noting how, according to Plastic Europe, given the market share of end-use applications, the 39.9% of the overall demand for plastic comes precisely from the packaging sector [4].

Focusing on the food industry, the use of reusable package is rising. According to the report from Stiftung Initiative Mehrweg, in Europe the 40% of market share is associated with the usage of reusable package for the transportation of fruit and vegetables [5]. Along with the increasing global concern about the environmental impact reduction, researchers have concentrate efforts on the assessment of the environmental performance of food package through Life Cycle Assessment (LCA) studies [6][7]. Among these, some contributions discuss the environmental impact of reusable plastic crates (RPC) for fresh products [8].

Despite the recognized value of the LCA methodology, researchers point out limitations related to some sources of uncertainties. Particularly, [9] list three causes to the generation of uncertainties. These are the normative choices, the stochastic nature of some of the parameters, and lack of knowledge of the observed system. Particularly, the latter can induce an excessive use of secondary data, therefore, affecting the reliability of the LCA results. This is due to the fact that the collection of primary data is far more complex and requires a deep understanding of the dynamics of the observed system. However, at present, the literature does not include structured guidelines for the collection of primary data on closed-loop RPC networks. For this reason, the aim of this paper is to support scholars and managers during the LCA study by proposing a tailored data architecture for closed-loop RPC networks and to suggest a set of guidelines for the data collection. The proposed data architecture summarizes the characteristics of most important entities that must be taken into account while assessing the environmental impact of a closed-loop RPC network, describing their interactions during the daily execution of the production, the washing, the storage and the transportation of the RPCs. Therefore, this paper not only presents a structured data collector, but also provides a user-friendly tool to map the flows of goods, people and trucks within a closed-loop RPC network during a given time horizon.

This paper is organized as follows. Section 2 outlines an overview of the literature on the topic. Section 3 illustrates the two levels of analysis at the basis of the data architecture, as well as, the tables composing the database. Section 4 describes an example of application of the proposed data architecture to the case study of an Italian RPC pooling company. Section 5 discusses the obtained results and proposed a set of guidelines and, finally, Section 6 concludes the paper and explores some further developments.

2. Literature background

The LCA is an internationally standardized method [10] [11] with structured guidelines [12] for the calculation of the environmental impacts of products or services along the overall value chain, from cradle-to-grave. At present, the study of the environmental impacts of products in closed-loop networks is limited [13] and, among the main contributions, several aim to compare the environmental performance of single-use package and reusable package networks [14]. Particularly, these studies highlight how the complexity generated by the introduction of the washing process and the required backhaul trips highly affects the overall environmental impact of closed-loop reusable packaging networks with respect to single-package systems [15]. Given such complexity, the minimization of the data approximation, caused by errors, uncertainties, statistical variations, subjective judgments, in the study of closed-loop systems assume a pivotal role to produce reliable and robust results [16].

However, despite the topic of data quality has been widely explored in the last years [17], as well as the identification of the methods to calculate the uncertainties [18], the robustness of the results is not easily addressed in many LCA studies [19]. The literature reveals a gap in the development of methods, models and framework for the minimization of the level of approximation of the input data.

3. A data architecture for closed-loop RPC networks

The presented data architecture finds its target users in the managers of RPC pooling networks. For this reason, it is built upon the point of view of the pooler. In other words, it collects all the information required to quantify the effects of those processes that generate costs for the pooler. Such processes are four and involve the transportation, the production, the storage, and washing of RPCs. The following sub-sections deeply analyse the data architecture.

3.1. A two-level data architecture

The presented data architecture is built upon two different levels that are shown in Fig.1.

The *Network level* includes all the actors involved in a closed-loop RPC network. These are the pooler plants, the retailers, the suppliers of fresh products, the plastic recycling centers, and the raw material suppliers. The new RPCs are produced and placed in the network by the pooler plants, which partly buy virgin raw materials (e.g. PP) from the raw material suppliers (1) and partly utilize recycled plastic from recycling centers (2). The latter receive broken RPCs from the pooler plants to be recycled (3). The suppliers of fresh products (e.g. fruit, meat, vegetables products) receive the RPCs by the pooler (4), fill them with the fresh products, and supply the retailers to fulfil their demand (5). After the selling, the retailers return the empty RPCs directly to the pooler (6) or to the suppliers (7). Therefore, such network constitutes a closed-loop system, since RPCs that reach the end of their life are not disposed but re-enter the network as recycled PP.

The *Intra-node level* narrows down the focus to the pooler plant. This can be considered as a sub-network, where nodes are represented by the Control Points (CPs). These are the significant physical locations and zones in the plant layout where the products (as raw materials, semi-finished products or finished RPCs) are handled, stocked and transformed. Specifically, the figure shows some example of Control Points identified by CP1, CP2 and CP3. Whether at the *network level* the same flows configuration can be easily found in different networks, the intra-node flows among Control Points vary greatly with the pooler plant in accordance with the layout characteristics and processes management. Therefore, in order to generalize the set of intra-node flows is indicated in the Figure with the number (8). The combination of these two levels allows to build a comprehensive database, enabling to map the flows of RPCs both outside and inside the pooler plant.

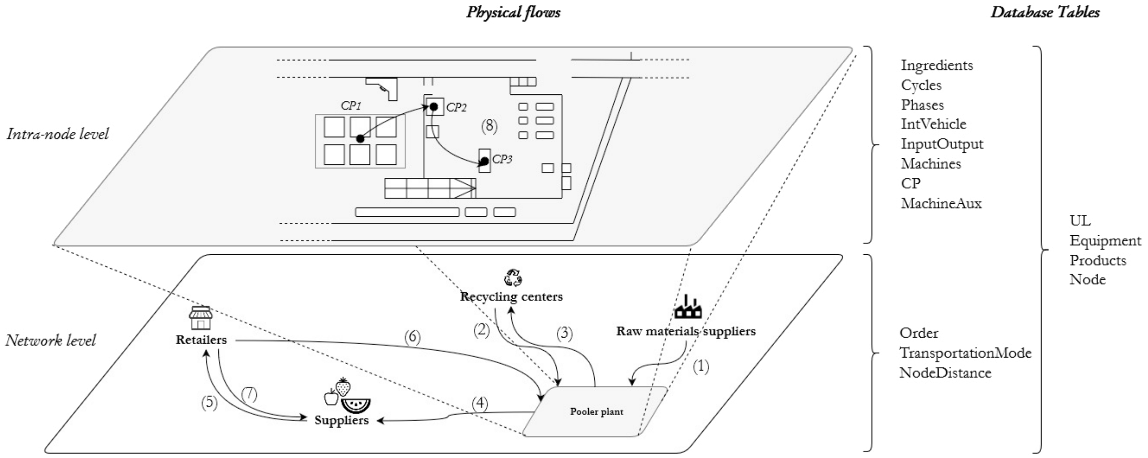

Fig. 1. The two levels of the database.

3.2. The database

The proposed data architecture is developed as a relational SQL database through Microsoft Access. However, it can be easily implemented by the means of different commercial DBMS (e.g. Oracle, Microsoft SQL Server, MySQL).

The database is composed by 15 tables containing all the information required to describe a closed-loop RPC network in its whole. The tables are summarized in the right side of Figure 1 and belong to three sets: 1) those describing the intra-node physical flows of goods and personnel during the production, the storage, and washing of RPCs, 2) the ones describing the physical flows of goods and trucks within the network during the transportation, and, lastly, 3) the tables including the characteristics of those entities (unit loads, equipment, products, and networks nodes) that are common to the two levels. Fig. 3 shows the Entity Relationship Diagram behind the proposed data architecture.

All tables are linked to each other thanks to a set of foreign keys that refer to the primary keys of the other tables. These relations are represented as arrows. As can be seen from the Figure, both arrows and tables belong to different sets characterized by specific colors. Particularly, grey tables belong to 1), green tables belong to 2), and red tables to 3). Consequently, grey arrows have their origin in foreign keys of grey tables, while green arrows depart from green tables and red arrows from red tables. It is worth noting how the number of columns of each table can be highly customizable with respect to the specific observed instance. For this reason and due to space limitations, Fig.1 reports the primary and foreign keys only.

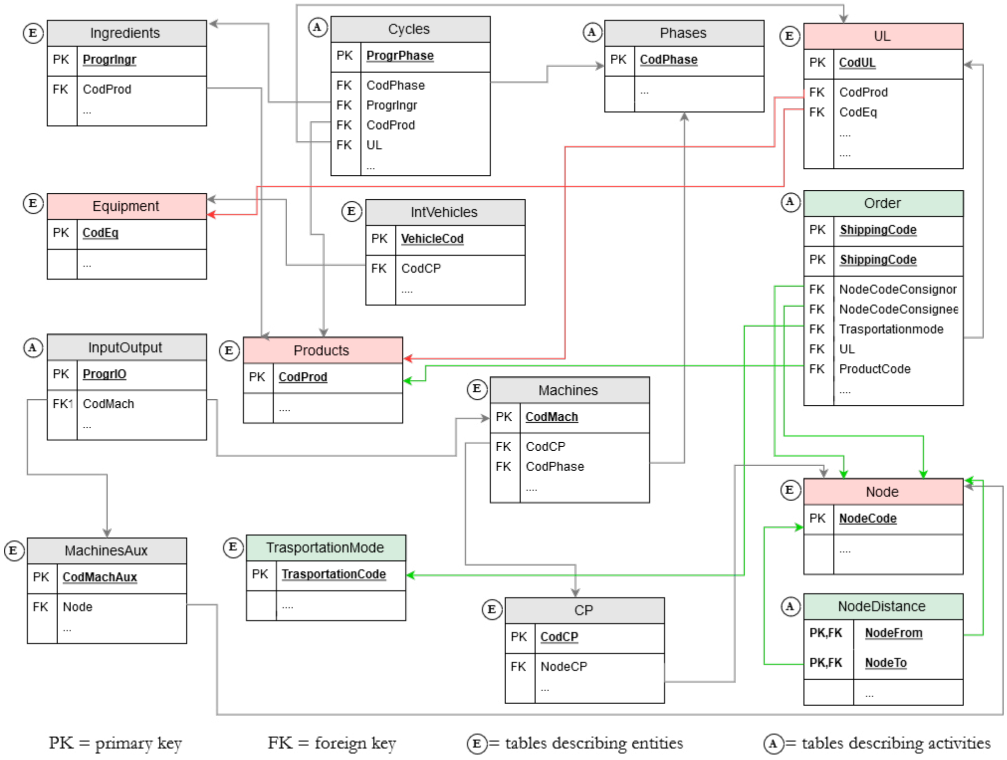

Fig. 2. Entity Relationship (E-R) Diagram.

Another classification is introduced by the letter ‘E’ and ‘A’, which indicate respectively tables collecting the characteristics of the physical entities (e.g. products, transportation means, machines, etc.) and tables including all the information required to describe activities and sub-processes of the four main processes. In other words, ‘A’ tables state the interactions among the physical entities during the daily activities of a pooler plant and a pooling network.

At the *network level,* all the information about the physical locations of the actors of the observed network, i.e. network nodes, are reported in the table ‘Node’, while ‘NodeDistance’ reports the from-to-chart of the distances between each pair of nodes. The table ‘Order’ maps the flows of different type of RPCs, whose characteristics are described in ‘Products’, within the network collecting all the information described in the set of shipping documents referring to a given horizon of time. Since the transport process entails the use of different transport modes (i.e. road, sea, air), the table ‘TransportMode’ gathers the characteristics of each specific transport means, such as capacity, emissions and class. In addition, the information on the shipping units (e.g. dimensions, weight, volume) are reported in the table ‘UL’.

At the *intra-node level*, the production, the washing and the storage of the RPCs, in turn, involves a set of sub-processes or phases (see table ‘Phases’), which are included into working cycles (see table ‘Cycles’) that state the order of execution of the phases, the obtained final products, the utilized materials (described in the table ‘Ingredients’) and the type of palletization. Each phase can involve both manual activities, e.g. the RPC repair, and automatic activities, such as the washing of RPCs through a washing machines. All the characteristics of the utilized machines are listed in the table ‘Machines’ (e.g. speed, dimensions, and capacity), while the table ‘MachinesAux’ includes all the auxiliary machines that are not utilized in a specific phase but serve the whole plant, such as the air conditioning system. In addition, the table ‘InputOutput’ lists the set of inputs and output of each machine, including the amount of energy consumption, the generated waste and the environmental emissions. Among the phases, some involve the handling of finished or semi-finished products between CPs (see ‘CP’). Therefore, the types of utilized containers or pallets (e.g. EPAL) to move such products among the CPs are listed in the table ‘Equipments’, while the type of handling unit is reported in the table ‘UL’, similarly to the shipping units. Finally, the table ‘IntVehicles’ includes all the means for the handling of products, such as walkie stacker and forklift trucks.

4. Example of application

To assess the benefits generated by the application of the proposed data architecture to map a real-world instance, the case of an Italian closed-loop RPCs pooling network was analyzed. This application represents the first step of an ampler project in which the final aim deals with a LCA study. Outcomes of the project are out of the scope of this paper. However, the application of the proposed data architecture during the data gathering provides the readers with a valuable proof-of-concept.

The observed network includes more than 1000 vegetable, fruit and meat suppliers, which distribute to retailers located all over the Italian country, a set of pooler facilities located in each Italian region, a recycling center and a raw material supplier. The data collection process was carried out through the extraction of data from the company ERP and through the direct observation of the operators inside the principal pooler plant located in the Emilia Romagna region. Since this process is highly time- and cost-intensive, the current version of the database includes only information on the principal pooler plant. This performs the production, the storage and washing processes, rather than other smaller plants. The pooler produces four types of RPCs starting from more than 60 different ingredients as listed in the table ‘Ingredients’. The study of the layout and the direct observation of the operators during the working shifts allowed to identify 56 Control Points and 64 phases. With respect to the transportation process, the database includes data related to an observed horizon of time of one year. Particularly, the table ‘Order’ contains 671,560 shippings where more than 965,300 tons of RPCs were transported among the 1609 nodes of the network.

The extensive phase of data gathering to fill the data tables was rewarded by the ease in consulting the database to export data for the LCA study. In order to showcase how pooler managers and scholars can easily utilize the proposed database to extract data on the observed system, the following sub-sections illustrate three viable analysis resulting from three possible SQL query.

4.1. Working cycles details

Query 1 allows to gain information on the working cycles. Particularly, Tab.1 represents the formulation of the query in the SQL language and a sample of the resulting data table. This reports the phases and the ingredients required to produce Prod1, including the total working time.

Table 1. Example of the results from Query 1.

Products	Phases	Phases description	Ingredients	Ingredients Description	Total Working Time
Prod1	40	Molding	2	Recycled PP	450 s.
Prod1	40	Molding	3	Virgin PP	455 s.
Prod1	41	Handling trough conveyor	6	Prod1	10 s.

Query formulation:

```
SELECT Cycles.CodProd, Phases.CodPhase, Phases.DescrPhase, Ingredients.CodIngr, Ingredients.DescrIngr, Sum (Cycles.WorkingTime) AS
SommaDiWorkingTime FROM Phases INNER JOIN (Ingredients INNER JOIN Cycles ON Ingredients.ProgrIngr = Cycles.ProgrIngr) ON Phases.CodPhase
= Cycles.CodPhase GROUP BY Cycles.CodProd, Phases.CodPhase, Phases.DescrPhase, Ingredients.CodIngr, Ingredients.DescrIngr HAVING
(((Cycles.CodProd)= "Prod1"));
```

4.2. Travelling information

Query 2 focuses on the *Network level*, cumulating the total travelled distance per day. Particularly, a time horizon of 15 days is selected, from October 1st to October 15th. Figure 3 reports the query formulation and its visual representation through a histogram. The figure also shows the number of shipments per day.

Query formulation:

```
SELECT Order.DeliveryDate, Order.ShippingCode, Sum(NodeDistance. DistanceRoad) AS
SommaDiDistanceRoad FROM [Order] INNER JOIN NodeDistance ON (Order.NodeCodeConsignee =
NodeDistance.NodeCodeTo) AND (Order.NodeCodeConsignor = NodeDistance.NodeCodeFrom) GROUP BY
Order.DeliveryDate, Order.ShippingCode HAVING (((Order.DeliveryDate) Between #Oct.1# And #Oct.15#));
```

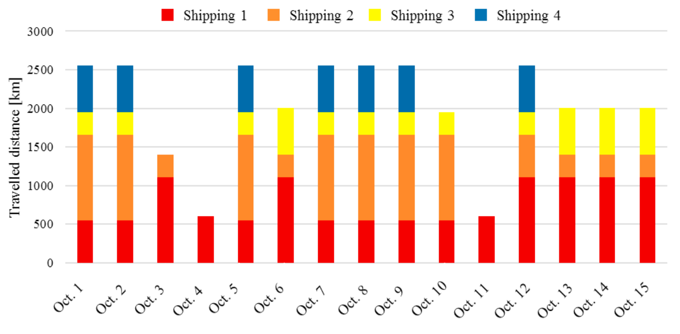

Fig. 3. Results from Query 2.

4.3. Network distribution

Query formulation:

```
SELECT Order.NodeCodeConsignor,
Node.Province, Count(Order.PdkQuantity) AS
ConteggioDiPdkQuantity, Order.DeliveryDate
FROM Node INNER JOIN [Order] ON
Node.NodeCode =
Order.NodeCodeConsignee
GROUP BY Order.NodeCodeConsignor,
Node.Province, Order.DeliveryDate
HAVING
(((Order.NodeCodeConsignor)=“Pooler plant
1" Or (Order.NodeCodeConsignor)=“Pooler
plant 2“Or
(Order.NodeCodeConsignor)=“Pooler plant
3") AND ((Order.DeliveryDate) Between
#Sep.1# And #Dec.1#));
```

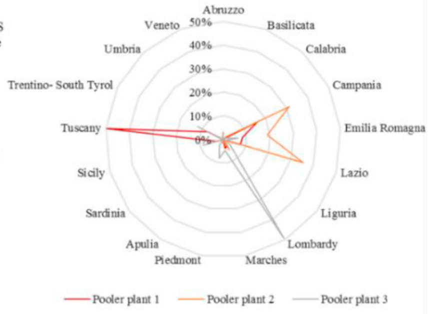

Fig. 4. Results from Query 3.

Query 3 can be used to analyze the flows of empty RPCs sent by the pooler plants to the suppliers. Particularly, the radar graph in Fig.4, underpinned by the query, compares the geographical distribution of the suppliers served by three pooler plants. The axes represent the Italian region, while the colored lines show the percentage of nodes served by each pooler for each region along a time horizon of three months (from September 1st to December 1st). As instance, the 50 % of the nodes served by the pooler plant 1is located in Tuscany.

5. Discussion and guidelines

Despite the need of further analysis and other case studies to validate the proposed data architecture, results give rise to some considerations. Outcomes from the previous section highlights the relative ease of consultation of the data architecture and introduce some possible types of data analysis. Nevertheless, the data collection process requires a considerable amount of time and resources (i.e. working hours) according to the principle that the reliability of the results rely on the accuracy of the data input. For this reason, a set of guidelines is proposed for the application of the data architecture to real-world instances. These are summarized in the following.

- An initial phase of general comprehension of the system is fundamental for the database filling. Particularly, to explore the *intra-node level*, the direct observation of the operators during the working shifts allows to identify the flows of goods and people across the plant and, furthermore, to identify the Control Points.

- The data provided by the company ERP are often ‘rough’. In other words, it includes duplicates, missing values and wrong formats. The phase of data cleaning could require a significant amount of time and, therefore, should be taken into account while developing the project plan.

- A great deal of attention should be devoted to the codification, such as the creation of codes whenever not present in the company’s data. This could facilitate the query formulation and the data analysis.

- In order to verify the correctness of the imported data, the continuous control of the database should be realized through the run of ‘control query’ to detect possible missing data or mistakes.

6. Conclusion

This paper proposes a data architecture tailored for closed-loop reusable plastic crates (RPC) networks. The aim of the paper is to support managers and scholars in the data collection process for the realization of LCA studies. The data architecture is articulated among two levels of analysis and is developed through a relational SQL database, including 15 tables. In order to provide an example of its application to a real-world instance, a case study provided by an Italian RPC pooling company is illustrated. Despite the fact that the results of the LCA study are out of the scope of this paper, some analyses showcase the benefits generated by the database. Furthermore, a set of guidelines supporting managers and scholars during the application of the data architecture to other real-world instances are provided. Ample opportunities exist for future research in the development of graphic user interfaces to facilitate the interaction between the user and the data architecture. In addition, the analysis of other case studies could allow to further standardize the protocol of application of the data architecture, enabling also to extend the number of target sectors (e.g. reusable containers for machines’ parts).

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