A closed-loop packaging network design model to foster infinitely reusable and recyclable containers in food industry

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Abstract

The current public and private policies pursuing environmental sustainability targets mandate incisive management of packaging waste, starting with those sectors that use virgin materials most. Food industries and food supply chains adopt huge volumes of plastic crates, cardboard boxes, and wooden boxes as transport packaging, thereby representing a hotspot and an urgent call for scholars and practitioners to address. Whilst wooden and cardboard boxes are disposable solutions, plastic containers can be employed as infinitely reusable and recyclable packages but require complex logistic systems to manage their life cycle. Optimization techniques can be exploited to aid the design and profitability of such complex packaging networks. This paper falls within the scarce literature on the design of pooling networks for reusable containers in the food industry. It proposes a strategic mixed-integer linear programming model to design a closed-loop system from the perspective of the packaging maker responsible for serving a food supply chain. The container's lifespan, i.e. the number of cycles a package can be reused before recycling, represents a crucial aspect to consider when modeling such networks. Incorporating lifespan constraints within the proposed closed-loop network design model is the main novel contribution we provide to the literature. This model is applied to a real-world instance of an Italian package pooler operating with a consortium of large-scale retailers for the distribution of fruits, vegetables, bakery, and meat products. A multi-scenario what-if analysis showcases how the optimal network evolves according to potential variations in the packaging demand, as well as in the container lifespan, demonstrating how to lead packaging makers to the profitability and the long-term sustainability of the closed-loop network.

Keywords: Reusable plastic container, Packaging, Recycling, Food supply chain, Closed-loop network, Optimization.

1. Introduction

The current public and private policies pursuing environmental sustainability targets mandate incisive management of packaging which accounts, so far, for 15% of the municipal solid waste, and shows an increasing trend (OECD, 2013; Eurostat, 2017). To face this issue, the European Waste Framework Directive (2008/98/EC) stated the importance of preventing waste generation. The European Council Directive on Packaging (2004/12/EC) indeed prioritizes the reuse of packaging, before recycling and recovery, as the main strategy to implement in those sectors that use virgin materials most (Corvellec, 2016).

Food industries and food supply chains adopt huge volumes of transport packaging, thereby representing an urgent call for scholars and practitioners to address. Given the nature of food, consumed every day and needing protection until consumption, the contribution of packaging to the entire environmental impact of the food industry is estimated at almost 45% depending on product variety and package material (Del Borghi et al., 2014). Some investigated the environmental impact of packaging in several areas and processes of the food industry by the mean of the Life Cycle Assessment (LCA) analysis (Toniolo et al., 2013; Siracusa et al., 2014; Del Borghi et al., 2018) and confirmed that most carbon emissions result from the use of virgin materials. Beyond the technological barriers to the adoption of waste-reducing eco-innovations in the packaged food sector (Vitale et al., 2018; Simms et al., 2020), reusable packaging represents a promising strategy for preventing virgin materials extraction and reducing such impacts (Tonn et al., 2014).

In Europe, reusable packaging employed for distributing fruit and vegetable products accounts for 40% of the sector (Stiftung Initiative Mehrweg, 2009). Whilst wooden and cardboard boxes are disposable solutions, plastic containers can be employed as infinitely reusable and recyclable packages but require complex logistic systems to manage their life cycle. Reusable packaging systems require more logistic operations than disposable packaging: the collection of containers after use, the storage, the cleaning (especially in the food sector), and the recycling at end of life (Wu and Dunn, 1995; Pålsson and Hellström, 2016). The debate around reusable package compels then analyzing the impacts that such logistic processes have (Baruffaldi et al., 2019).

Some compared the environmental impact of reusable and disposable food packaging through LCA analyses (Kostela et al., 2014). Levi et al. (2011) stated that the Reusable Plastic Containers (RPCs) lead to environmental benefits but that the transportation phase might enhance costs and carbon emissions more with reusable than with disposable packaging. In addition to the complexity of logistic operations, Salhofer et al. (2008) underlined that higher management costs, the absence of a collaborative strategy among supply chain actors, and conflicts of interest might discourage RPCs.

In this scenario, optimization techniques can be exploited to aid the design and profitability of such complex packaging networks (Govindan et al., 2015; Resat and Unsal, 2019). Optimization could find the enabling conditions for adopting RPCs within the food supply chain by modeling the integrated food and packaging networks. The food industry is characterized by a multitude of actors and facilities (i.e. growers, producers, packagers, retailers) whose capacities, locations, and connections affect the overall cost of products and services. The forward and reverse flows of reusable packaging exacerbate the complexity of the logistics but could provide costs and environmental benefits whether optimized. Because of the large volumes of food and package and the number of supply chain actors involved, the food retailer chain represents the environment of reference for this paper. Figure 1 draws the main players and nodes within the network. The suppliers pack food received from growers into containers shipped by the package provider, i.e. the pooler, then serve the retailers' distribution centers. Whilst disposable containers are delivered to the retailers' shops and sent to end of life treatments, RPCs are collected from the retailers and managed at the pooler's plants, thus entailing a tight interaction between the retailer and the pooler. The pooler decision-making concerns the location of the plants, the utilization of production, storage, and washing capacities, the transport of containers across the network. Whether optimally made, such decisions guarantee profitability to the pooler and long-term sustainability of the closed-loop network of reusable containers.

This paper fosters the adoption of reusable containers in the food industry by proposing an optimization mixed-integer linear programming model (MILP) intended to design the pooler's reusable packaging network. After a lifespan of several years, the reusable containers are sent to recycling to produce new crates. The proposed model sets the former number of available containers and forces the fulfillment of the packaging demand over the planning horizon fostering infinitely reuse and recycling. A set of tailored constraints formulated in the model manage the containers' lifespan and enable exploring the thresholds of packaging demand satisfied with a fixed volume of initial plastic. Therefore, this model supports the cost-effective management of the closed-loop network whilst reducing the extraction of virgin material.

The remainder of the paper is organized as follows. Section 2 provides the background to the field and summarizes the literature on closed-loop packaging networks. Section 3 formulates the models with the objective, the assumptions, and the boundaries of the analysis. Section 4 presents a case study of the retail supply chain. A sensitivity analysis illustrates future scenarios of the pooler's network while Section 5 discusses the obtained solutions and findings. Lastly, Section 6 concludes the paper and lists further directions of the research.

2. Background and literature review

Closed-loop supply chain (CLSC) combines forward distribution operations with reverse logistics, which includes the handling, storage, and transport of reusable products, components, waste, or packaging (Tibben-Lembke, 2002, Di Francesco and Huchzermeier, 2016; Battini et al., 2017). The management of CLSC entails identifying the compromise between the impacts of reverse operations (e.g. transport flows) and the benefit of reducing the extraction of virgin materials (Ross and Evans, 2003, Brüning and Jacobsen, 2016). Krikke (2010) and (2011) provided proofs of this in the automotive and copiers sectors respectively encouraging the remanufacturing of equal-to-new quality products to gain both economic and environmental benefits.

The impact of transportation on the environmental and economic sustainability of CLSC has been early enquired by Pearce (1997). In his article, Pearce turns on its head the conventional wisdom about recycling, underlining the costs and impacts of waste collection and treatment. Recently, Bazan et al. (2016) surveyed the inventory management problem in closed-loop networks revealing the issues behind the good practice. The impact of transport operations for disposable and reusable packaging in the fruits and vegetable sector is assessed by Albrecht et al. (2013) through LCA analysis. In their surveys, Diabat et al. (2013) and Aravendan and Panneerselvam (2014) conclude that support-decision models to manage facility location and transport operations are needed to achieve the economic sustainability of the CLSC. For comprehensive review on CLSC design support models refer to Guide and Van Wassenhove (2009) and recently by Stindt and Sahamie (2014), whilst Ko and Evans (2007), Pedram et al. (2017) and Accorsi et al. (2015) modeled 3PL, tire industry, and furniture closed-loop networks respectively.

Less attention is given to design closed-loop networks for reusable packaging and returnable transport items. Jarhe and Hatteland (2004) studied the adoption of returnable roll-racks for the distribution of fresh milk. Singh et al. (2006) illustrated the implementation of RPCs in the food retail sector and highlighted relevant economic and environmental advantages for all stakeholders. Kostela et al. (2014) compared the impacts of RPCs and recyclable corrugated cardboard boxes in bread distribution revealing a lower carbon footprint of recyclable cardboard boxes. Accorsi et al. (2014) overviewed the economic and environmental savings of disposable and reusable containers in the fruit and vegetable catering sector. Both concluded that transportation played a very important role in the environmental impacts of the analyzed systems and that changes in logistic network distances could affect the results considerably.

A few studies focused on support-design methods, optimization, and simulation of reusable packaging networks. Cheng and Jang (2005) used simulation to assess operational cost-benefits of reusable transport container in the automotive sector. Chung et al. (2018) provided a modified genetic algorithm that maximize the reuse of tertiary packaging in CLSC. Soysal (2016) proposed an inventory-routing MILP model for returnable transport items that involves for forward and reverse transport operations and explicit fuel consumption within an uncertain environment. Elia and Gnoni (2015) developed a simulation-based tool to aid design a pooling network for pallet management. Carrano et al. (2015) and Accorsi et al. (2019) illustrated alternative pallet management scenarios through carbon footprint analysis both concluding that optimization models to design closed-loop networks are needed. Soysal (2016) and Iassinovskaia et al. (2017) propose

probabilistic and deterministic MILP inventory-routing models for reusable handling items and adopt simulation and metaheuristics to solve large-instances, respectively. However, they both focused on operational issues and left the design of the pooler's network uncovered. Tornese et al. (2018) used agent-based simulation to study a pallet network and define strategies (e.g. reducing the logistic distance from the remanufacturer) to minimize environmental impacts and costs. Bortolini et al. (2018) proposed a bi-objective optimization model to set the theoretical mix between disposable and reusable containers within a regional catering supply chain yet illustrated in Accorsi et al. (2014). Nevertheless, this study identifies the optimal mix of disposable and reusable containers for the whole chain, without addressing to the target of any actor involved (i.e. catering firm, distribution center, pooler, suppliers), neither to the profitability of the package pooler.
Table 1 summarizes a comparative literature review on reusable packaging networks. Contributions are classified by the perspective of analysis, the boundaries of the network, the support-design approach and the solving method, and the case study under investigation alike.

[Insert Table 1 about here]

Table 1. Comparative literature review on reusable packaging networks.

To guarantee the profitability of the package pooler and, hence, the long-term sustainability of the reusable packaging network, this paper provides a MILP model intended to design the pooler's logistic network. Compared to the literature, the novel contribution of this model lies in supporting the pooler's decision-making in the retail food supply chain, whilst incorporating containers lifespan constraints and fixing the overall capacity of virgin material within the closed-loop network. In fact, the proposed model sets the former number of available containers (i.e. which corresponds to a volume of virgin plastic within the network) and forces the fulfillment of the packaging demand over the planning horizon fostering infinitely reuse and recycling after a lifespan of several years. Aiding the pooler's network planning, this model reveals the enabling conditions for fulfilling the food containers demand over time, fostering the transition toward circular packaging ecosystems in the food industry. Such benefits are shortlisted in the following Research Questions (RQ), which this study attempts to respond:

- *RQ 1*. How to define the optimal configuration of a closed-loop packaging network constrained to containers' storage and washing capacities?
- *RQ 2*. How to accomplish with varying packaging demand in compliance with a fixed number of available containers and lifespan constraints?

To the authors' knowledge, this model is a first attempt to integrate the design of closed-loop reusable containers networks under package lifespan constraints.

3. Methodology

This section formulates an optimization MILP model to design the pooler's closed-loop packaging network serving a nation-wide retail food supply chain. The model aims (1) to locate new pooler's plants, (2) to allocate the flows of reusable containers to either the food suppliers or the retailer's distribution centers, (3) to collect the containers from the retailer and wash them at the pooler's plants, (4) and to recycle the containers at end of life and remanufacture new package, whilst minimizing the overall pooler's costs. The objective function minimizes the infrastructural costs for new facilities and the operational costs for container transportation, storage, washing, and recycling/remanufacturing. Other operating costs are negligible because containers are typically stored in non-refrigerated block-stacking systems and handling operations are already paid within the storage costs. By optimizing the pooler's costs, the model contributes to reducing the service fee paid by retailers and food suppliers, thereby encouraging the adoption of RPCs instead of disposable packaging.

Whilst this model is cost-driven, environmental aspects are considered by fixing the overall capacity of virgin material within the closed-loop network and incorporating containers lifespan constraints that impose new containers remanufactured solely as recycling of disposed ones.

The undertaken assumptions and the problem boundaries are illustrated in Figure 1, while the model's notation and formulation are presented in the following sub-sessions.

[Insert Figure 1 about here]

Figure 1. Infinitely reusable and recyclable packaging network framework.

3.1. Network modeling

The pooler's network includes several actors operating in the retail food supply chain as exemplified in Figure 2 through the following numerical references. There are food suppliers providing fruits, vegetables, meat, and bakery products, the retailer's distribution centers which demand packed food, and the retailer's stores served by the distribution center (0). The pooler collects and sanitizes the RPCs (1), provides recovery treatments and recycling at containers' end of life (2), then supplies clean containers on demand. Containers washing, a peculiarity of reusable packaging in the food industry, is intended for reducing the transfer of pathogens (e.g., *E. Coli*) from the package to the product, and is recommended for fruits and vegetable (Lanciotti et al., 2014; Siroli et al., 2015) but mandatory for meat.

Usually, the pooler serves the retailer's distribution centers (3) rather than the suppliers directly (4). In such a scenario, the suppliers (3.1) collect clean containers in the return trip of food distribution. The dirty containers are held at the retailer's stores until collected by a return trip or directly by the pooler. In the former scenario, the containers are temporarily stored at the retailer's distribution center and collected by the pooler (5). In the latter uncommon scenario, the containers are retrieved by the pooler from the stores with a milk-run tour.

The optimization of the network logistic distances leads to the minimization of the reusable packaging service costs, whilst the geographic distribution of food suppliers and consumer areas might affect the optimum considerably. Unbalanced containers inventory is distributed among the pooler's facilities (6) to avoid shortage and meet the packaging demand from the nearby facility.

[Insert Figure 2 about here]

Figure 2. Reusable packaging network and model notation.

3.2. Problem formulation

We consider a set of P pooler facilities (including current and new ones), a set of S supplier facilities, and a set of C retailer's distribution centers operating in the network. We recognize three types of pooler facilities, the so-called facility uses: a generic storage facility, a storage, and washing facility, and a storage, washing, and manufacturing facility. These evidently incur different fixed and variable costs. Each facility has its own storage, washing, and production capacity. The opening costs of each facility i of usage u is defined by CP_{iu}. While the opening costs are quantified in terms of the initial investment, the mortgages for the existing facilities are not differential and hence neglected. Opening a new facility with *manufacturing use* increases the recycling capacity of the network and enables re-manufacturing the containers nearby the retailer's distribution centers.

The containers are reused for several periods and then recycled to manufacture new packaging. This horizon is called lifespan L (expressed as an integer number of time periods). Since the pooler manufactured the current containers population over a decade, the residual life of containers is different. The distribution of residual life among the containers (i.e. at $t = 0$) is incorporated into the model through the set c, defined as class of residual life.

The *washing use* of the facility enables sanitizing the containers received from the retailer. The set D represents the status of a container flow (i.e. dirty or clean). To evaluate the operating costs generated within the network the parameters $Cprod$, $Cstock$, and CL_i are defined for the container remanufacturing, storage, and washing, respectively. The unit washing cost CL_i varies with the facility i because of different water grid costs occurred in several geographic regions. Alternative transportation modes to truck (i.e., railways, seaways) are not considered in the model and left to future research investigations. The unit transport costs are defined per each arc of the network given the route and the number of closed containers loaded per truck (i.e. 8000 RPCs/shipment). Lastly, the packaging demand is given for the suppliers and the retailers as dom_{jt} and $cons_{zt}$ respectively for all periods t of the planning horizon T. The model sets, parameters, and decision variables are formulated as follows.

Sets

$i,i' \in P$ Pooler facilities.

$u \in U:\{1, 2, 3\}$ Use of a plant: *1* is for the storage facility; *2* is for the storage and washing facility; *3* is for the storage, washing and production facility.

$d \in D:\{1,2\}$ Status of the RPC: *1* for a dirty RPC; *2* for a clean RPC.

$j \in S$ Suppliers providing food products.

$z \in C$ Retailer warehouse generating dirty RPCs

$t \in T$ Time periods

$c \in K$ Class of containers' residual life

Parameters

dom_{jt}	RPCs demand to fulfill in period t from supplier j (e.g., annual number of RPCs)
$cons_{zt}$	RPC consumption in t from market z (e.g., annual number of RPCs)
$stock_i$	Storage capacity of facility i (RPCs per period t)
lav_{iu}	Washing capacity of facility i with use u (RPCs per period t)
$prod_{iu}$	Production capacity of facility i with use u (RPCs per period t)
CP_{iu}	Opening cost for facility i with use u (€/facility).
CTF_{ij}	Cost of transportation of an RPC from facility i to supplier j via truck (€/RPC)
CTC_{zi}	Cost of transportation of an RPC from shop z to facility i via truck (€/RPC)
$CT_{ii'}$	Cost of transportation of an RPC from facility i to facility i' via truck (€/RPC)
$Cprod$	Cost of production (€/RPC)
CL_i	Cost of washing (€/RPC)
$Cstock$	Cost of storage (€/t RPC)
L	RPC lifespan (integer time periods)

n_c	Lot of production of RPCs of class *c*
m	Very small number
M	Very large number

Decision variables

We distinguish four types of decision variables. The first includes binary decision variables that open new facilities. The second contains the flows of RPCs remanufactured, stored, washed into a generic facility, whilst the third type describes the flows of RPCs throughout the closed-loop network. Lastly, EOL_{ct} expresses the residual life span of the containers at time *t*.

y_{iut}	1 if plant *i* with use *u* is open in *t*; 0 otherwise.
φ_{ct}	1 if RPCs of class *c* must be recycled and remanufactured in *t*; 0 otherwise.
wr_{iut}	Stock of clean RPCs in plant *i* with use *u* at time *t* (RPC)
wl_{iut}	Stock of RPCs to be washed in plant *i* with use *u* at time *t* (RPC)
xp_{iut}	RPCs produced by plant *i* with use *u* at time *t* (RPC)
xl_{iut}	RPCs washed by plant *i* with use *u* at time *t* (RPC)
xf_{ijt}	flow of RPCs from plant *i* to supplier *j* at time *t* (RPC)
xc_{zit}	flow of RPCs from customer *z* and plant *i* at time *t* (RPC)
$x_{ii'td}$	flow of RPCs in status *d* from plant *i* to plant *i'* at time *t* (RPC)
EOL_{ct}	residual life of the RPC of class *c* at period *t* (t)

Objective Function

The model is built on a single objective function (1), defined as follows:

$$min \sum_{i=1}^{P}\sum_{u=1}^{U}\sum_{t=1}^{T} CP_{iu}\cdot y_{iut} +$$
$$\sum_{i=1}^{P}\sum_{j=1}^{S}\sum_{t=1}^{T} CTF_{ijb}\cdot xf_{ijt} +$$
$$\sum_{i=1}^{P}\sum_{z=1}^{C}\sum_{t=1}^{T} CTC_{zi}\cdot xc_{zit} +$$
$$\sum_{i=1}^{P}\sum_{i'=1}^{P}\sum_{t=1}^{T}\sum_{d=1}^{D} CT_{ii'}\cdot x_{ii'td} +$$
$$\sum_{u=1}^{U}\sum_{i=1}^{P}\sum_{t=1}^{T} Cprod\cdot xp_{iut} +$$
$$\sum_{u=1}^{U}\sum_{i=1}^{P}\sum_{t=1}^{T} Cstock\cdot (wr_{iut} + wl_{iut}) +$$
$$\sum_{u=1}^{U}\sum_{i=1}^{P}\sum_{t=1}^{T} Cl_{i}\cdot xl_{iut}$$

The term $\sum_{i=1}^{P}\sum_{u=1}^{U}\sum_{t=1}^{T} CP_{iu} \cdot y_{iut}$ of Equation (1) accounts for the infrastructural cost of opening new facilities in planning period T with use u. The term $\sum_{i=1}^{P}\sum_{j=1}^{S}\sum_{t=1}^{T} CTF_{ij} \cdot xf_{ijt}$ of Equation (1) represents the cost of transportation from the P facility to the S supplier in the planning horizon T. Similarly, $\sum_{i=1}^{P}\sum_{z=1}^{C}\sum_{t=1}^{T} CTC_{zi} \cdot xc_{zit}$ is the cost of transportation from the retailer's distribution centers to the pooler plants in T. In Equation (1), $\sum_{i=1}^{P}\sum_{i'=1}^{P}\sum_{t=1}^{T}\sum_{d=1}^{D} CT_{ii'} \cdot x_{ii'td}$ indicates the cost of containers transportation between pooler facilities. The term $\sum_{u=1}^{U}\sum_{i=1}^{P}\sum_{t=1}^{T} Cprod \cdot xp_{iut}$ is the cost of recycling and remanufacturing new containers in T, while $\sum_{u=1}^{U}\sum_{i=1}^{P}\sum_{t=1}^{T} Cstock \cdot (wr_{iut}+wl_{iut})$ and $\sum_{u=1}^{U}\sum_{i=1}^{P}\sum_{t=1}^{T} Cl_{i} \cdot xl_{iut}$ are, respectively, the total storage and washing costs over the planning horizon T.

Constraints

The set of constraints can be clustered in three different groups. Constraints (2)-(8) control the status of the facility i; Constraints (9)-(14) to regulate the flows of the RPCs among the nodes of the network; and Constraints (15)-(22) on the status of the RPCs and the management of their residual life. These clusters of constraints are formulated as follows:

$$y_{iut} \geq y_{iu(t-1)} \qquad \forall i \in P,\ t \in T,\ u \in U \quad (2)$$

$$\sum_{u=1}^{U} y_{iut} \leq 1 \qquad \forall i \in P,\ t \in T \quad (3)$$

$$wr_{iut} + wl_{iut} \leq stock_i \cdot y_{iut} \qquad \forall i \in P,\ t \in T,\ u \in U \quad (4)$$

$$\sum_{u=1}^{U} wr_{iut} = \sum_{u=1}^{U} wr_{iu(t-1)} + \sum_{i'=1}^{P} x_{i'itd} + \sum_{u=1}^{U} xl_{iut} + \sum_{u=1}^{U} xp_{iut} - \sum_{j=1}^{S} xf_{ijt} - \sum_{i'=1}^{P} x_{ii'td} \qquad \forall i \in P,\ t \in T,\ d=2 \quad (5)$$

$$\sum_{u=1}^{U} wl_{iut} = \sum_{u=1}^{U} wl_{iu(t-1)} + \sum_{z=1}^{C} xc_{zit} + \sum_{i'=1}^{P} x_{i'itd} - \sum_{u=1}^{U} xl_{iut} - \sum_{i'=1}^{P} x_{ii'td} - \sum_{u=1}^{U} xp_{iut} \qquad \forall i \in P,\ t \in T,\ d=1 \quad (6)$$

$$xl_{iut} \leq lav_{iu} \cdot y_{iut} \qquad \forall i \in P,\ t \in T,\ u \in U \quad (7)$$

$$xp_{iut} \leq prod_{iu} \cdot y_{iut} \qquad \forall i \in P,\ t \in T,\ u \in U \quad (8)$$

$$\sum_{i=1}^{P} xf_{ijt} = dom_{jt} \qquad \forall j \in S,\ t \in T \quad (9)$$

$$\sum_{i=1}^{P} xc_{zit} = cons_{zt} \qquad \forall z \in C,\ t \in T \quad (10)$$

$$\sum_{j=1}^{S} xf_{ijt} \leq stock_i \cdot \sum_{u=1}^{U} y_{iut} \qquad \forall i \in P,\ t \in T \quad (11)$$

$$\sum_{z=1}^{C} xc_{zit} \leq stock_i \cdot \sum_{u=1}^{U} y_{iut} \qquad \forall i \in P,\ t \in T \quad (12)$$

$$\sum_{i'=1}^{P} x_{ii'td} \leq \left(stock_i + prod_{iu}\right) \cdot \sum_{u=1}^{U} y_{iut} \qquad \forall i \in P,\ t \in T,\ u \in U,\ d \in D \quad (13)$$

$$\sum_{i'=1}^{P} x_{i'itd} \leq stock_i \cdot \sum_{u=1}^{U} y_{iut} \qquad \forall i \in P,\ t \in T,\ u \in U,\ d \in D \quad (14)$$

$$EOL_{ct} \leq EOL_{c(t-1)} - 1 + M \cdot \varphi_{c(t-1)} \qquad \forall c \in K,\ t \in T \quad (15)$$

$$EOL_{ct} \geq EOL_{c(t-1)} - 1 - M \cdot \varphi_{c(t-1)} \qquad \forall c \in K,\ t \in T \qquad (16)$$

$$EOL_{ct} \leq 1 - \varphi_{c(t-1)} + L \qquad \forall c \in K,\ t \in T \qquad (17)$$

$$EOL_{ct} \geq L \cdot \varphi_{c(t-1)} \qquad \forall c \in K,\ t \in T \qquad (18)$$

$$\varphi_{ct} \leq 1 - m \cdot EOL_{ct} \qquad \forall c \in K,\ t \in T \qquad (19)$$

$$\varphi_{ct} \geq 1 - EOL_{ct} \qquad \forall c \in K,\ t \in T \qquad (20)$$

$$\varphi_{ct} \geq \varphi_{c(t-1)} - 1 \qquad \forall c \in K,\ t \in T \qquad (21)$$

$$\sum_{u=1}^{U} \sum_{i=1}^{P} xp_{iut} = \sum_{c=1}^{K} \varphi_{ct} \cdot n_c \qquad \forall t \in T \qquad (22)$$

$$y_{iut} \in \{0,1\} \qquad \forall i \in P,\ t \in T,\ u \in U \qquad (23)$$

$$\varphi_{ct} \in \{0,1\} \qquad \forall c \in K,\ t \in T \qquad (24)$$

$$wr_{iut},\ wl_{iut},\ xp_{iut},\ xl_{iut} \geq 0 \qquad \forall i \in P,\ t \in T,\ u \in U \qquad (25)$$

$$xf_{ijt} \geq 0 \qquad \forall i \in P,\ t \in T,\ j \in S \qquad (26)$$

$$xc_{zit} \geq 0 \qquad \forall i \in P,\ t \in T,\ z \in C \qquad (27)$$

$$x_{ii'td} \geq 0 \qquad \forall i,i' \in P,\ t \in T,\ d \in D \qquad (28)$$

Equation (2) forces a new facility i opened in t to remain operative along the left planning period T-t. Equation (3) imposes that a single use u is allocated to generic new facility i. Constraints (4) require that the storage capacity of the generic facility i is respected.

Equation (5) imposes that the number of clean RPCs available at the generic facility i is equal to the inventory at time t-1 plus the clean containers received by other facilities at time t and the containers washed or remanufactured in the same facility. Equation (6) balances the inventory of the dirty containers over the planning horizon. Constraints (5) and (6) control the flows of dirty, clean, and recycled containers through a generic facility i and impose that the quantity of clean containers supplied xf_{ijt} do not exceeds the on-hand inventory. Equation (7) limits the throughput of the washing line of the generic facility i. Similarly, equation (8) refers to the re-manufacturing capacity of the facility. Equation (9) requires fulfilling the packaging demand of suppliers in t. Equation (10) guarantees that dirty containers are collected from the retailer's distribution centers. Equations (11) to (14) link the open/close status of a facility to the availability of containers flows moving from/to that node.

Equations (15) to (18) update the variable EOL_{ct}, which measures the residual life of a container of class c until the period t. From periods t to $t+1$, EOL_{ct} decreases by one period. When the EOL_{ct} is equal to zero, the containers of class c reach end of life and are dismantled for recycling to produce new containers.

Equations (19) to (21) impose that the variable φ_{ct} remains 0, i.e., no containers of class c recycled and remanufactured in t, whether EOL_{ct} is not 0. When containers of class c reach the end of life, φ_{ct} forces the recycling and re-manufacturing of new ones in t. Equation (22) guarantees that the containers that achieve end of life in t are recycled at the same period. Lastly, Constraints (23)-(28) define the domain of the decision variables.

3.3. Model limitations

Some limitations of the proposed model deal with the problem framework and boundaries of the analyzed network. Despite the detailed input dataset required, optimization has been chosen among other techniques to aid network design purposes. The model minimizes the costs of the pooler which include the investment for new facilities, the storage and washing activities, transportation across the network, the recycling/remanufacturing of containers. Nevertheless, the model does not consider the cost of the initial virgin polypropylene granulate used to produce the former population of containers.

Given the strategic nature of the model, the operational problem of vehicle routing is not considered in this research. The residual life of the containers per each class c is assumed to decrease linearly with the time periods, and the integer variable EOL_{ct} approximates such behavior. For each container class c, the residual life is deterministic and ruled by the lifespan L, whilst the management of uncertain and anticipated end of life (e.g. due to mishandling, fracture, or misuse) is left to future model developments.

Despite the model's objective function is cost-driven, environmental aspects are considered by fixing the overall capacity of virgin material within the network and incorporating constraints that impose new containers remanufactured solely as recycling of disposed ones. Furthermore, the minimization of transportation costs seconds the reduction of carbon emissions from packaging logistics.

As the number of containers within the network is high (i.e. around 16 Million), the flow variables are considered continuous, and the ex-post approximation to integers is tolerated.

4. Case study

This model is applied to the closed-loop network of the main Italian pooler operating in the retail food supply chain. This case depicts national trends of circular economy transition (Ghisellini and Ulgiati, 2020). The geography of the observed network presents a peculiarity of the country. Suppliers of fruits and vegetables are abundant in the Southern regions where climate and soil favor agriculture, while retailers predominate the distribution channels in the Northern regions. The concentration of (fifteen) retailer's distribution centers in the North entailed the former (seventeen) pooler's facilities established nearby the retailer. Among these, one facility provides recycling/remanufacturing, washing and storage operations, four provide washing and storage services, and the latter solely storage. The pooler is wondering how the network will evolve according to variation in the packaging demand.

Whilst several packaging distribution scenarios are modeled (i.e. flows (3) and (4) of Fig. 1), the retailer's distribution centers receive clean containers from the pooler and collects the dirty packaging from the stores. Then, suppliers collect clean containers in the return trip of food distribution (i.e. flow (3.1) of Fig. 1). Therefore, the retailer distribution centers are pivotal in the closed-loop network and considered as anchors for the location-allocation problem.

Decision-making on network design considers a long-term planning horizon where the period t corresponds to a year. The packaging supply and collection flows (i.e. dom_{jt} and $cons_{zt}$) coincide in the case study per each period t.

Despite the broad offer in packaging size, the analysis refers to a specific container (i.e., RPC 6416 detailed in Table 2), which is largely the most used in the network. The container is made of polypropylene polymers (PP) to ensure performance along the lifespan L and infinitely recyclability at end of life.

[Insert Table 2 about here]

Table 2. Characteristics of the reusable container.

A single transportation mode i.e., a truck, is considered with a loading capacity of 8,000 containers per shipment. The lifespan of a new container is about seven years (i.e. periods) as suggested by the pooler. The overall planning horizon is 10 years. The input dataset required to fuel the model is gathered from the pooler's Information Systems and organized after interviews with the managers. The investment for a new facility is 3 million Euro. Figure 3 reports the map of the network with the unit transportation costs between the poolers' facilities and the retailer's distribution centers.

[Insert Figure 3 about here]

Figure 3. Map of the pooler network and transportation costs.

The model is formulated in AMPL and solved with Gurobi through a standard branch-and-bound algorithm. For each scenario, Gurobi takes a few seconds to find the optimum solution on a computer configured with Intel® Quad Core 2.4 GHz processors and 8 GB of RAM. By solving the model within a multi-scenario sensitivity analysis, the *RQs* are investigated and findings discussed in the following.

4.1. Multi-scenario Analysis

A multi-scenario analysis provides guidelines to the pooler about the strategic planning of the closed-loop network. Despite the packaging sector is less volatile than others, the packaging demand varies considerably with the number of actors (i.e. suppliers, retailers) signing a deal with the pooler and the types of packed food categories (e.g. fruit and vegetable, meat, bakery, seafood). To study how the configuration of the network changes with the demand, a first analysis considers several locations for new facilities. The business-as-usual scenario (i.e. *As-Is*) considers no variation in the packaging demand over the planning horizon. Then, in agreement with the pooler's managers, we assumed seven demand scenarios over the planning horizon (i.e., 0%, +5%, ±10%, +15%, and ±20%). The retailer's distribution centers are grouped into two geographic areas as illustrated in Figure 4: the northern regions and the southern regions. The combination of regions and demand variation generates 49 different scenarios.

[Insert Figure 4 about here]

Figure 4. Example of variation in the packaging demand by the retailer' distribution centers (containers/period).

As stated by the pooler, the distribution of the lifespan of the former containers inventory was: 50% of containers with a residual life of two years, 30% with a residual life four year and 20% with a residual life of six years.

Two locations were considered for new facilities: Forlì and Bari in the North and the South of the country, respectively. The washing costs of these facilities are higher in the North than in the South, while the package manufacturing and storage costs are roughly the same. Figure 4 shows the two clusters of regions and provides some examples of the packaging demand variation over the planning horizon. The results obtained by solving the business-as-usual scenario are reported in Figure 5 as the variable xc_{zit} and xl_{iut}. No facilities are opened whether no variation of the packaging demand occurs.

[Insert Figure 5 about here]

Figure 5. Solution of the *As-Is* scenario in terms of collected (xc_{zit}) and washed (xl_{iut}) containers.

Figure 6 compares the scenarios and draws the thresholds of demand that justify opening new facilities. The dot plot also shows the unfeasible demand scenarios which correspond to a network configuration not able to fulfill the packaging demand under the capacity and lifespan constraints thereby addressing *RQ 1*. Particularly, this corresponds to an increase of demand equal to or greater than 10% and 15% respectively in the Northern and Southern regions. It is worth noting that despite the container production capacity increases with the new facilities, new containers can be manufactured solely as recycling of disposed ones as imposed by the lifespan and virgin material capacity constraints.

[Insert Figure 6 about here]

Figure 6. Multi-scenario analysis and feasibility assessment with two and four new facilities.

Figure 7 plots the value of variable y_{iut} highlighting the periods of opening new facilities. Over the horizontal axis, the notation "*x;y*" means a variation of *x%* of the demand from Northern regions (NC) and of *y%* of Southern regions (SC). For example, given an increase of demand 5;10, the facility in Bari is opened at the period *t=2,* while the facility in Forlì at *t=8*. This figure also evaluates the effects of different washing costs between North and South. Figure 7 (a), assumes different washing costs (i.e. 0.067 €/container vs. 0.096 €/container in the South and the North respectively), while Figure 7 (b) considers equal costs.

[Insert Figure 7 about here]

Figure 7. Multi-scenario analysis: Timeline of the new facilities. *a*) Different washing cost between North and South; b) equal washing costs.

Equal washing costs favor opening both facilities to reduce transportation costs. Furthermore, the establishment of new facilities is recommended in seven scenarios out of eleven. Such decisions result from the combination of several parameters, as the logistics costs, the retailer's demand, and, undoubtedly, the investment CP_{iu} for new facilities.

With further potential new facilities, the planning of the network follows different pathways. The considered potential locations are two in the North (i.e. Alessandria and Forlì), one in the Center (i.e. Firenze), and one in the South (i.e. Bari). Equal unit washing costs are assumed for all the facilities. The main outcome is to reduce the number of infeasible scenarios (as the right plot of Figure shows), whilst the new facilities timeline is provided in Figure 8.

[Insert Figure 8 about here]

Figure 8. Multi-scenario analysis: Timeline of the new four facilities.

To address *RQ 2*, the impact of containers residual life on the network configuration is investigated. The former two locations of Forlì and Bari are considered. Given the low awareness on the residual life of the former inventory, we assumed six scenarios representing different distributions of the ages of containers. The model suggests when opening new facilities in agreement with the flow of containers disposed and recycled period by period.

In Figure 9, the notation "*x-y-z*" (e.g., "20-30-50") on the horizontal axis indicates as *x*% (e.g., 20%) the percentage of containers with a residual life of two years, as *y*% (e.g., 30%) the containers with a residual life of four years, and *z*% (e.g., 50%) those with a residual life of six years. It comes out that an older inventory (e.g., scenario "50-30-20") anticipates opening new facilities over the planning horizon. Whilst confirming a commonplace, the model highlights the impact of containers lifespan on network decision-making and provides the proper suggestion on when and where opening new facilities to the pooler's managers.

[Insert Figure 9 about here]

Figure 9. Multi-scenario analysis: Timeline of the new facilities according to container's lifespan scenarios.

5. Discussion

The importance of reusable containers is broadly recognized in logistics and in the supply chain of several industrial sectors. Particularly in the food industry characterized by daily consumption and large volumes of packaging, reusable containers contribute significantly to reduce the extraction of virgin materials, waste, and associated environmental impacts (Li et al., 2015, Govindan, 2018). Despite the stated benefits (Battini et al., 2016; Coelho et al., 2020), the main reason why food companies (i.e. suppliers, retailers) do not adopt reusable packaging is high service costs (Gustavo et al., 2018). The illustrated case study provides decision-support to strategically design a reusable packaging network from the perspective of the pooler within a nation-wide food retail supply chain. This industrial application is interesting because of the peculiar geography of suppliers and consumer areas, that unbalances the flows of reusable containers between the Southern and Northern regions. The cost-drive model optimizes the infrastructural and operating costs of the pooler over a strategic planning horizon (i.e. 10 years) providing pathways to minimize the service cost in agreement with packaging demand variation. Figure 10 summarizes the reusable packaging service costs corresponding to several demand scenarios and network configurations optimized with the model. This analysis has a twofold aim. First, it enables the pooler to estimate how the service costs might vary with the demand and when new investment on the network infrastructure is needed (i.e. *RQ 1*). Secondly, it reveals to other stakeholders (i.e. policymakers) the threshold of profitability of the pooler and encourages targeted regulation and incentives to foster the reusable packaging market share.

[Insert Figure 10 about here]

Figure 10. Cost of reusable packaging (service fee) with different demand scenarios and network configurations.

Two general considerations arise from the results. The variation of the packaging demand is the main issue of the pooler decision-making about the optimal configuration of the closed-loop network. The conducted multi-scenario analysis behaves as an abacus that estimates the impact of serving/losing clients (i.e. suppliers and retailers) or market shares. Secondly, the geography of the former pooler's network affects the operating costs considerably. For example, the different water grid price between South and North (i.e. surprisingly 30% cheaper for the Southern regions!) determines a concentration of flows of dirty containers in the South, thereby encouraging opening a new washing facility in those regions.

The container lifespan plays a role in the network configuration, confirming the impact of such packaging attribute (Accorsi et al., 2014; Lindh et al., 2016; Wikström et al. 2016) upon a network perspective. The sensitivity analysis exemplifies that the container lifespan and residual life influences decision-making on new pooler's facilities. Therefore, this model might aid the pooler to address *RQ 2* and to estimate the revenues resulting from new container materials, design features (e.g., expected lifespan, tensile strength, thickness, and weight) and technical performance. Moreover, the set of linear constraints controlling the residual life of containers, makes the model suitable to deal with other of reusable handling/container systems and networks (Glock, 2017) characterized by supply and collection operations and a given lifespan.

The model can be quickly updated into a tactical decision-support tool (i.e. let periods be weeks, y_{iut} be constant $\forall i \in P, t \in T, u \in U$ and revise the *Constraints (2)-(4)*, *(7)* and *(8)* accordingly) to study the optimal allocation of packaging flows across the closed-loop network given inventory balance and service level constraints (e.g., percentage of clean RPC received by a client).

Lastly, this model aids policymakers in developing infinitely reusable and recyclable packaging systems (Tonn et al., 2014). Because of the fixed capacity of former containers within the network, the model might serve as a cap-and-trade tool to measure and control the extraction of virgin material for new packaging and the resulting environmental impact.

6. Conclusions

Motivated by the still slow transition of food industry toward the adoption of reusable packaging, and the stated lack of support-decision tools for the poolers, this paper develops an optimization model to design a closed-loop packaging network. The nature of aided decision-making is strategic and deals with facilities opening, and allocating containers flows across the network over the planning horizon. The novel contribution of this work lies in a location-allocation model that incorporates the container lifespan into the design of an infinitely reusable and recyclable packaging network intended for the food industry.

An industrial case study from an Italian pooler is presented to validate the model and a sensitivity analysis illustrated to address the research questions. Broad opportunities exist for future research developments. The model could be revised into a multi-objective formulation able to achieve environmental targets, like reducing water consumption. Furthermore, the management of uncertain and anticipated container's end of life (e.g. due to mishandling, fracture, or misuse) is left to future model developments.

New research, under development to date, adopts robust optimization to study the impact of an uncertain collection of containers from the retailer's distribution centers upon tactical and operational perspectives. Lastly, a further target includes the design of data architectures, solving tools, and graphical interfaces to facilitate the interaction between the pooler's managers and the observed network.

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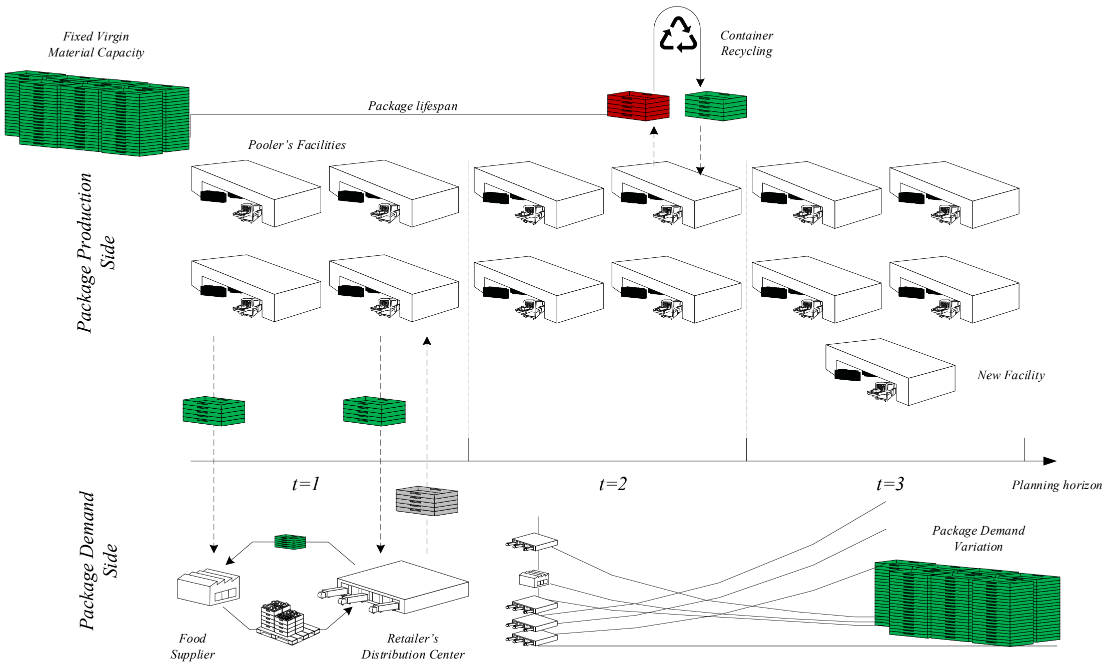

Figure 1. Infinitely reusable and recyclable packaging network framework.

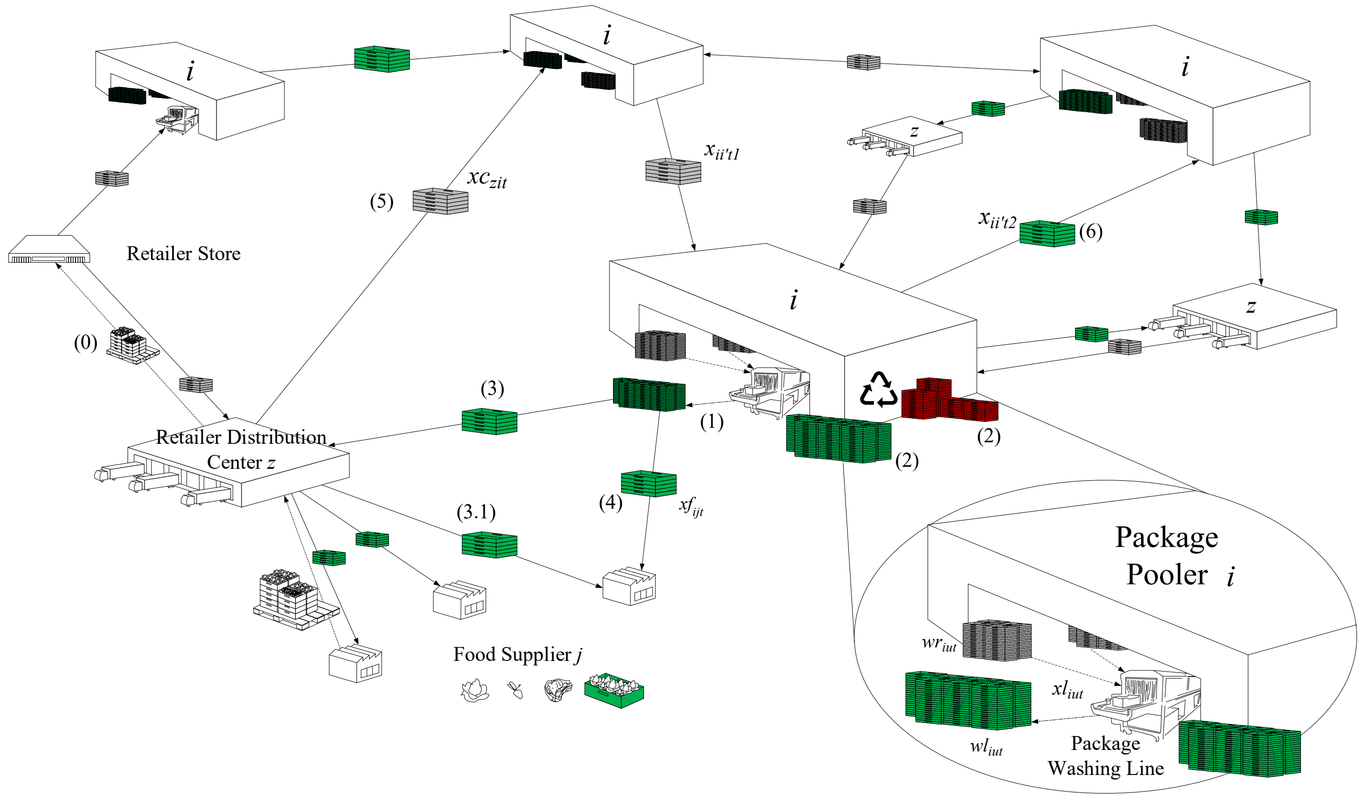

Figure 2. Reusable packaging network and model notation.

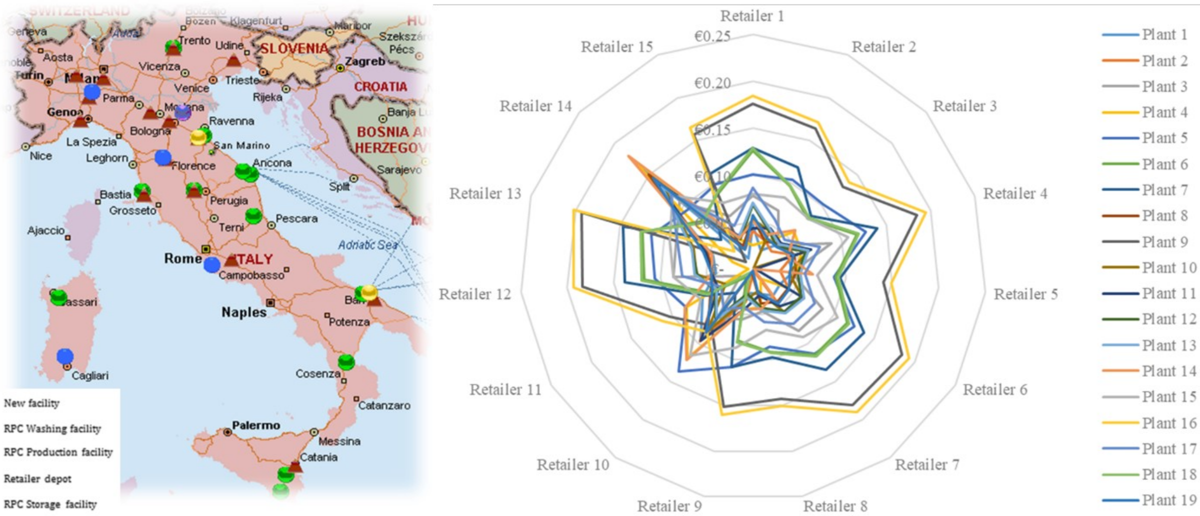

Figure 3. Map of the pooler network and transportation costs.

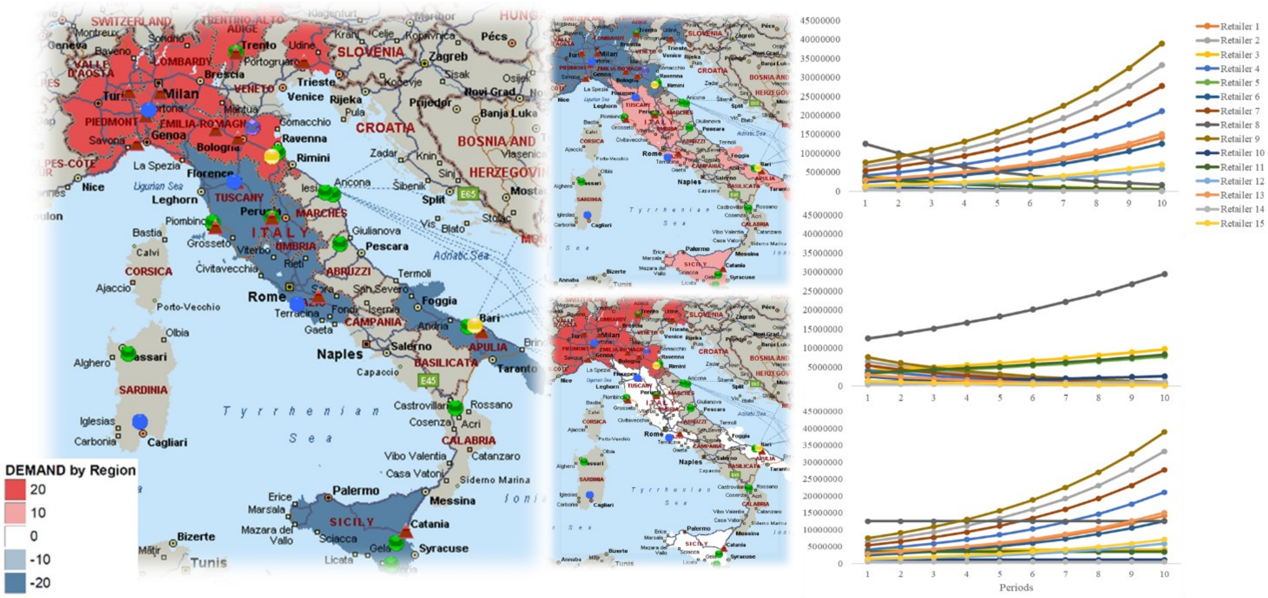

Figure 4. Example of variation in the packaging demand by the retailer' distribution centers (containers/period).

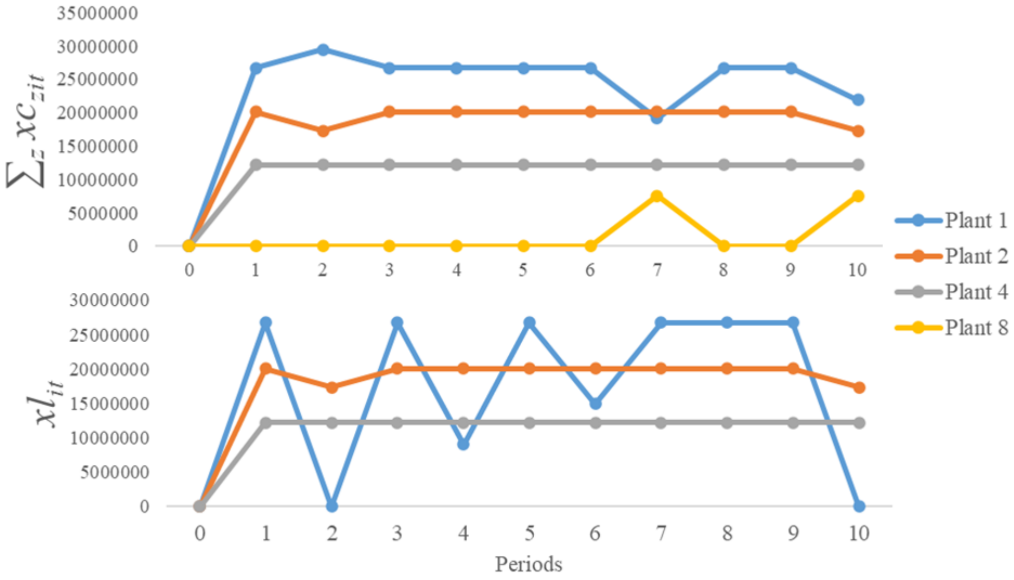

Figure 5. Solution of the *As-Is* scenario in terms of collected (xc_{zit}) and washed (xl_{iut}) containers.

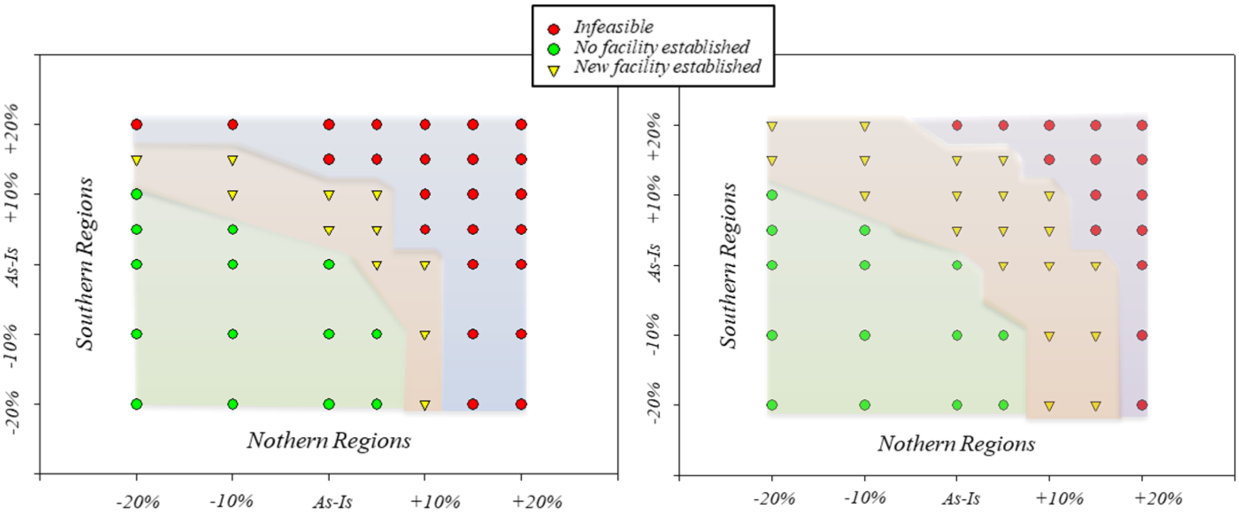

Figure 6. Multi-scenario analysis and feasibility assessment with two and four new facilities.

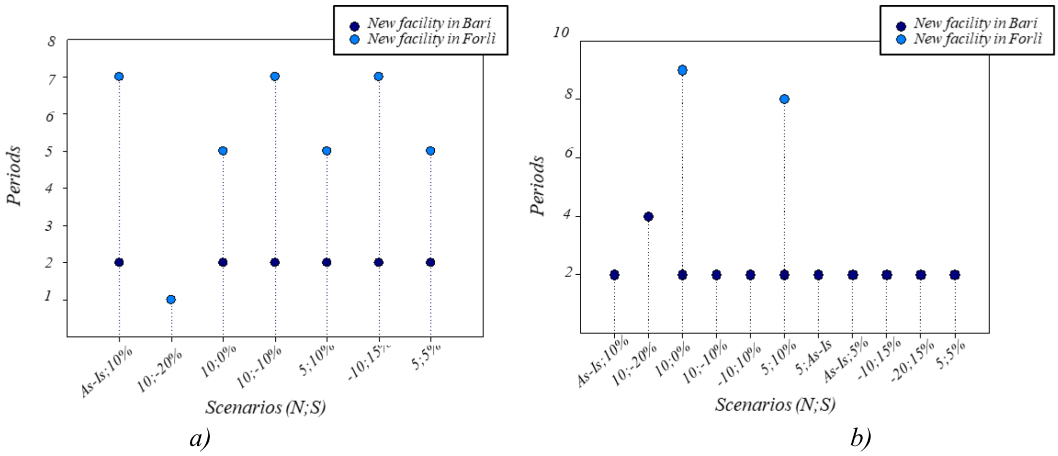

Figure 7. Multi-scenario analysis: Timeline of the new facilities. *a*) Different washing cost between North and South; b) equal washing costs.

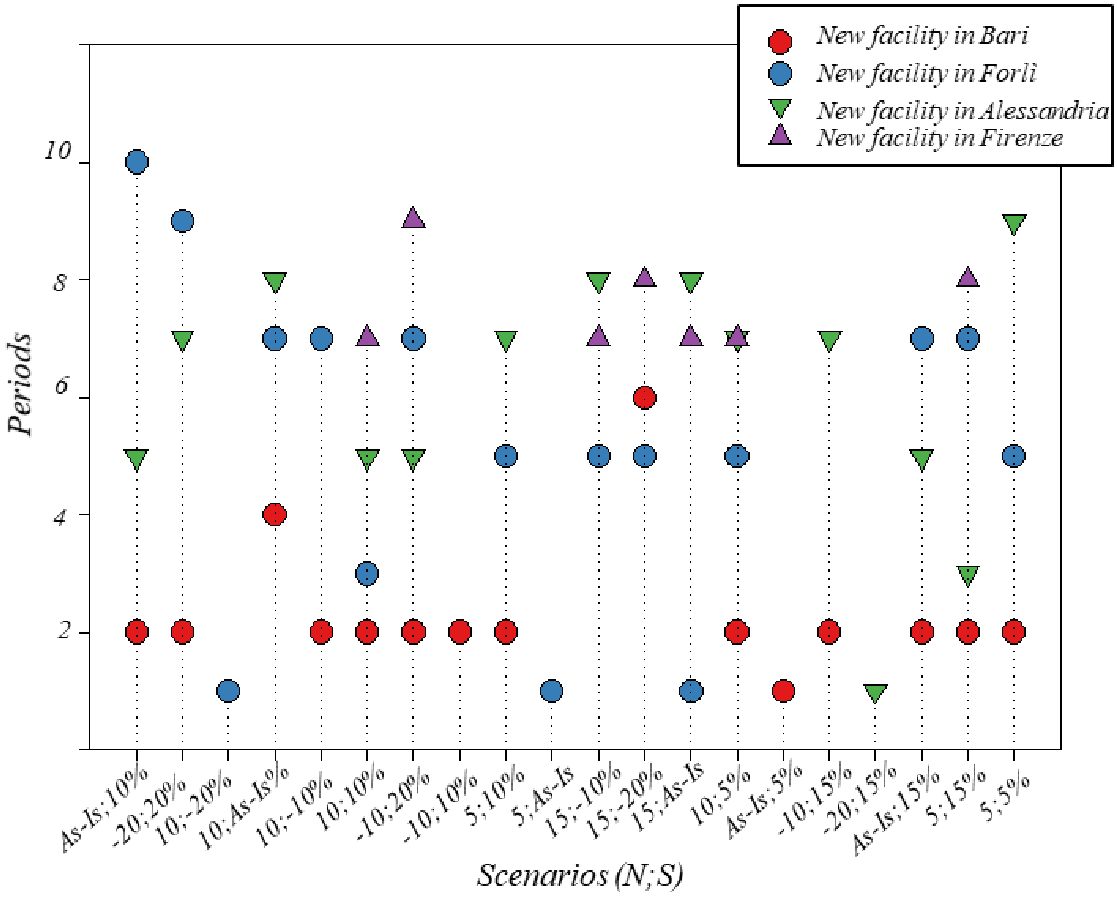

Figure 8. Multi-scenario analysis: Timeline of the new four facilities.

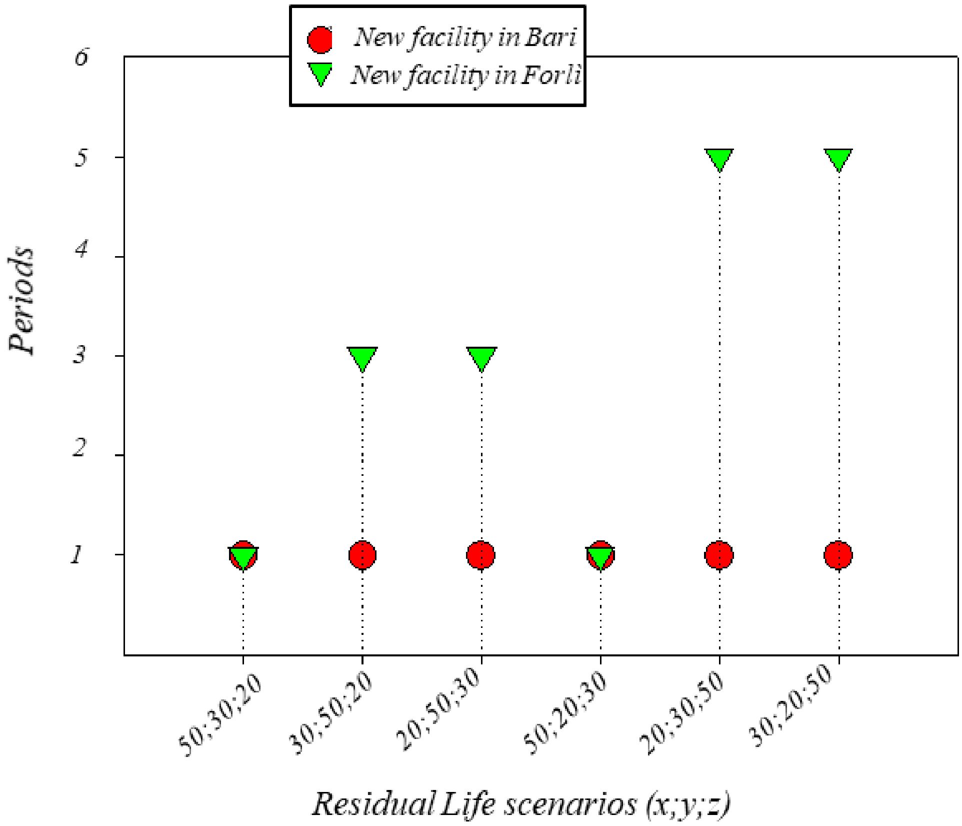

Figure 9. Multi-scenario analysis: Timeline of the new facilities according to container's lifespan scenarios.

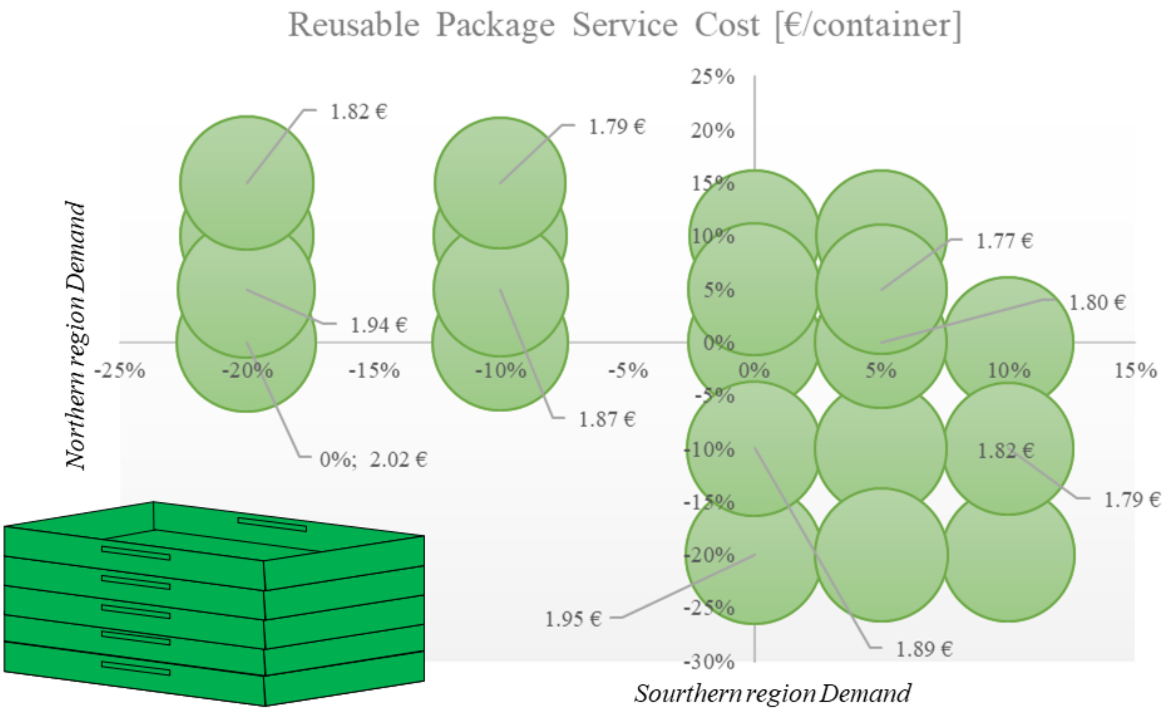

Figure 10. Cost of reusable packaging (service fee) with different demand scenarios and network configurations.