Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 67 (2022) 163–171

Transportation Research Procedia

www.elsevier.com/locate/procedia

6th International Conference on Food and Wine Supply Chain

Economic and environmental optimization of packaging containers choice in Food Catering Supply Chain

Michele Ronzoni[a*], Riccardo Accorsi[a,b], Beatrice Guidani[a], Riccardo Manzini[a]

[a]*Department of Industrial Engineering, Alma Mater Studiorum – University of Bologna, Viale del Risorgimento, 2, Bologna*
[b]*CIRI AgroAlimentare, Alma Mater Studiorum – University of Bologna, Via Quinto Bucci, 336, Cesena*

Abstract

Disposable containers are widely employed throughout food supply chains (FSCs) to transport, sell, or store perishable products. These containers are made of several materials, like plastic and cardboard. Albeit the widespread use of such containers, not all the materials are suitable for food contact, and a barrier layer between perishable products and the container is needed. Moreover, a high percentage of waste along the FSC consists of primary and secondary packages. Food Catering Supply Chain (FCSC), made of multi-stage logistic networks, represents a challenging scenario for minimizing packaging disposal. Chosen for reducing waste, reusable plastic containers (RPCs) are gaining ground within the food supply chain network. We propose a multi-objective optimization model to improve the business as usual (BAU) of FCSC, quantifying saving in terms of cost and environmental impact due to the employment of RPCs. The model virtualizes the logistic and operational costs as well as the transportation and disposal impact of reusable and recyclable plastic containers. This paper evaluates the use of RPCs by comparing the performances of as-is and to-be scenarios derived from an industrial case study. The analyzed network comprises perishable product suppliers, RPC poolers, cross-docking facilities, customers, and collectors. The results show the reduction of environmental impacts and logistic, handling, and operational costs in the proposed FCSC topology. A new network configuration and insights for future research investigations are presented.

Keywords: Reusable Containers; Food Catering Supply Chain; Circular network; MILP; Packaging Sustainability.

1. Introduction and state of the art

Food production and post-production operations are responsible for about 30% of the human-made greenhouse gasses (GHGs) emissions (Saeter et al., 2020). Moreover, the package used to supply, store, conserve, and sell food items might be a hotspot for reducing the total GHGs emissions (Abejón et al., 2020). In the food supply chain (FSC), several actors contribute to the production of ready-to-sell food items. The system's complexity increases with the number of involved actors (Aceves Lara et al., 2018). The food catering supply chain (FCSC) made of multi-stage logistic networks represents a challenging scenario for optimizing the primary, secondary, and tertiary package choice (i.e., package hierarchy). The secondary package material and the end-of-life strategies are crucial drivers as they quantify the supply chain's costs or environmental impacts. Several studies emphasized the benefit or disadvantages of the reuse strategy compared to the single-use package and the choice of plastic polymers instead of wood or carton board boxes (CCBs) (Accorsi et al., 2022a).

* Corresponding author e-mail address: michele.ronzoni2@unibo.it

2352-1465
10.1016/j.trpro.2022.12.047

Camps-Posino et al. (2021) evaluate the environmental performance of reusable plastic containers (RPCs) and single-use recyclable systems, concluding that the reusable ones are less polluting than the disposables. Levi et al. (2011) suggest adopting the reusable container for fresh vegetables and fruit distribution whether traveling within a range of 1200 km. Logistics and inventory management tip the balance in the environmental impacts associated with reusable packaging networks (Accorsi et al., 2022b). This work highlights the importance of considering the configuration of material-driven networks involved in the packaging decision. On the contrary, Koskela et al. (2014) proved that the impact of CCB can be lower than RPC in a specific bakery supply chain. In contrast, Abejón et al. (2020) impose the use of RPC in a retailer distribution supply chain instead of CCBs or polypropylene containers (PPCs). The study comprises a multi-scenario analysis, where the percentage of virgin materials, number of rotations, and breakage rate are varied.
As the literature shows, the optimal mix of the secondary package to adopt depends on the observed supply chain. Within a complex supply chain like the FCSC, the importance of the secondary package increases, and holistic decision-making, refusing partial answers, is encouraged. The package for a specific product at a particular network stage involves different drivers and considerations. The container's type leads to different material-driven networks to supply and collect empty containers, different package-product pairs with specific truckload utilization, or different routes to satisfy customers' demands (Sel et al., 2017). Combined with a capillary and distributed network, such complexity requires tailor-made decision-making.

This paper introduces and validates a mixed integer linear programming (MILP) optimization model aimed to identify the trade-off between environmental impact and economic convenience by choosing a secondary package mix at each stage of the FCSC. The optimization model chose the secondary package (i.e., container) in terms of material and end-of-life strategy, which minimizes both the cost and the environmental impact resulting from transportation, production, and disposal of packaging. Compared to close research conducted by Bortolini et al. (2018), this paper takes into account the packaging hierarchy (i.e., configuration of secondary, the crate, and tertiary package, the pallet) and is tailored to a cross-docking system serving a catering distribution network (as in Ronzoni et al., 2022).

The remaining of this paper is organized as follows. Section 2 presents the objective of this paper, the FCSC network, and the model used to evaluate the trade-off between cost and environmental impact. Section 3 introduces the case study and the obtained results, while section 4 concludes the papers by discussing model limitations and possible further developments.

2. Methods and Materials

This section formulates a MILP model aimed to investigate the optimal configuration of the package hierarchy used to handle, store, and distribute perishable products throughout a real-world FSCS. The model aims (1) to propose the secondary package type for each order, from suppliers to warehouses and from warehouses to customers. Secondly, (2) it manages the flow of used and empty containers, (3) and selects the location of collectors, package maker or poolers facilities, and suppliers. Lastly, (4) sets the handling operations at the cross-docking facilities. Two different objective functions are implemented in order to optimize the FCSC. One minimizes the transportation cost to fulfill catering customers' demands, the purchase and disposal fee for the secondary package, and the overall inbound logistic cost performed within the cross-docking facility. The second minimizes the GHGs emission generated through secondary package transportation, production, and end-of-life operations. The generic FCSC network and the model notation and formulation are presented in the following sessions.

2.1 Network modeling

The food catering supply chain involves different actors: growers, suppliers, package maker's facilities, package pooler's facilities, order-picking warehouses, customers, and collectors. As shown in Fig. *1*, the growers send products to the suppliers where tasks like washing, peeling, sizing, packing, and all is needed to sell the food items are carried out. Suppliers send the packaged products to an intermediate warehouse that sorts customers' orders. Usually, customers are public (e.g., hospitals and schools) or private entities (e.g., industries, catering services, and offices) that cannot be supplied directly from retailers' distribution centers. The warehouse decides the secondary package to adopt, while the customers impose the tertiary package (e.g., roll container) according to their facilities' specificities. The package makers and the pooler manage empty crates throughout the FCSC. The poolers are responsible for collecting, washing, and repairing tasks, replenish the inventory of cleaned containers when and where needed. Due to the Italian legislation (D.M. 21.03.1973 and update D.M. 220 26.04.1993), collectors are the only players allowed to manage the flow of non-reusable containers, collecting them at each stage of the FCSC. In such a context, suppliers, customers, and the warehouse evaluate the best package hierarchy configuration to distribute food and serve the catering consumers.

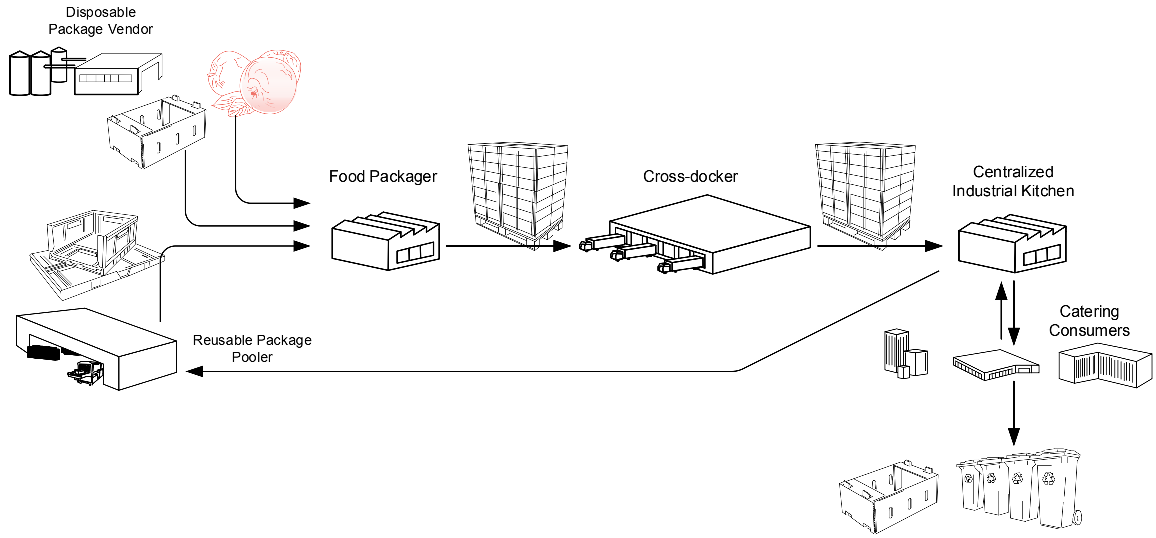

Fig. 1. FCSC package network models.

2.2 Model formulations

The pooler's facilities behave as package makers and collectors for reusable containers, replenishing the inventory of suppliers and warehouses and collecting empty packages throughout the FCSC. This model drives the total cost and environmental impact minimization by suggesting the best secondary package mix to satisfy the customers' demand. It considers a set V of supplier's facilities, a set C of catering customers, a set H of waste collectors, a set R of package maker's facilities, a set M of food products, a set Pkg^{II} of secondary packages, and a set Pkg^{III} of tertiary packages.

Sets:

$v \in V$	Set of vendors
$c \in C$	Set of customers
$h \in H$	Set of pooler facilities/collectors
$r \in R$	Set of package makers
$i \in M$	Set of products
$p \in Pkg^{II}$	Set of secondary packages
$t \in Pkg^{III}$	Set of tertiary packages

The cost function involves transportation costs to supply and collect empty secondary packages and to provide packaged products to each stage of the FCSC. The inbound operations (i.e., registration, put-away, and handling) are also accounted for, as well as the purchase and disposal cost for the secondary packages and the daily depreciation cost of packaging lines. To quantify the environmental impact, the model considers the emissions associated with full and empty container transportation and the secondary packaging production and disposal stage. To assess the transportation cost, the model considers the distance between the facilities (div_v, dic_c, $dirv_{rv}$, $dich_{ch}$), the truck transportation cost per kilometer ($ETruck$), and the number of trucks involved in the supply and collection stages ($nTruck_c^{wc}$, $nTruck_v^{vw}$) needed to satisfy the customer demand (i.e., d_{ict}). To quantify the cost for inbound operations, the model considers the labor cost (hc), the handling time to transfer food into containers of different types ($ht_{ip^{in}p^{out}}$), and the tracking time per pallet at the cross-docking inbound dock ($treg$). The disposal cost for the single-use container considers the regional fee paid by the customers to dispose of it ($cw\_w_{p^{in}}$) and the flow of received containers ($cContainers_{chp}$). The purchasing contribution accounts any crate sent from the pooler or the package vendor to the packager or the cross-docker (x_{ivp})with the unit price Ec_p. Regarding the environmental function, this model considers the number of trucks involved during the shipment, the distance between the facilities, and the full truck emission per kilometer. The impact derived from package production and end-of-life treatment is calculated as tons of CO_2 eq. emitted per container.

Parameters:

ps_v	Maximum number of different packaging lines at vendor *v* [\]
o_{iv}	Daily availability of product *i* at vendor *v* [kg]
kgc_{ip}	Capacity of container *p* for product *i* [kg]
d_{ict}	Demand of customers *c* of product *i* in tertiary package *t* [kg]
kp_p	Maximum number of containers *p* in a pallet EPAL [#containers/pallet]
kpt_{pt}	Maximum numbers of containers *p* in tertiary package *t* [#containers/tertiary package]
ktt_t	Maximum numbers of tertiary package *t* in a truck [# tertiary package]
$ktnPl$	Maximum numbers of pallet in a truck [#pallet/truck]

$pCapacity_{rp}$	Number of package p available at the package maker facility r [#package]
y_{chp}	1 if customer c sends package p to collector/pooler facility h [binary]
cp_{vp}	Daily depreciation cost of packing line for type p container [€/day]
$ht_{ip^{in}p^{out}}$	Handling time for transferring 1 [kg] of product i from package p^{in} to p^{out} [h]
hc	Labor hourly cost [€/h]
$ETruck$	Transportation cost for one truck [€/truck*km]
Ec_p	Cost for one container of type p [€/container]
div_v	Distance between supplier v to cross-docker facility [km]
dic_c	Distance between cross-docker facility to customer c [km]
$dirv_{rv}$	Distance between package maker facility to vendor v [km]
$dich_{ch}$	Distance between customer c to collector/pooler facility h [km]
$dist_i$	Distance from in bays and storage area for product i [km]
vel	Average velocity of internal logistic operation vehicle [km/h]
$treg$	Registration time for one pallet at cross-docker facility [h]
cw_{cp}	Cost to dispose one container of type p for the customer c
$cw\_w_{p^{in}}$	Cost to dispose one container p^{in} at the cross-docker facility after transferring operation
TCO_{2eq}	Emission per kilometers due to the goods transportation throughout the FCSC [kg CO_2eq./km]
LCA	Emission due to container production and end-of-life treatment [kg CO_2eq]

Variables:

y_{vp}	1 if vendor v has packaging lines for packaging p, 0 otherwise [binary]
x_{ivp}	Flow of product i in p type container from vendor v to the cross-docker [#containers]
$z_{ip^{in}p^{out}}$	Kg of product i transferred from container p^{in} to container p^{out} [kg]
$containers_{ip}$	Availability of product i in container p at cross-docker facility [#containers]
nPl_{ivp}	Flow of pallet of product i in container of type p from vendor v to cross-docker facility [#pallets]
$eContainers_{rvp}$	Number of empty containers p from packager maker r to vendor v [#containers]
$orders_{icpt}$	Order of product i in container p in tertiary package t sent from cross-docker facility to customer c [kg]
nUL_{ct}	Number of unit load of type type t sent from cross-docker facility to customer c [#tertiary package]
$nTruck_c^{wc}$	Number of truck [#truck] from cross-docker facility to customer c
$nTruck_v^{vw}$	Number of truck [#truck] from cross-docker facility to customer c
$cContainers_{chp}$	Number of used containers sent from customer c to collector/pooler facility h

The model is built upon two objective functions. The former (1) minimizes total cost, while the latter (2) minimizes CO_2 emissions.

Objective functions:

$$\begin{aligned} min \sum_{v\in V}\sum_{p\in Pkg^{II}} y_{vp}\cdot cp_{vp} + \sum_{i\in M}\sum_{p^{in}\in Pkg^{II}}\sum_{p^{out}\in Pkg^{II}} z_{ip^{in}p^{out}}\cdot ht_{ip^{in}p^{out}}\cdot ch \\ + \sum_{i\in M}\sum_{v\in V}\sum_{p\in Pkg^{II}}\left(x_{ivp} + \sum_{p^{in}\in P}\frac{z_{ip^{in}p}}{kgc_{ip^{in}}}\right)\cdot Ec_p + \sum_{p,p^{in}\in Pkg^{II}}\frac{z_{ip^{in}p}}{kgc_{ip^{in}}}\cdot cw\_w_{p^{in}} \\ + \sum_{i\in M}\sum_{c\in C}\sum_{p\in Pkg^{II}}\sum_{t\in Pkg^{III}}\frac{orders_{icpt}}{kgc_{ip}}\cdot cw\_cp_{cp} \\ + \sum_{i\in M}\sum_{v\in V}\sum_{p\in Pkg^{II}} nPl_{ivp}\cdot\left(\frac{dist_i}{vel}+treg\right)\cdot hc + \sum_{r\in R}\sum_{v\in V}\sum_{p\in Pkg^{II}} di_{rv}^{rv}\cdot\frac{eContainers_{rvp}}{eContPl_p\cdot ktnPl}\cdot ETruck \\ + \sum_{v\in V} nTruck_v^{vw}\cdot div_v\cdot ETruck + \sum_{c\in C} ETruck\cdot nTruck_c^{wc}\cdot dic_c \end{aligned} \quad (1)$$

The first term of Eq. (1) takes into account the daily depreciation cost for a packaging line within a generic supplier's facility. The second term evaluates the transferring operations cost needed when the package configuration change within the cross-docker facilities. The third term is referred to the purchase cost for the containers employed throughout the FCSC, while the fourth and fifth terms compute the cost to dispose of the involved secondary packages during storage and supply operations. To evaluate the cost of the inbound operations in the first objective function is implemented the item cost $\sum_{i\in M}\sum_{v\in V}\sum_{p\in Pkg^{II}} nPl_{ivp}\cdot\left(\frac{dist_i}{vel}+treg\right)\cdot hc$. The last terms evaluate the transportation cost in each stage of the FCSC.

$$min \sum_{r\in R}\sum_{v\in V}\sum_{p\in Pkg^{II}} di_{rv}^{rv} \cdot \frac{eContainers_{rvp}}{eContPl_p \cdot ktnPl} \cdot CO_{2eq} + \sum_{v\in V} nTruck_v^{vw} \cdot div_v \cdot CO_{2eq} + \sum_{c\in C} nTruck_c^{wc} \cdot dic_c \cdot CO_{2eq} + \sum_{i\in M}\sum_{c\in C}\sum_{p\in Pkg^{II}}\sum_{t\in Pkg^{III}} LCA_p \cdot \frac{orders_{icpt}}{kgc_{ip}} \quad (2)$$

The second objective function (2) evaluates the total carbon emissions that occurred throughout the FCSC. The first three terms of such a function consider the transportation emissions in each stage of the real-world supply chain, while the last term accounts for the total emissions due to the production and end-of-life processes.

The set of constraints is clustered into three different groups. Eqs (4-6) is referred to the facilities' capacity, Eqs (7-17) manage the flow between and within the facilities, and Eqs. (18-26) define the domain of the variables.

Constraints:

$$\sum_{p\in Pkg^{II}} y_{vp} = ps_v, \forall v \in V \quad (3)$$

$$x_{ivp} \le \frac{o_{iv}}{kgc_{ip}} \cdot y_{vp}, \forall i \in M, v \in V, p \in Pkg^{II} \quad (4)$$

$$\sum_{p\in Pkg^{II}} x_{ivp} \cdot kgc_{ip} \le o_{iv}, \forall i \in M, v \in V \quad (5)$$

$$\sum_{v\in V} eContainers_{rvp} \le pCapacity_{rp}, \forall r \in R, p \in Pkg^{II} \quad (6)$$

$$\sum_{p^{out}\in Pkg^{II}} z_{ipp^{out}} \le \sum_{v\in V} x_{ivp}\, kgc_{ip}, \forall i \in M, p \in Pkg^{II} \quad (7)$$

$$\sum_{v\in V}\sum_{p\in Pkg^{II}} x_{ivp} \cdot kgc_{ip} \ge \sum_{c\in C}\sum_{t\in Pkg^{III}} d_{ict}, \forall i \in M \quad (8)$$

$$\sum_{v\in V} x_{ivp} + \sum_{p^{in}\in Pkg^{II}} \frac{z_{ip^{in}p}}{kgc_{ip}} - \sum_{p^{out}\in Pkg^{II}} \frac{z_{ipp^{out}}}{kgc_{ip}} \ge containers_{ip}, \forall i \in M, p \in Pkg^{II} \quad (9)$$

$$nPl_{ivp} \ge \frac{x_{ivp}}{kp_p}, \forall i \in M, v \in V, p \in Pkg^{II} \quad (10)$$

$$\sum_{i\in M}\sum_{p\in Pkg^{II}} \frac{nPl_{ivp}}{knPl} \le nTruck_v^{vw}, \forall v \in V \quad (11)$$

$$containers_{ip} \cdot kgc_{ip} \ge \sum_{c\in C}\sum_{t\in Pkg^{III}} orders_{icpt}, \forall i \in M, p \in Pkg^{II} \quad (12)$$

$$\sum_{p\in Pkg^{II}} orders_{icpt} \ge d_{ict}, \forall i \in M, c \in C, t \in Pkg^{III} \quad (13)$$

$$\sum_{i\in M}\sum_{p\in Pkg^{II}} \frac{orders_{icpt}}{kgc_{ip} \cdot kpt_{pt}} \le nUL_{ct}, \forall c \in C, t \in Pkg^{III} \quad (14)$$

$$\sum_{t\in Pkg^{III}} \frac{nUL_{ct}}{ktt_t} \le nTruck_c, \forall c \in C \quad (15)$$

$$\sum_{r\in R} eContainers_{rvp} \ge \sum_{i\in M} x_{ivp}, \forall v \in V, p \in Pkg^{II} \quad (16)$$

$$\sum_{i\in M}\sum_{t\in Pkg^{III}} \frac{orders_{icpt}}{kgc_{ip}} \le \sum_{h\in H} cContainers_{chp} \cdot y_{cph}, \forall c \in C, p \in Pkg^{II} \quad (17)$$

$$y_{vp} \in \{0,1\}, \forall v \in V, p \in Pkg^{II} \quad (18)$$

$$x_{ivp}, nPl_{ivp} \ge 0, \forall i \in M, v \in V, p \in Pkg^{II} \quad (19)$$

$$z_{ip^{in}p^{out}} \ge 0, \forall i \in M, p^{in}p^{out} \in Pkg^{II} \quad (20)$$

$$eContainers_{rvp} \ge 0, \forall r \in R, v \in V, p \in Pkg^{II} \quad (21)$$

$$orders_{icpt} \ge 0, \forall i \in M, c \in C, p \in Pkg^{II}, t \in Pkg^{III} \quad (22)$$

$$nUL_{ct} \ge 0, \forall c \in C, t \in Pkg^{III} \quad (23)$$

$$nTruck_c^{wc} \ge 0, \forall c \in C \quad (24)$$

$$nTruck_v^{vw} \ge 0, \forall v \in V \quad (25)$$

$$cContainers_{chp} \ge 0, \forall c \in C, h \in H, p \in Pkg^{II} \quad (26)$$

Eq. (3) impose the maximum number of packaging line available in the supplier facility (v). To fix the daily availability of fresh products, the model uses Eqs. (4-5). The former imposes x_{ivp} equal to zero if the facility v does not provide the packaging line for the container of type p, while the latter fixed the maximum quantity of product i deliverable from the supplier v to the cross-docker. Eq. (6) imposes the storage capacity and the production rate of empty containers at poolers and package maker facilities, while Eqs. (7÷10) balance the flow between the actors of the FCSC. Eqs. (12÷16) links the variables to each other allowing key performance indicators (KPIs) in the result and discussion session, while Eq. (17) imposes the collector's node h for a customer c and container type p. Eqs. (18÷26) delimit the domain of the variables.

3. Application and Results

This section presents a proof-of-concept and discusses the obtained results, providing additional comments and interpretations to the using chart, maps, and plots.

3.1 A food catering supply chain

The real-world instance is provided by an Italian catering supply chain involving a cross-docker, a player of the food service industry, the packaging makers and poolers, and a list of food suppliers. Fig. *2* draws the supply chain network's entities.

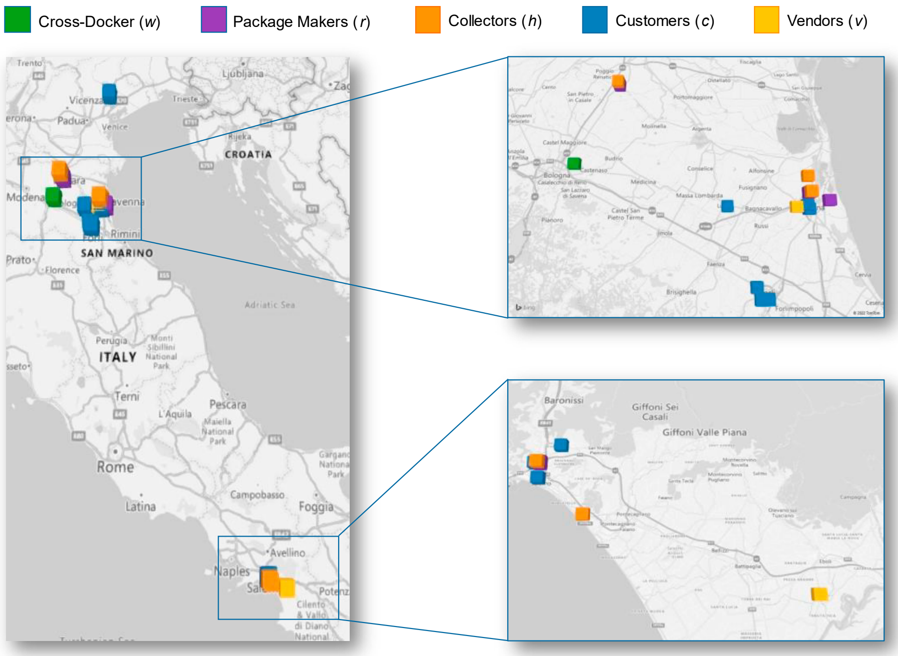

Fig. 2. FCSC network geography.

The FCSC network comprises ten customers, five collectors, six package maker and pooler facilities, one cross-docker, and two suppliers/vendors distributed over the north and south of Italy. Such players may opt for three alternative secondary packages (i.e., reusable plastic container, single-use cardboard container, and single-use polypropylene container), generating different material-driven networks needed to supply, to dispose or to collect the containers. Some actors (i.e., suppliers and customers) impose the tertiary package (e.g., EPAL or roll container) to the cross-docker, influencing the package change and the composition of the transport unit load. The chosen order profile corresponds to a typical daily demand handled by the cross docker. As Fig. *3* shows, the order profile comprises about 60 tons of fruit and vegetables, corresponding to more than 200'000 individual portions of fruit and vegetables for canteens, schools, and hospitals. Customers do not order all the varieties necessarily. For instance, customers "*TV1*", "*RA1*", and "*FC3*" do not demand salad.

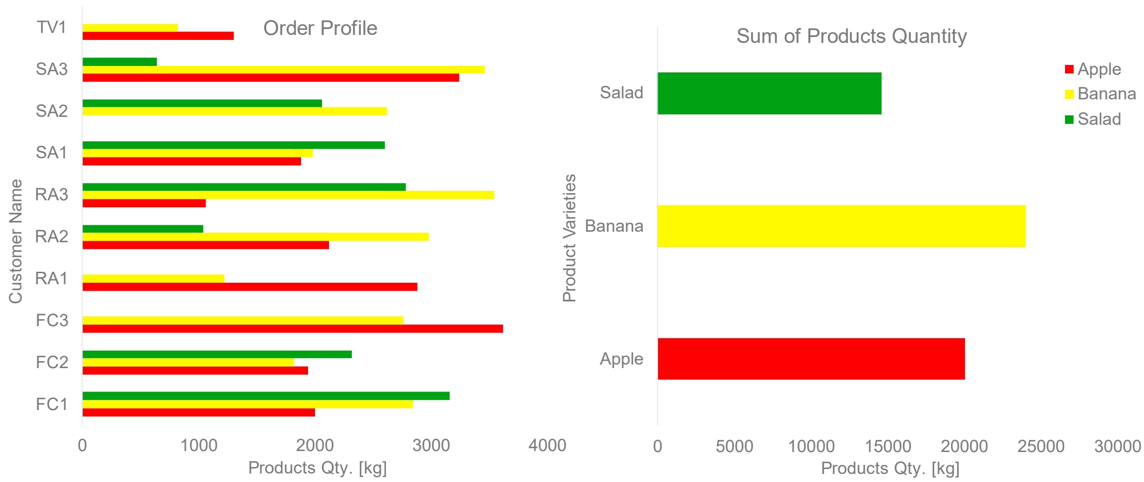

Fig. 3 Typical order profile handled by the cross-docker and product quantity.

The numerical example provides validation to this model allowing the investigation of which costs drives the adoption of reusable containers in the FCSC. By considering the carbon objective function, the model explores the trade-off between economic convenience and the minimization of environmental impacts. Finally, a Pareto frontier analysis (PFA) is drawn to understand better the strategies and thresholds of environmental impact reduction within a real-world FCSC.

3.2 Results

In the business-as-usual scenario, cross-docker and suppliers use CCB or PPC, and the price of such containers is known. The adoption of reusable containers compels new fees and involves more players, increasing the overall cost of the FCSC. The service cost to manage the reusable crates needs to incorporate somehow the annual movements, rotations, and the number of crates used over the year to satisfy the customers' demand. The average daily demand is scaled accordingly, resulting in a unit cost for the RPC of 0.2 [€/containers]. A first result is shown in Fig. *4* considering sensitivity of the reusable container service's unit cost.

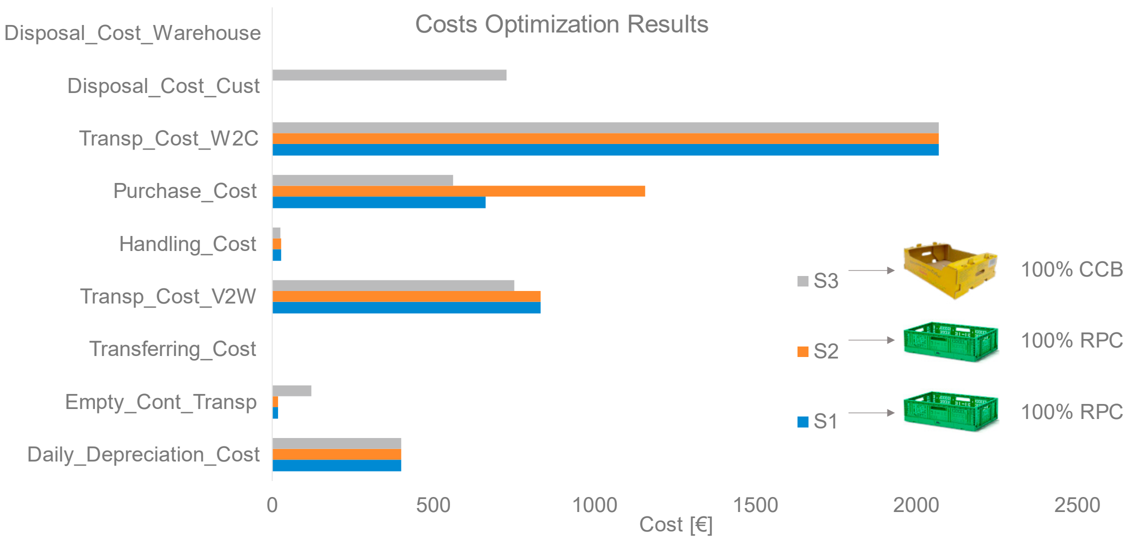

Fig. 4. Result of cost optimization at different RPC service prices.

Fig. 4 compares different scenarios built by increasing the reusable container service's unit cost. This varies from 0.2 [€/container] to 0.5 [€/container]. In the first two scenarios, the network prefers the adoption of reusable containers in each stage of the FCSC. The model does not involve a different packaging mix until the last scenario (S3) where the service cost rises to 0.5 [€/container]. In such a scenario, the model imposes the use of CCB, influencing the network of packaging suppliers throughout the FCSC. There is no scenario where the model opts for disposable PP containers. Table 1**Errore. L'origine riferimento non è stata trovata.** summarizes the obtained results, highlighting the cost for a different type of container, the adopted container mix, and the overall network costs.

Table 1. Overall cost optimization

Cost	S1	S2	S3
PPC single-use	0.22 €	0.22 €	0.22 €
CCB single-use	0.17 €	0.17 €	0.17 €
RPC	0.20 €	0.35 €	0.50 €
SC mix	100% RPC	100% RPC	100% CCB
Total	4012 €/day	4509 €/day	4658 €/day

The adoption of CCB in S3 increases the transportation cost for empty containers and the cost to dispose of disposables. Transportation emits CO_2, increasing the FCSC's carbon footprint. Multi-objective optimization analysis is carried out, using the ε-constrained method, to investigate the trade-off between the economic convenience and the environmental impact of the adopted container mix. Fig. 5 shows the results from the multi-objective optimization. The first iteration suggests adopting a mix of CCB and RPC to serve FCSC. This configuration minimizes the total environmental impact, in terms of GHGs equivalent emissions, but increases the economic burden up to three times the scenarios S1. By iterating the optimization problem, the total cost decreases rapidly while the carbon footprint increases slightly, remaining almost stable.

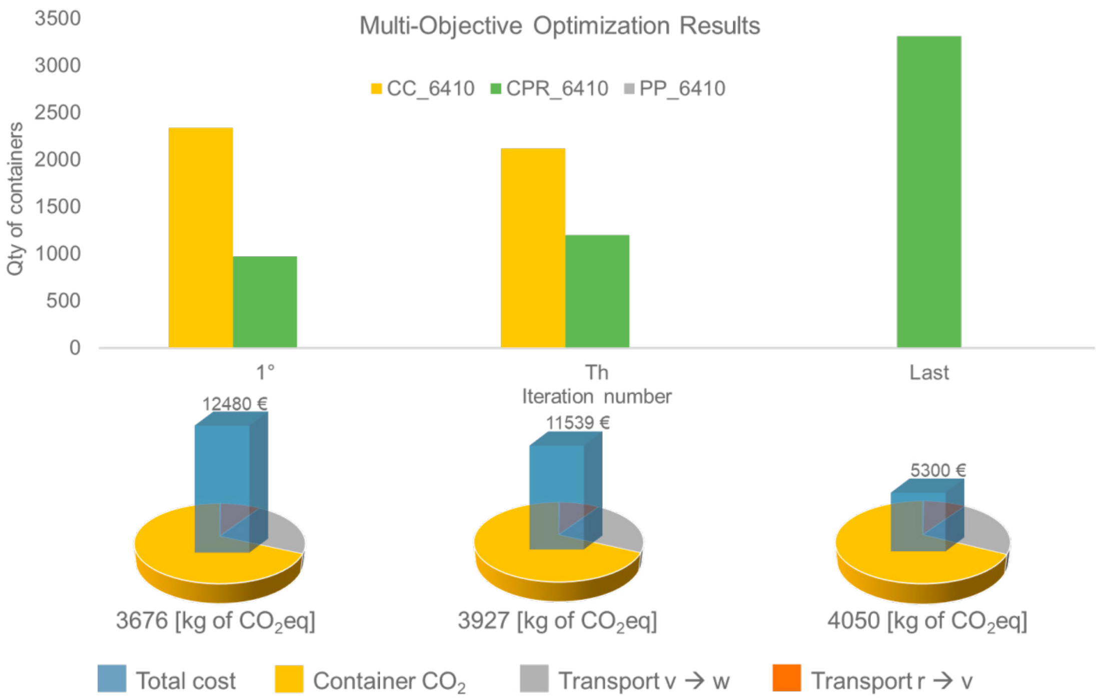

Fig. 5. Multi-objective optimization results.

The value of ε affects the results, and a PFA is required to understand the possible configuration of the FCSC better. Fig. 6 shows the main points of the PFA, shedding light on the environmental impact and overall cost arising from adopting a specific secondary package mix. The first and last iterations (points 1 and 3) correspond to the two problem's anchor points. The former optimizes the overall cost without considering the environmental impact whilst the second optimizes the network's carbon footprint. A promising trade-off for this FCSC is as at the corresponding solution 2 in Fig. 6. In such a configuration, the reuse represents the only strategy adopted, with GHGs emissions reduced by 400 kg/day compared to a rise of costs of 300 € per day. Obviously, iterating the model provides a more expensive solution at a lower environmental burden.

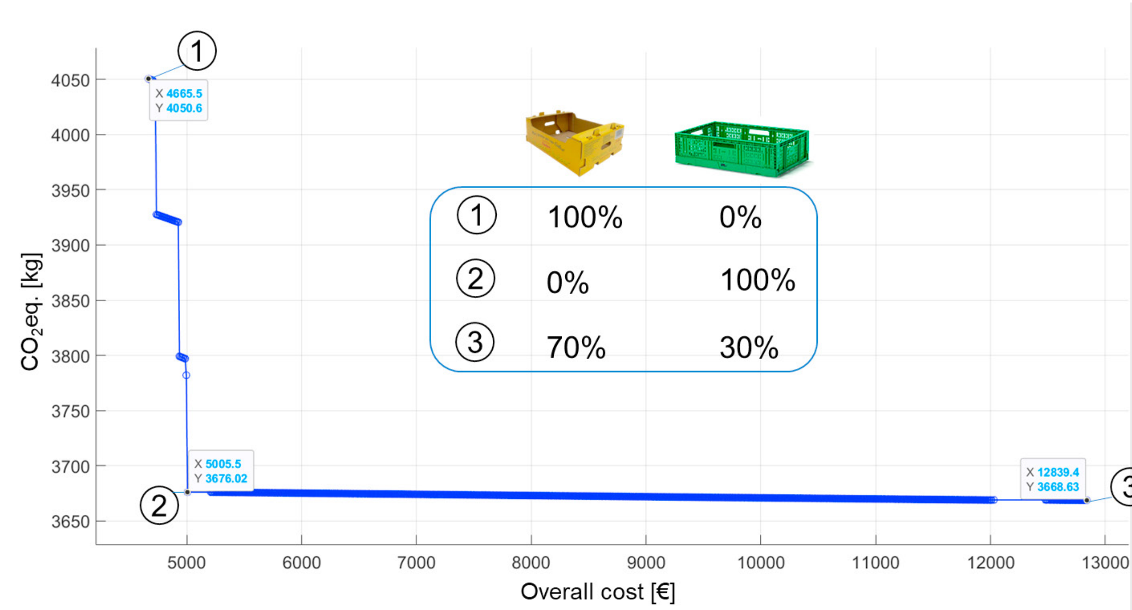

Fig. 6. Pareto frontier analysis.

4. Conclusions

The package plays a pivotal role in every supply chain, especially in agri-food systems. The investigation of which type of package is the best choice entails comparing material-driven networks that drastically change the players involved, the facilities of the supply chain, and the flows. This study proposes an optimization problem that aims to suggest the configuration of packaging hierarchy to be used in a food catering supply chain. The proposed model is applied to an Italian catering industry network. The results suggested that adopting reusable containers is the most performing choice both from an economic and environmental perspective. The considerations on the packaging hierarchy enable optimizing the operational performance associated with truck utilization and material handling throughout the whole catering supply chain. The model's generality allows its application to different supply chains or case studies with a broader or more complex network geography.

References

Abejón, R., Bala, A., Vázquez-Rowe, I., Aldaco, R., & Fullana-i-Palmer, P. (2020). When plastic packaging should be preferred: Life cycle analysis of packages for fruit and vegetable distribution in the Spanish peninsular market. *Resources, Conservation and Recycling*, *155*(January), 104666. https://doi.org/10.1016/j.resconrec.2019.104666

Accorsi, R., Battarra, I., Guidani, B., Manzini, R., Ronzoni, M., Volpe, L. (2022)a. Augmented spatial LCA for comparing reusable and recyclable food packaging containers networks, *Journal of Cleaner Production*, 2022, 375, Article number: 134027, pp. 1 – 21.

Accorsi, R., Cholette, S., Manzini, R., Mucci, L. (2022)b. Managing uncertain inventories, washing, and transportation of reusable containers in food retailer supply chains. *Sustainable Production and Consumption*, v 31, 331–345.

Aceves Lara, C. A., Athès, V., Buche, P., della Valle, G., Farines, V., Fonseca, F., Guillard, V., Kansou, K., Kristiawan, M., Monclus, V., Mouret, J. R., Ndiaye, A., Neveu, P., Passot, S., Pénicaud, C., Sablayrolles, J. M., Salmon, J. M., Thomopoulos, R., & Trelea, I. C. (2018). The virtual food system: Innovative models and experiential feedback in technologies for winemaking, the cereals chain, food packaging and eco-designed starter production. *Innovative Food Science and Emerging Technologies*, *46* (August 2017), 54–64.

Bortolini, M., Galizia, F.G., Mora, C., Botti, L. Rosano, M. (2018). Bi-objective design of fresh food supply chain networks with reusable and disposable packaging containers. *Journal of Cleaner Production,* v 184 (2018), 375-388.

Camps-Posino, L., Batlle-Bayer, L., Bala, A., Song, G., Qian, H., Aldaco, R., Xifré, R., & Fullana-i-Palmer, P. (2021). Potential climate benefits of reusable packaging in food delivery services. A Chinese case study. *Science of the Total Environment*, 794, 10 November 2021, 148570. https://doi.org/10.1016/j.scitotenv.2021.148570

Koskela, S., Dahlbo, H., Judl, J., Korhonen, M. R., & Niininen, M. (2014). Reusable plastic crate or recyclable cardboard box? A comparison of two delivery systems. *Journal of Cleaner Production*, *69*, 83–90. https://doi.org/10.1016/j.jclepro.2014.01.045

Levi, M., Cortesi, S., Vezzoli, C., & Salvia, G. (2011). A comparative life cycle assessment of disposable and reusable packaging for the distribution of italian fruit and vegetables. *Packaging Technology and Science*, *24*(7), 387–400. https://doi.org/10.1002/pts.946

Ronzoni, M., Accorsi, R., Battarra, I., Guidani, B., Manzini, R., Rubini, S. (2022). Optimizing food ordering in a multi-stage catering supply chain network using reusable containers. *IFAC-PapersOnLine* 55-10 (2022) 3196-3201.

Saeter, F., Alvarado, I. O., & Pettersen, I. N. (2020). Reuse principle for primary packaging circularity in the food system. In *NordDesign*.

Sel, Ç., Soysal, M., & Çimen, M. (2017). A green model for the catering industry under demand uncertainty. *Journal of Cleaner Production*, *167*, 459–472. https://doi.org/10.1016/j.jclepro.2017.08.100