R3PACK - REDUCE, REUSE, RETHINK PACKAGING TOWARDS NOVEL FIBRE-BASED PACKAGING AND REUSE SCHEMES

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INTRODUCTION

Food Supply Chains (FSCs) are responsible for over 25% of all anthropogenic GHG emissions (Poore and Nemecek, 2018). To meet global sustainable development goals, the players involved in food production and distribution must improve the environmental sustainability of their systems, interactions, and operations (Campbell et al., 2018; Govindan, 2018). Circular food packaging reuse networks represent one possibility to do so (Matthews et al., 2021; Yadav et al., 2022). 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 particularly in those sectors that use virgin materials most (Corvellec, 2016). While the benefit of reducing (or substitute) the use of virgin plastic polymers is well-known, some barriers limit the adoption of reusable packaging in the food industry (Salhoder et al., 2008; Accorsi et al., 2014; Coelho et al., 2020). The geographic distribution and capillarity of grocery shops (e.g., retailers, markets) affect the cost and the management of the package backhauls and washing, which need a deep understanding of the logistic interactions among food producers, packaging suppliers, and packagers with the distribution channels (Gallego-Schmid et al., 2018).

The location and capacities of the facilities enabling reverse logistics, the transportation distances among them, the number of rotations of each package, the consumers behaviour in the return choice, the long-term performance of the package, its reliability and resistance to breakage are crucial levers in designing sustainable reuse networks (Ross and Evans, 2003; Krikke, 2011; Gonzalez et al., 2018; Cottavafava et al., 2021). Recent surveys about closed-loop networks for returnable industrial items identifies optimisation techniques as promising methodology to explore such topic and contribute to the strategic planning and design of sustainable reuse systems (Glock, 2017; Rosa et al., 2019; Mahmoudi and Parviziomran, 2020).

In general, an optimization problem consists of maximizing or minimizing a function (e.g., cost, environmental impacts, time) by systematically choosing variables values required to compute the function itself from an allowed set of solutions (domain). The complexity of the optimization problem depends on the nature of its variables that can be continuous (real number), like the flow of products among facilities, or discrete (integer or binary), like the number of machines to install or the choice of establishing a facility in a given location (yes or no). Such a distinction result into the following well-known classification: Linear Programming (LP) problems made of continuous variables only and combinatorial or integer and Mixed- Integer linear problems (MILP) made of integer variables or a mix of real and integer or binary. The design of logistic networks represents a popular branch of application of optimization MILP problems and applied mathematics solving methods (i.e., problem decomposition, heuristics or metaheuristics like genetics and simulated annealing).

The scientific literature early developed support-design methods based on optimization for reusable packaging networks, not necessarily within the food industry. Chung et al. (2018) provided a genetic algorithm to maximize the reuse of tertiary packaging in closed-loop supply chains. Soysal (2016) solved an inventory-routing MILP problem for returnable transport items that involves for forward and reverse transport operations and explicit fuel consumption. 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) assess pallet management scenarios through carbon footprint analysis both concluding that optimization models to design closed-loop networks are needed. Iassinovskaia et al. (2017) propose a deterministic MILP inventory-routing model for reusable handling items and adopt simulation and metaheuristics to solve large-instances, respectively. However, all of them focused on operational issues and left the design of the reuse network uncovered. Tornese et al. (2018) used 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 recyclable and reusable containers within a regional catering supply chain yet illustrated in Accorsi et al. (2014). Recent advances in the field of network design for reusable secondary plastic containers (RPCs) in nation-wide retailer's supply chain using optimization are discussed in Accorsi et al. (2020) and Accorsi et al. (2022).

Nevertheless, no previous research investigates the strategic design of logistic network of reusable primary packaging for food products in retailers supply chain. Such reuse network entails the following peculiarities: the need for sanitization processes after use, the response from consumers and their returning behavior, the breakage rate, the possible packaging multi-material composition, and the returning and collection systems (e.g. Collection bins, reusable vending machines (RVM), sorter).

This deliverable introduces a novel optimisation location-allocation MILP model to aid designing the closed-loop network of reusable primary food packaging defined by R3PACK project. The following pages show the main entities (packaging, lines, facilities, shops) handled by the optimisation model and explain the nature of decision variables, the goal of the objective function, and the domain of the potential solution respecting the constraints. The optimisation model is then applied to the R3PACK demonstrator case, and preliminary results illustrated and discussed in the following.

1. REUSE MODEL

1.1 Reuse Network Modelling

The REUSE WP aims to design the enabling logistic scenario that would make reusing food packaging sustainable for the environment and economically for the players involved. The proposed optimization model seeks to describe the main network physical entities and their behavior with mathematical equations. The optimization models, falling into the category of the so-called Location Allocation Problems (LAP), allows determining the optimal allocation of the facilities and the optimal flows of material (both package only and packaged food) shipped between them. The variables also called unknowns, which defines the solution of the problem, are of two types:

- Binary variables (x ∈ {0,1}): opening variables that allow defining the optimal location of a facility, a packing or washing line, or a collection system.
- Continuous variables (x ∈ R^+): Linear positive flow representing the amount of material that is exchanged between facilities.

The optimal solution (i.e. the values of the variables which minimize the overall cost function) is search within a feasible region, i.e. the values of the variables that are acceptable according to a set of linear constraints. Figure 1 shows a general scheme of a Location-Allocation optimization problem.

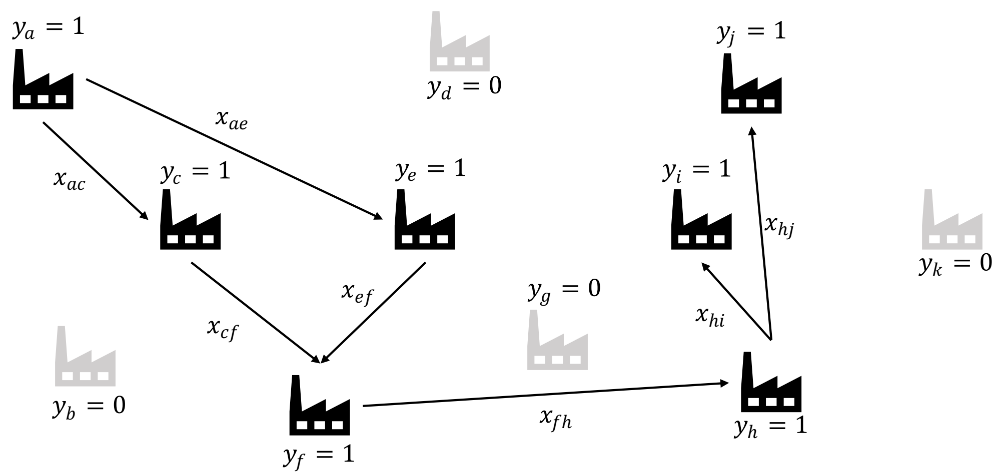

Figure 1. Exemplification of LAP solution.

The model is formulated through the following elements and written using the high-level language AMPL (A Mathematical Programming Language):

- SETS, declared with "set + the name of the set + ;". Defines the entities that populate the model;
- PARAMETERS, declared with "param + the parameter name + {SET} + ;". They are the known values used as input in the model definition. The parameters describe the input data set of the instance to be solved.

- VARIABLES, declared with "var + variable name + {SET} + variable domain + ;". They are the values that represent the solution of the problem.
- The objective function defined with "maximize/minimize + name of the quantity: + expression of the function + ;". It is the target of the problem that one wishes to maximize or minimize. In the following formulation we consider costs, but environmental impacts will be considered in the following.
- Problem constraints defined with "subject to + constraint name + {SET}: + constraint expression + ;". They represent the limitation to the variables' values and draw the solution domain. If a constraint is not respected, the associated solution is defined as infeasible.

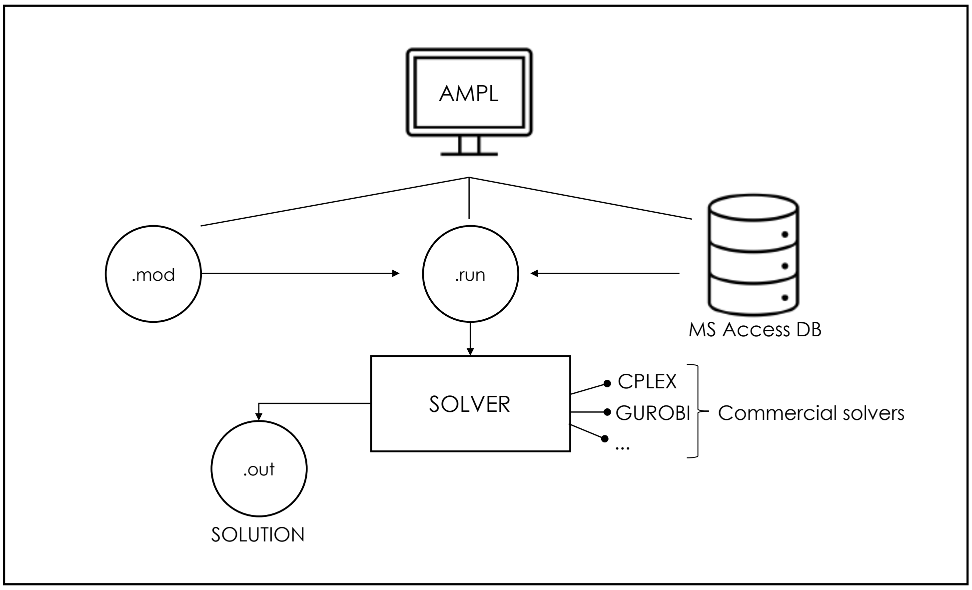

Figure 2. Interaction between inputs, optimisation model, solver and solution.

The optimization model is fed through a database implemented on MS Access. The database, is a set of homogeneous in type record stored within multiple tables connected to each other through relationships (mapped within an Entity-Relationship diagram). Drawing the ER diagram means designing the tables (i.e. the entities/sets) and its relationships for each entity. MS Access is used to achieve three different purposes:

- Generate a database for data collection with partners and industrials used as data repository (high-level database);
- Generate a database containing the sets and parameters of the optimisation model (low-level database);
- Write queries to explicit combinations between table elements and connect the two databases through admissible tuples of keys

In particular, the structure of SETS, PARAMETERS and VARIABLES in AMPL must be aligned with the tables, the relationship and the keys of the database. For each entity (SET) defined for the model in AMPL a corresponding table is set on MS Access database which collects the parameters to describe that entity. Each table indeed consists of primary keys that uniquely identify each entity forbidding duplication, and other columns representing the attributes (numeric, string, binary) of that entity.

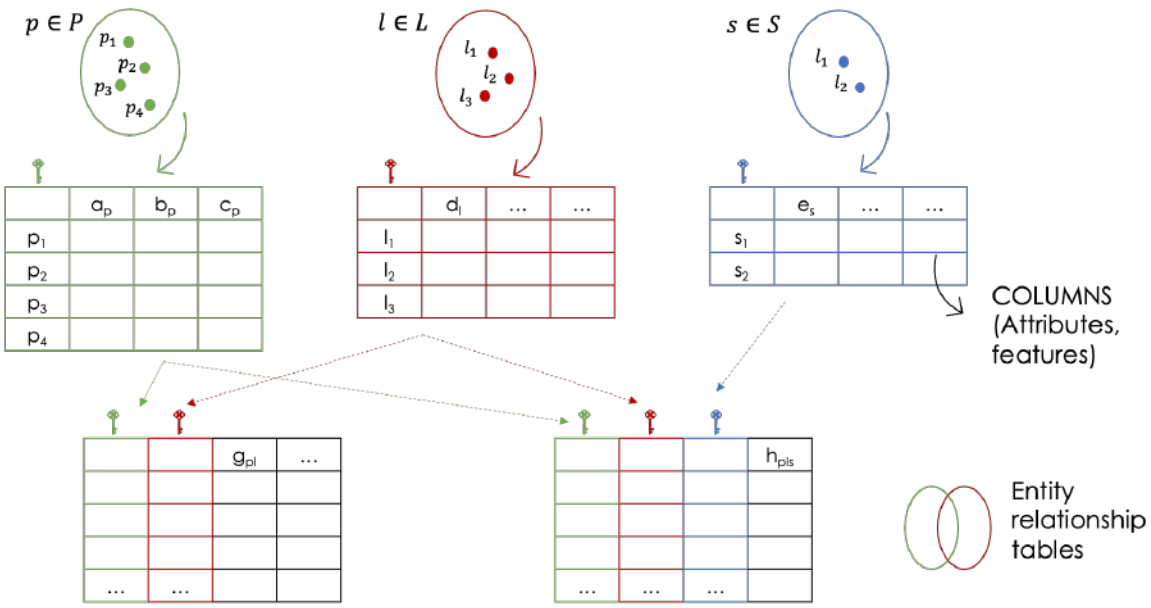

Figure 3. Sets, tables, keys, and entities.

In the following the detailed description of the model entities, the decision variables, the objective functions defined so far, and the problem contraints is proposed.

1.1.1 Network Entities

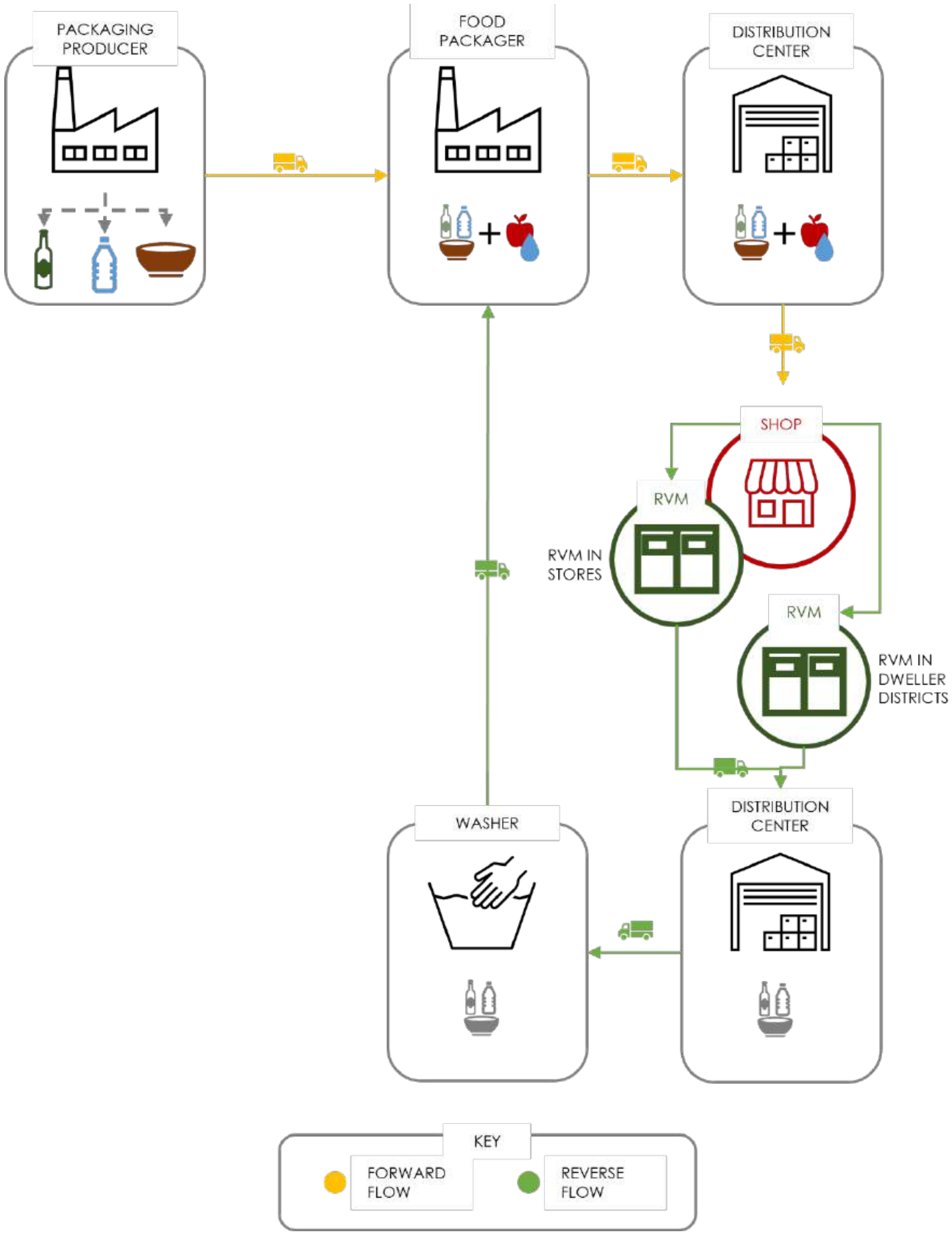

Figure 4. Network entities and logistic connections

Figure 2 shows the entities modeled and the related logistic connections between them. Packaging producers (*p*) manufacture the reusable packaging (*mp*) and send it to the food packagers (*f*). Packaging producers represent the upstream network of the network manufacturing new packaging from virgin raw material. After the production, the model can exploit the reuse cycle to reduce the economic and environmental impact of the packaging production and disposal. The need to reintroduce new packaging within the logistics network is driven by containers' breakage due to transport, washing, and storage, and the need to comply with the safety requirements on maximum number of cycles allowed.

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Each packaging producer specializes the adopted materials and formats. Food packagers couple packaging and food items (*m*) according to the food brand offer and ship the packaged product (*a*) to the retailer distribution centers (*d*). The shops (*s*) receive the packaged product in compliance with the sales forecast. Stores (shops) differ by brand, location and size, and each handles a well-defined set of products. After consumption, the customers willing to return the used packaging have two ways. Collection containers, called Reusable Vending Machines (RVM) (*rvm*), are placed in dweller districts (*dd*), besides other municipal differentiated trash bins, or at the shops, where consumers can return the packaging during shopping. Dweller districts represent areas of residential neighbourhoods that can be considered homogeneous in terms of consumers density and behaviour. A dweller district corresponds to the coordinates of the area's barycentre, and must be defined small enough to make such a approximation realistic.

RVMs have dedicated storage capacity for specific packaging materials and formats. RVMs' distance from residential areas and consumer preferences influence the collection location' choice. Figure 5 schematizes the possible alternatives exploited by consumers and the corresponding flows handled by the model.

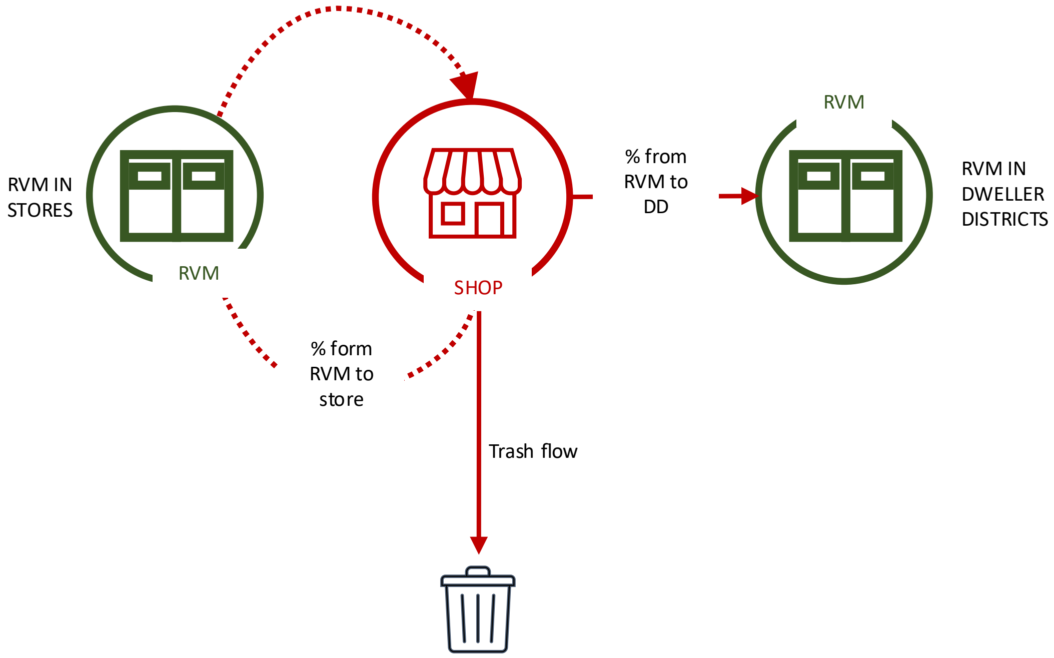

Figure 5. Return flow of empty packaging

RVMs allow collecting and consolidating dirty packaging from consumers households. They may provide monetary incentives (deposit in cash or vouchers) to encourage the return. From RVMs, the dirty packaging is sent to the distribution centers for consolidation, and then to the washing facilities (*w*) to be checked and washed (other return ways can easily formulated an tried by modifying the model). Washers represent key actors within the reuse network and enable providing the food packagers with sanitized empty packages. The washing facilities may differ in the cleaning process, the shape and material of containers handled, and the washing lines' capacity. The sanitized reusable containers are sent to the food packager, whose inventory is eventually refilled with new containers that balance the losses. These losses result from breakage, wear, or the consumers' choice to retain or throw the empty packaging.

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Lastly, the transportation modes define the available means of transportation between each couple of network facilities.

The network's mathematical formulation defines the entities involved through sets and subsets. The list of sets and subsets of the developed model is presented below.

Sets:

$p \in P$	Packaging producer facilities
$f \in F$	Food packager facilities
$d \in D$	Distribution centers of the two retailers' companies involved in R3PACK. These warehouse facilities are used to store both packaged food items and returned packaging collected from RVMs
$s \in S$	Stores of the two retailer companies involved in R3PACK
$rvm \in RVM$	RVMs typologies
$dd \in DD$	Dweller Districts, barycentric points of residential areas
$w \in W$	Packaging Washer facilities
$a \in A$	Packaged food items. Each item is identified by its EAN code
$m \in M$	Components of the Bill Of Materials (BOM) of the packaged products. Raw food (e.g., whole milk UHT), and reusable containers (e.g., 1000 ml glass bottle) belong to this set
$t \in T$	Allowed means of transportation

Subsets:

$(a,m) \in B \subset A \times M$	Bill Of Materials of packaged products. Each product $a \in A$ is composed of several components $m \in M$, such as the food and the container
$(m) \in \mathrm{MP} \subset M$	Subset of components representing reusable containers
$(dd,s) \in \mathrm{DDS} \subset DD \times S$	Allowed connections between dweller districts and stores. Each store serves at least one dweller district, and the residents of a dweller district can return the reusable container in the stores serving such district
$(s,rvm) \in \mathrm{RS} \subset S \times RVM$	RVM typologies allowed in each store. The store dimensions influence the space available for RVMs and the installable machines
$(dd,rvm) \in RDD \subset DD \times RVM$	Allowed RVMs in the collection area of each dweller district
$(rvm,m) \in \mathrm{RVMM} \subset RVM \times MP$	Allowed reusable containers in each RVM (some RVMs can collect only the containers of a specific material, while other discriminate over the packaging size)

$(dd, d) \in \mathrm{DDD} \subset DD \times D$	Couples of dweller districts and distribution centers accepting dirty containers from such districts. The connection is allowed if the distance between the two facilities is not over 120 km
$(p, m) \in \mathrm{PM} \subset P \times MP$	Reusable packaging items manufactured in each packaging producer facility. Each packaging producer specializes in the production of specific packaging materials, formats, and capacity
$(f, a) \in \mathrm{FA} \subset F \times A$	Packaged products' produces in each food packager facility. Each food packager is dedicated to specific food categories (e.g., dairy products) and specific brands
$(w, m) \in \mathrm{WM} \subset W \times MP$	Reusable packaging items that can be washed by each washer facility. The washer can be specialized to handle only some packaging materials and formats
$(p, f) \in \mathrm{PF} \subset P \times F$	Allowed connections between packaging producers and food packagers. Each food packager supplies the food containers from a few packaging producers
$(d, a) \in \mathrm{DA} \subset D \times A$	Allowed packaged products handled by each distribution center. Usually, each distribution center can handle every packaged product, except for the retailer-branded products. Those are handled only by the distribution centers of the same retail company
$(d, m) \in \mathrm{DM} \subset D \times MP$	Allowed reusable containers handled by each distribution center as reverse flow. Distribution centers can handle used containers that are used in products sold in the store of the retailer company
$(d, s) \in \mathrm{DS} \subset D \times S$	Allowed connections between stores and distribution centers. The distribution centers' network of a retail company can serve all the stores of the same company. Moreover, it is assumed that a distribution center cannot serve the stores outside a 120 km radius (a closer and more convenient distribution center should be present in the area)
$(d, w) \in \mathrm{DW} \subset D \times W$	Allowed connection between distribution centers and washers. The allowed couples are those between distribution centers and washers that handle the same reusable packaging containers
$(w, f) \in \mathrm{WF} \subset W \times F$	Available connections between washer facilities and food packagers. A washer sends clean containers only to food packagers producing items that require such components
$(f, d) \in \mathrm{FD} \subset F \times D$	Available connections between food packagers and distribution centers. The connections are defined for those couple that handle the same packaged products
$(s, a) \in \mathrm{SA} \subset S \times A$	Packaged products sold in each store (e.g., the retailer-branded packaged products can only be sold in such retailer's stores)

1.1.2 Reuse Network parameters

To model the entities' behavior, a series of input parameters are introduced. Usually, the entities and the parameters defining their behavior are defined on the same sets or subsets (e.g., each transportation mode t will have cost parameters defined per each $t \in T$). The list of the designed parameters used in the developed model is presented in Table 1 below.

Param.	Description	Unit of measure
wkg_a	Weight of one item of packaged product	*kg*
vol_a	Volume of one item of a packaged product	*m*^{3}
ref_a	Binary: 1 if packaged product ***a*** is refrigerated, 0 otherwise	-
sat_a	Weight of one pallet of packaged product ***a***	*kg/pallet*
qm_b	Quantity of component ***b*** used to produce one piece of packaged product ***a***	*kg/item*
sat_{mp}	Weight of one pallet of reusable packaging ***mp*** (clean or dirty). It is assumed that the containers cannot be stacked one inside the other	*kg/pallet*
$ScrapRate_{mpw}$	Scrap-rate of reusable packaging ***mp*** due to the washer w cleaning system	*%*
$\%s_m$	Likelihood of citizens to return dirty containers to an RVM located in a store	*%*
$\%dd_m$	Likelihood of citizens to return dirty containers to an RVM located in a dweller district	*%*
$\%not_m$	Likelihood of citizens not to return dirty containers in any RVM	*%*
dc_t	Transportation cost for transportation mode ***t***	$\frac{€}{km * truck}$
d_{pf}	Distance between packaging producer ***p*** and food packager ***f***	*km*
d_{fd}	Distance between food packager ***f*** and distribution center ***d***	*km*
d_{ds}	Distance between distribution center ***d*** and store ***s***	*km*
d_{dw}	Distance between distribution center ***d*** and washer ***w***	*km*
d_{ddd}	Distance between dweller district ***dd*** and distribution center ***d***	*km*
dem_{sa}	Demand for packaged product ***a*** in store ***s***	$\frac{pieces}{year}$
fc_p	Fixed opening cost for the facility/new production lines of packaging producer ***p***	€
fc_f	Fixed opening cost for the new food packaging lines of food packager ***f***	€
fc_d	Fixed cost for activating the handling of the new reusable containers in the distribution center ***d***	€

fc_w	Fixed cost for activating the handling of the new reusable containers in the washer facility *w*	€
fc_{rvm}	Installation cost of one RVM *rvm*	€
plt_{pm}	Production line throughput at packaging producer *p* for component *m*	$\frac{pieces}{year}$
cp_{pm}	Production cost of 1 kg of component m at packaging producer p	€/kg
is_f	Inbound capacity of food packager *f*	$\frac{kg}{year}$
$osref_f$	Outbound capacity for refrigerated products at food packager *f*	$\frac{pieces}{year}$
$osnonref_f$	Outbound capacity for non-refrigerated products at food packager *f*	$\frac{pieces}{year}$
$palt_{fa}$	Production line throughput at food packager *f* for packaged product *a*	$\frac{pieces}{year}$
c_{fa}	Production cost for packaged product *a* at food packager *f*	€/piece
$isref_d$	Inbound capacity for refrigerated products at distribution center *d*	$\frac{kg}{year}$
$osref_d$	Outbound capacity for refrigerated products at distribution center *d*	$\frac{kg}{year}$
$isnonref_d$	Inbound capacity for non-refrigerated products at distribution center *d*	$\frac{kg}{year}$
$osnonref_d$	Outbound capacity for non-refrigerated products at distribution center *d*	$\frac{kg}{year}$
hc_{da}	Material handling cost for packaged product *a* at distribution center *d*	€/piece
hc_{dm}	Material handling cost for reusable packaging *m* at distribution center *d*	€/kg
cap_{rvmm}	RVM *rvm* capacity for reusable packaging *m*	$\frac{kg}{year}$
c_{rvm}	Operating cost for RVM *rvm*	€/kg
is_w	Inbound capacity of washer package *w*	$\frac{kg}{year}$
os_w	Outbound capacity of washer package *w*	$\frac{kg}{year}$
c_{wm}	Washing cost of component *m* at washer *w*	€/kg
wt_{wm}	Washing line throughput for component *m* at washer *w*	$\frac{kg}{year}$

Table 1 Model parameters

1.1.3 Decision variables

The model variables represent the choices that minimize the total cost for the entire network. The MILP model includes the two variable typologies introduced before, binary and continuous variables. The former represent ***opening variables*** in this context, outlining decisions on the activation of specific functions in the network facilities. Examples of ***opening variables*** are the activation of a specific washer for the reverse logistics or the installation of an RVM in a store. Binary variables assume value 1 if the facility/machine/function depicted is activated, or 0 if it is not activated. Continuous variables are the ***flow variables*** representing the shipments of packages or products between two network facilities. These indicate the quantity of an entity (In pieces, kg, pallets, or trucks) moved from one facility to another in a period of time (one year in the assessed case). The objective of the model is to find the optimal value for all the variables to suggest the decision-makers the most efficient choices. A complete list of the variables implemented in the presented model is given in Table 2 below.

Variable	Domain	UoM	Description
y_p [0;1]	$p \in P$	-	1 if packaging producer facility ***p*** is activated, 0 otherwise
y_f [0;1]	$f \in F$	-	1 if packaging lines at food packager ***f*** are activated, 0 otherwise
y_d [0;1]	$d \in D$	-	1 if distribution center ***d*** is used in the network reverse logistics, 0 otherwise
y_w [0;1]	$w \in W$	-	1 if washer facility ***w*** is activated, 0 otherwise
y_{rs} [0;1]	$(s, rvm) \in RS$	-	1 if RVM ***rvm*** is installed in store ***s***, 0 otherwise
y_{rdd} [0;1]	$(dd, rvm) \in RDD$	-	1 if RVM ***rvm*** is installed in dweller district ***dd***, 0 otherwise
$x_{pfmt} \geq 0$	$(p, f) in\ PF, m\ in\ MP, t\ in\ T: (p, m)\ in\ PM$	kg	Flow of component ***m*** from packaging producer ***p*** to food packager ***f*** with transportation mode ***t***
$x_{fdat} \geq 0$	$(f, d) in\ FD, a\ in\ A, t\ in\ T: (f, a)\ in\ FA\ and\ (d, a)\ in\ DA$	$pieces$	Flow of product ***a*** from food packager ***f*** to distribution center ***d*** with transportation mode ***t***
$x_{dsat} \geq 0$	$(p, f) in\ PF, m\ in\ MP, t\ in\ T: (p, m)\ in\ PM$	$pieces$	Flow of product ***a*** from food packager ***f*** to store ***s*** with transportation mode ***t***
$x_{ddsrvmm} \geq 0$	$(dd, s) in\ DDS, rvm\ in\ RVM, m\ in\ MP: (s, rvm) in\ RS\ and\ (rvm, m)\ in\ RVMM$	kg	Flow of component ***m*** from dweller district ***dd*** to RVM ***rvm*** in store ***s***
$x_{dddd1rvmm} \geq 0$	$(dd, s) in\ DDS, rvm\ in\ RVM, m\ in\ MP: (dd, rvm)\ in\ RDD\ and\ (rvm, m)\ in\ RVMM$	kg	Flow of component ***m*** from dweller district ***dd*** to RVM ***rvm*** in the same dweller district
$x_{rddmt} \geq 0$	$(dd, rvm) in\ RDD, d\ in\ D, m\ in\ MP, t\ in\ T: (dd, d)\ in\ DDD\ and\ (rvm, m) in\ RVMM\ and\ (d, m) in\ DM$	kg	Flow of component ***m*** from RVM ***rvm*** in dweller district ***dd*** to distribution center ***d*** with transportation mode ***t***

$x_{trash} \geq 0$	(dd, s) in DDS, m in M	kg	Flow of component *m* (bought in store s) not returned from consumers in dweller district *dd*
$x_{rsdmt} \geq 0$	(s, rvm) in RS, d in D, m in MP, t in T: (rvm, m) in $RVMM$ and (d, m) in DM and (d, s) in DS,	kg	Flow of component *m* from RVM *rvm* in store *s* to distribution center *d* with transportation mode *t*
$x_{dwmt} \geq 0$	(d, w) in DW, m in MP, t in T: (d, m) in DM and (w, m) in WM	kg	Flow of component *m* from distribution center *d* to washer package *w* with transportation mode *t*
$x_{wfmt} \geq 0$	(w, f) in WF, m in MP, t in T: (w, m) in WM and m in MP	kg	Flow of component *m* from washer *w* to food packager *f* with transportation mode *t*

Table 2 Model variables

1.1.4 Objective function and constraints

The Objective Function (FO) is a function used to drive the search for the optimal solution. It includes all the cost components the decision-makers aim to minimize and consists of three main parts: the ***investment cost*** to activate facilities, such as installation cost of production and washing lines, or purchasing cost of RVMs; the logistics cost associated to the flow of products and packaging throughout the supply chain, such as the fuel cost; the ***operations cost*** of the supply chain, such as packaging production cost, handling cost at the distribution centers, and RVMs' maintenance cost. The FO is presented below:

OF component	Mathematical formulation
Investments cost	
Activation costs of packaging producers, food packagers, distribution centers, washers, and RVMs	$\sum_{p \text{ in } P} fc_p \cdot y_p + \sum_{f \text{ in } F} fc_f \cdot y_f + \sum_{d \text{ in } D} fc_d \cdot y_d + \sum_{w \text{ in } W} fc_w \cdot y_w + \sum_{(s,rvm) \text{ in } RS} fco_{rvm} \cdot y_{rs} + \sum_{(dd,rvm) \text{ in } RDD} fco_{rvm} \cdot y_{rdd}$
Operations cost	
Reusable packaging production	$+ \sum_{\substack{(p,f) \text{ in } PF, m \text{ in } MP, t \text{ in } T: \\ (p,m) \text{ in } PM}} x_{pfmt} \cdot cp_{pm}$
Packaged food production	$+ \sum_{\substack{(f,d) \text{ in } FD, a \text{ in } A, t \text{ in } T: \\ (f,a) \text{ in } FA \text{ and } (d,a) \text{ in } DA}} x_{fdat} \cdot c_{fa}$
Material handling for packaged products at distribution center	$+ \sum_{\substack{\{(d,s) \text{ in } DS, a \text{ in } A, t \text{ in } T: \\ (d,a) \text{ in } DA \text{ and } (s,a) \text{ in } SA}} x_{dsat} \cdot hc_{da}$
RVMs maintenance in store	$+ \sum_{\substack{(dd,s) \text{ in } DDS, rvm \text{ in } RVM, m \text{ in } MP: \\ (s,rvm) \text{ in } RS \text{ and } (rvm,m) \text{ in } RVMM}} x_{ddsrvmm} \cdot c_{rvm}$

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RVMs maintenance in dweller districts	$+\sum_{\substack{(dd,s)\text{ in } DDS, rvm \text{ in } RVM, m \text{ in } MP: \\ (dd,rvm) \text{ in } RDD \text{ and } (rvm,m) \text{ in } RVMM}} x_{dddd1rvmm} \cdot c_{rvm}$
Material handling for reverse flow of reusable packaging at distribution center	$+\sum_{\substack{(d,w)\text{ in } DW, m \text{ in } MP, t \text{ in } T: \\ (d,m) \text{ in } DM \text{ and } (w,m) \text{ in } WM}} x_{dwmt} \cdot hc_{dm}$
Reusable packaging washing	$+\sum_{\substack{(w,f)\text{ in } WF, m \text{ in } MP, t \text{ in } T: \\ (w,m) \text{ in } WM \text{ and } m \text{ in } MP}} x_{wfmt} \cdot c_{wm}$
Logistics cost	
Transportation of reusable packaging from packaging producer to food packager	$+\sum_{\substack{(p,f)\text{ in } PF, m \text{ in } MP, t \text{ in } T: \\ (p,m) \text{ in } PM}} \frac{x_{pfmt}}{satMP \cdot cap_t} \cdot d_{pf} \cdot dc_t$
Transportation of packaged product from food packager to distribution center	$+\sum_{\substack{(f,d)\text{ in } FD, a \text{ in } A, t \text{ in } T: \\ (f,a) \text{ in } FA \text{ and } (d,a) \text{ in } DA}} \frac{x_{fdat}}{satA \cdot cap_t} \cdot d_{fd} \cdot dc_t$
Transportation of packaged product from distribution center to store	$+\sum_{\substack{(d,s)\text{ in } DS, a \text{ in } A, t \text{ in } T: \\ (d,a) \text{ in } DA \text{ and } (s,a) \text{ in } SA}} \frac{x_{dsat}}{satA \cdot cap_t} \cdot d_{ds} \cdot dc_t$
Transportation of dirty packaging from distribution center to washer	$+\sum_{\substack{(d,w)\text{ in } DW, m \text{ in } MP, t \text{ in } T: \\ (d,m) \text{ in } DM \text{ and } (w,m) \text{ in } WM}} \frac{x_{dwmt}}{satMP \cdot cap_t} \cdot d_{dw} \cdot dc_t$
Transportation of clean packaging from washer to food packager	$+\sum_{\substack{(w,f)\text{ in } WF, m \text{ in } MP, t \text{ in } T: \\ (w,m) \text{ in } WM \text{ and } m \text{ in } MP}} \frac{x_{wfmt}}{satMP \cdot cap_t} \cdot d_{wf} \cdot dc_t$
Transportation of dirty packaging from RVM in store to distribution center	$+\sum_{\substack{(s,rvm)\text{ in } RS, d \text{ in } D, m \text{ in } MP, t \text{ in } T: \\ (rvm,m)\text{ in } RVMM \text{ and } (d,m)\text{ in } DM \\ \text{and } (d,s) \text{ in } DS}} \frac{x_{rsdmt}}{satMP \cdot cap_t} \cdot d_{ds} \cdot dc_t$
Transportation of dirty packaging from RVM in dweller district to distribution center	$+\sum_{\substack{(dd,rvm)\text{ in } RDD, d \text{ in } D, m \text{ in } MP, t \text{ in } T: \\ (dd,d)\text{ in } DDD \text{ and } (rvm,m)\text{ in } RVMM \text{ and} \\ (d,m)\text{ in } DM}} \frac{x_{rdddmt}}{satMP \cdot cap_t} \cdot d_{ddd} \cdot dc_t$

Table 3 Components of the model OF

The model constraints are defined to ensure that only feasible solutions are explored and evaluated. Feasible solutions must respect the physical, temporal and financial limits of the real network. In this case, the constraints can be classified into three categories. The *capacity constraints* prevent the manufactured quantities and the shipped quantities to exceed the facility capacity. Moreover, food producers and distribution centers might have dedicated capacities for refrigerated and non-refrigerated products, increasing the accuracy of the results. The f*low constraints* balance the inbound and outbound flow of packaging or product in each facility. The d*emand constraints* force the demand fulfillment in each store, for every packaged product. The table below outlines all the constraints designed for the reuse network problem.

Constraint	Mathematical formulation
Capacity constraints	
PP_CapacityOut:	$\forall\ (p,m)\ \in\ PM$:

production capacity of packaging producers	$$\sum_{f \text{ in } F, t \text{ in } T:(p,f) \text{in } PF} x_{pfmt} \leq plt_{mp} \cdot y_p$$
FP_CapacityIn: inbound packaging capacity of food packager	$\forall f \in F$: $$\sum_{\substack{p \text{ in } P, t \text{ in } T, m \text{ in } MP: \\ (p,m) \text{ in } PM \text{ and } (p,f) \text{in } PF}} x_{pfmt} \leq is_f \cdot y_f$$
FP_CapacityOut_Ref: outbound capacity of refrigerated packaged products at food packager	$\forall f \in F$: $$\sum_{\substack{d \text{ in } D, a \text{ in } A, t \text{ in } T: \\ (f,a) \text{in } FA \text{ and } (f,d) \text{in } FD \\ \text{and } (d,a) \text{ in } DA}} x_{fdat} \cdot wkg_a \cdot ref_a \leq osref_f \cdot y_f$$
FP_CapacityOut_NonRef: outbound capacity of non-refrigerated packaged products at food packager	$\forall f \in F$: $$\sum_{\substack{d \text{ in } D, a \text{ in } A, t \text{ in } T: \\ (f,a) \text{in } FA \text{ and } (f,d) \text{in } FD \\ \text{and } (d,a) \text{ in } DA}} x_{fdat} \cdot wkg_a \cdot (1 - ref_a) \leq osnonref_f \cdot y_f$$
DC_CapacityIn_Ref: inbound capacity of refrigerated packaged products at distribution center	$\forall d \text{ in } D$: $$\sum_{\substack{f \text{ in } F, a \text{ in } A, t \text{ in } T: \\ (f,a) \text{in } FA \text{ and } (f,d) \text{in} \\ FD \text{ and } (d,a) \text{ in } DA}} x_{fdat} \cdot wkg_a \cdot ref_a \leq isref_d \cdot y_d$$
DC_CapacityIn_NonRef: inbound capacity of non-refrigerated packaged products at distribution center	$\forall d \in D$: $$\sum_{\substack{f \text{ in } F, a \text{ in } A, t \text{ in } T: \\ (f,a) \text{in } FA \text{ and} \\ (f,d) \text{in } FD \text{ and} \\ (d,a) \text{ in } DA}} x_{fdat} \cdot wkg_a \cdot (1 - ref_a) \leq isnonref_d \cdot y_d$$
DC_CapacityOut_Ref: outbound capacity of refrigerated packaged products at distribution center	$\forall d \in D$: $$\sum_{\substack{(s,a) \text{in } SA, t \text{ in } T: \\ (d,a) \text{in } DA \text{ and} \\ (d,s) \text{ in } DS}} x_{dsat} \cdot wkg_a \cdot ref_a \leq osref_d \cdot y_d$$
DC_CapacityOut_NonRef: outbound capacity of non-refrigerated packaged products at distribution center	$\forall d \in D$: $$\sum_{\substack{(s,a) \text{in } SA, t \text{ in } T: \\ (d,a) \text{in } DA \text{ and} \\ (d,s) \text{ in } DS}} x_{dsat} \cdot wkg_a \cdot (1 - ref_a) \leq osnonref_d \cdot y_d$$
RS_Capacity: RVMs' packaging capacity in store	$\forall (s, rvm) \in RS$: $$\sum_{\substack{dd \text{ in } DD, m \text{ in } MP: \\ (rvm,m) \text{in } RVMM \text{ and} \\ cap_{rvmm[rvm,m]} \geq 0 \\ \text{and } (dd,s) \text{ in } DDS}} x_{ddsrvmm} \leq \sum_{\substack{m \text{ in } MP: \\ (rvm,m) \text{ in } RVMM}} cap_{rvmm} \cdot y_{rs}$$
RDD_Capacity:	$\forall (dd, rvm) \in RDD$:

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RVMs' packaging capacity in dweller district	$\sum_{\substack{s\ in\ S,m\ in\ MP:\\ (dd,s) in\ DDS\ and\\ (rvm,m) in\ RVMM\ and\\ cap\_rvmm[rvm,m]>0}} x_{dddd1rvmm} \leq \sum_{\substack{m\ in\ MP:\\ (rvm,m) in\\ RVMM}} cap_{rvmm} \cdot y_{rdd}$
W_CapacityIn: inbound capacity of washer facility	$\forall\, w \in W$: $\sum_{\substack{d\ in\ D,t\ in\ T,m\ in\ MP:\\ (w,m) in\ WM\ and\\ (d,m)\ in\ DM\ and\ (d,w)\ in\ DW}} x_{dwmt} \leq is_w \cdot y_w$
W_CapacityOut: outbound capacity of washer facility	$\forall\, w \in W$: $\sum_{\substack{f\ in\ F,t\ in\ T,m\ in\ MP:\\ (w,m)\ in\ WM\ and\ (w,f)\ in\ WF}} x_{wfmt} \leq os_w \cdot y_w$
Demand Constraints *StoreDemand:* demand satisfaction for every product in each store	$\forall\, (s,a) \in SA$: $\sum_{\substack{d\ in\ D,t\ in\ T:\\ (d,a) in\ DA\ and\\ (d,s)\ in\ DS}} x_{dsat} \leq dem_{sa}$
Flow Constraints *Flow_FP:* flow balance of packaging at food packager: from packaging producers and washers to distribution centers	$\forall\, f \in F, m \in MP$: $\sum_{\substack{p\ in\ P,t\ in\ T:\\ (p,f) in\ PF\\ and\\ (p,m)\ in\ PM}} x_{pfmt} + \sum_{\substack{w\ in\ W,t\ in\ T:\\ (w,m) in\ WM\\ and\\ (w,f)\ in\ WF}} x_{wfmt} \geq \sum_{\substack{d\ in\ D,t\ in\ T,\\ (a,m) in\ B:\\ (f,a) in\ FA\\ and\\ (d,a) in\ DA\\ and\\ ([illegible],d) in\ FD}} x_{fdat} \cdot qm_b$
Flow_DC: flow balancing of packaged product at distribution center: from food packagers to stores	$\forall\, (d,a)\ in\ DA$: $\sum_{\substack{f\ in\ F,t\ in\ T:\\ (f,a)\ in\ FA\ and\ (f,d)\ in\ FD}} x_{fdat} \geq \sum_{\substack{s\ in\ S,t\ in\ T:\\ (d,s)\ in\ DS\ and\ (s,a)\ in\ SA}} x_{dsat}$
Flow_RS: flow balance of packaging at RVMs in store according to return %	$\forall\, s\ in\ S, m\ in\ MP$: $\sum_{\substack{(s,a) in\ SA:\\ (a,m)\ in\ B}} dem_{sa} \cdot qm_b \cdot percs_m = \sum_{\substack{(dd,s) in\ DDS,\\ (s,rvm) in\ RS:\\ (rvm,m)\ in\ RVMM}} x_{ddsrvmm}$
Flow_RDD: flow balance of packaging at RVMs in store according to return %	$\forall\, s\ in\ S, m\ in\ MP$: $\sum_{\substack{(s,a) in\ SA:\\ (a,m)\ in\ B}} dem_{sa} \cdot qm_b \cdot percdd_m = \sum_{\substack{(dd,s) in\ DDS,\\ (dd,rvm) in\ RDD:\\ (rvm,m) in\\ RVMM}} x_{dddd1rvmm}$
Flow_Trash: flow balance of non-returned packaging according to return %	$\forall\, s\ in\ S, m\ in\ MP$: $\sum_{\substack{(s,a) in\ SA:\\ (a,m)\ in\ B}} dem_{sa} \cdot qm_b \cdot (1 - percdd_m - percs_m) = \sum_{\substack{(dd,s) in\\ DDS}} x_{trash}$
Flow_RSD:	$\forall (s,rvm) in\ RS, m\ in\ MP: (rvm,m) in\ RVMM$:

flow balancing of dirty packaging at RVMs in store: from dweller districts to distribution centers	$$\sum_{(dd,s)\,in\,DDS} x_{ddsrvmm} = \sum_{\substack{d\,in\,D,t\,in\,T:\\(d,m)\,in\,DM\,and\,(d,s)\,in\,DS}} x_{rsdmt}$$
Flow_RDDD: flow balancing of dirty packaging at RVMs in dweller district: from dweller districts to distribution centers	$\forall (dd,rvm)\ in\ RDD, m\ in\ MP: (rvm,m)\ in\ RVMM$: $$\sum_{s\,in\,S:\,(dd,s)\,in\,DDS} x_{dddd1rvmm} = \sum_{\substack{d\,in\,D,t\,in\,T:\\(d,m) in\,DM\,and\\(dd,d)\,in\,DDD}} x_{rddd mt}$$
Flow_CP: flow balancing of dirty packaging at distribution center: from RVMs in dweller districts and stores to washers	$\forall (d,m) in\ DM$: $$\sum_{\substack{(s,rvm) in\,RS,\\t\,in\,T:\\(rvm,m) in\\RVMM\\and\,(d,s)\,in\,DS}} x_{rsdmt} + \sum_{\substack{(dd,rvm) in\\RDD,\\t\,in\,T:\\(rvm,m) in\\RVMM\,and\\(dd,d) in\\DDD}} x_{rdddmt} = \sum_{\substack{w\,in\,W,t\,in\,T:\\(w,m) in\,WM\\and\\(d,m) in\,DM\\and\\(d,w)\,in\,DW}} x_{dwmt}$$
Flow_W: flow balancing of packaging at washer: from distribution centers to food packagers according to scrap %	$\forall (w,m) in\ WM$ $$\sum_{\substack{d\,in\,D,t\,in\,T:\\(d,m) in\,DM\\and\,(d,w)\,in\,DW}} (x_{dwmt} \cdot (1 - ScrapRate)) = \sum_{\substack{f\,in\,F,t\,in\,T:\\(w,f)\,in\,WF}} x_{wfmt}$$

Table 4 Model constraints

2. DATA COLLECTION AND ASSUMPTIONS

The data collection activity has been performed in several steps and involved most of the R3PACK project industrial partners. The goal of this task was to understand the industrial, technical, and financial boundaries of the problem and feed the mathematical model with realistic inputs. Once the system's boundaries and the constraints are formulated, the data collection supports the valorization of the model parameters/inputs (outlined in section 1.1.2). As explained in the introduction, sets, subsets, and parameters feed the model from the designed MS Access database. In order to facilitate make the data collection activity to the industrial partners, a user-friendly form in MS Excel interface has been developed.

Instruction	Enter ID	Brand name	°C	Days	Days	Number	g
Field	ProductID	Brand	Temperature	BestUseBy	ShelfLife	pH	Weight
Row 1	########	########	5	15	15	5	150
Row 2	########	########	10	10	8	6,5	200
…	…	…	…	…	…	…	…

Table 5 Example of MS Excel data collection sheet (Product table)

The MS Excel file has been sent to each company with filling instructions. A data collection guide sheet illustrates the priority table keys, the ideal filling order, and data collection over the timeline. Each Table in the database corresponds to a pre-set table in the MS Excel file to describe the table structure, the fields and attributes together with additional instructions. To give an example, Table 5 shows some of

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the columns of the preset data collection sheet for the ***Product*** table, designed for Food packagers. The file format and the compilation instructions have been joined by RESET.

The quantity and the quality of the received data drove the data manipulation process to define the model input file. In some cases, assumptions on parameters' value have been forced by the lack of accurate data. An overview of the main information gathered and a discussion of the main assumption made will now be presented.

2.1 Network entities

2.1.1 Logistic network

Figure 7 shows the geographical distribution of the different facilities of the logistic network. While Packaging producers, Food packagers, and Washers are distributed in the geographic area of France, Belgium, and Luxemburg, the Stores and Distribution centers are located in the North of France, Belgium, and Luxemburg. Indeed, the scope of this deliverable is to evaluate the optimal reuse logistic network for the demonstrator case, which will be centered in such a limited area. Notwithstanding the demonstrator's products will be distributed and sold in such a smaller area, the food packaging and the packaging production and handling activities may be performed elsewhere. For this reason, all the known locations of Packaging producers, Food packagers, and Washers facilities have been included. The optimization model will then be able to rule out the most inconvenient facilities.

A future deliverable of the project will address the logistic network optimization for a wider area.

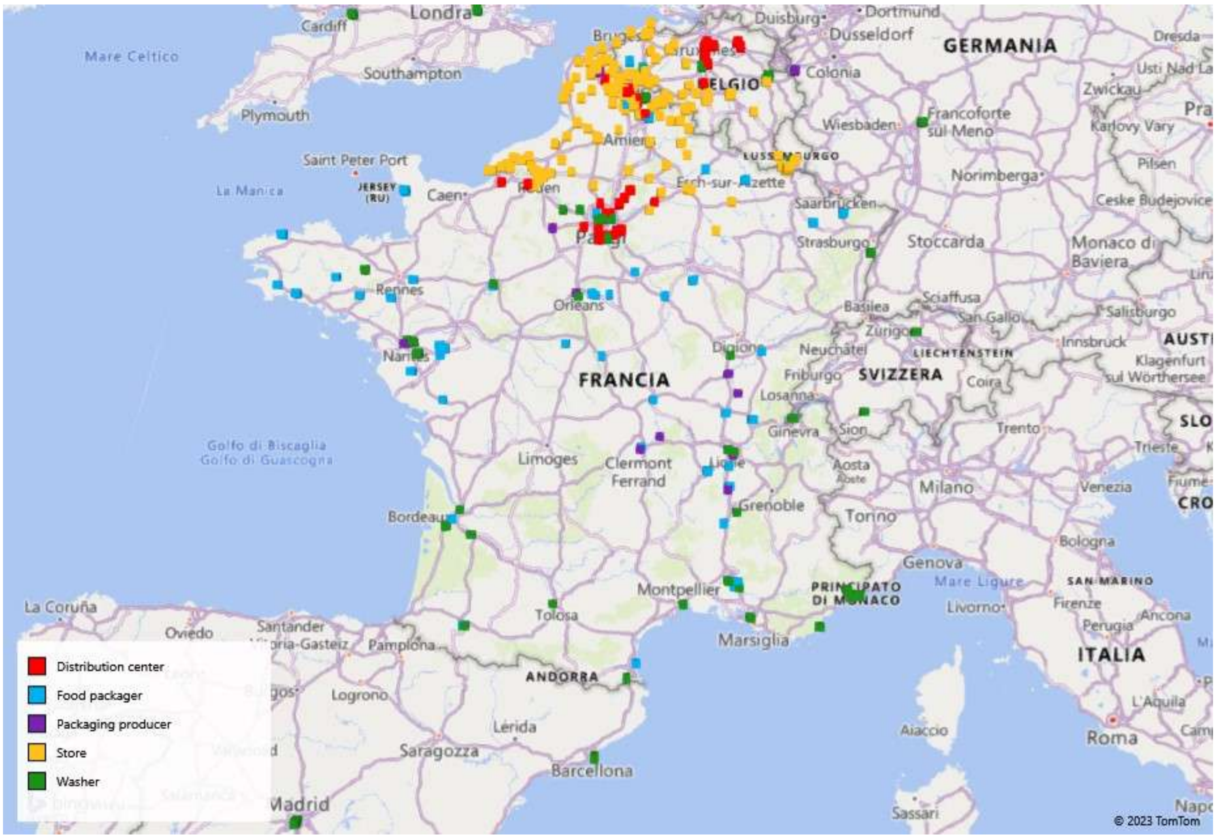

Figure 6 Network entities

The facilities' addresse received from the companies was not always complete. In some cases, online research on the facilities' location supplemented the companies' data. Unfortunately, it was not possible to receive accurate information from all the companies and some of them have been excluded. Below, Table 6 lists the industrial partners of the R3PACK consortium and highlights the belonging set and which ones have been excluded (in red).

Industrial Partner	Set	N° of Facilities	Notes
Guillin	$p \in P$	1	
Firplast	$p \in P$	1	
Monbento	$p \in P$	1	
Berry superfos	$p \in P$	1	
Cuitisan	$p \in P$	1	
Le Parfait	$p \in P$	1	
Arc	$p \in P$	1	
Duralex	$p \in P$	1	
Jokey	$p \in P$	1	
Knauf	$p \in P$	1	
Verallia	$p \in P$	1	
OI	$p \in P$	1	
Berny	$p \in P$	1	
Tiffin	$p \in P$	0	No locations found for the packaging production plants
Altho SAS	$f \in F$	2	

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Candia	$f \in F$	6	
Entremont	$f \in F$	0	No products found in the products EAN codes list
Yoplait	$f \in F$	2	
Europe Snacks	$f \in F$	3	
Floreale	$f \in F$	7	
LSDH	$f \in F$	9	
Schreiber	$f \in F$	1	
Agrial Boisson	$f \in F$	4	
Eurial	$f \in F$	5	
Monin	$f \in F$	1	
Biscuits bouvard	$f \in F$	11	
Carrefour	$d \in D$	40	
SystemeU	$d \in D$	3	
Carrefour	$s \in S$	85	
SystemeU	$s \in S$	63	
Dweller districts	$dd \in DD$	131	Dweller districts have been defined using all the ZIP codes where a store $s \in S$ is present
Options solutions	$w \in W$	22	
Impact group	$w \in W$	12	
Eternity systems	$w \in W$	4	
Uzaje	$w \in W$	2	
Bring back	$w \in W$	1	
Haut la consigne	$w \in W$	1	
Boutin service	$w \in W$	1	
Oc'consigne	$w \in W$	1	
Ma bouteille s'appelle revient	$w \in W$	1	
Serge cheveau	$w \in W$	1	
Bout à bout	$w \in W$	1	
Luz	$w \in W$	1	
Univerre	$w \in W$	1	
RVM	$rvm \in RVM$	7	

Table 6 Network facilities of the industrial partners

A complete list of the facilities' location expressed in latitude and longitude coordinates will be made available for the European Commission upon request.

2.1.2 Products and packaging

In order to simplify and speed up data collection, a set of ***Product Categories*** has been defined. Product categories represent generic food products (without brand). According to the Deliverable WP3.1, ten Product Categories have been defined in the R3PACK project. In order to deal with the variety of product weights and sizes, each Product Category can be divided into sub-categories, as shown in Table 6.

Icon	Food Category
	Cheese
	Chips
	Juices
	Milk
	Prepared Salads Big Prepared Salads Bowl
	Savory Biscuits Big Savory Biscuits Bucket Savory Biscuits Extreme
	Soups
	Fruits Vegetables Small Fruits Vegetables Medium
	Yoghurt Medium Yoghurt Big
	Sour Cream

Table 7 Product Categories

The data gathered from Food packager companies is related to specific product items, identified with an EAN code. Although the Product Categories have been used to quantify some parameters, the set products $a \in A$ corresponds to a more accurate list of 45 products provided by the Food packager companies. Table 8 shows the associations among the unique EAN code of a product, its food category, and the Item description. The Food packager company also indicated in which retailer the products were sold. This is the base for the definition of the subsets $(d, a) \in \mathrm{DA} \subset D \times A$ and $(s, a) \in \mathrm{SA} \subset S \times A$:

EAN	Food Category	Product denomination
3256550086286	Juices, Milk*	CIDRE LOIC RAISON DOUX FRUITE 75CL
3256550086309	Juices, Milk*	CIDRE LOIC RAISON BRUT INTENSE 75CL
3245414649194	Chips	Carrefour Nat Lisse 200g
3245414649309	Chips	Carrefour Nat Ancienne 150g
3256220031509	Chips	Retailer brand U Nat Lisse 150g
3256220363310	Chips	Retailer brand U Nat Paysanne 150g
3256221011432	Chips	Retailer brand U Nat Ancienne 150g
3497911101129	Chips	Bret's Aro Poulet Braisé 125g
3497911105127	Chips	Bret's Aro Vinaigre 125g
3497917000907	Chips	Bret's Aro Fromag du Jura 125g

3533630097531	Milk	GRAND LAIT FRAIS DEMI ECREME 1L
3245413442420	Cheese	FROMAGE FRAIS NATURE 3.2% 500 BIO
3256220362429	Cheese	FROMAGE FRAIS NATURE 3.2% 500 BIO
3256220359993	Savory Biscuits Big**	Croustillant cacahuète
3256221220223	Savory Biscuits Big**	Pétales salées
3256224365891	Savory Biscuits Big**	Crackers Puzzle Emmental
3270190155584	Savory Biscuits Big**	Pétales salées
3560070718450	Savory Biscuits Big**	Crackers Puzzle Emmental
3280221507169	Fruits Vegetables Small	ANANAS FIF 230g
3280221611149	Fruits Vegetables Small	CAROTTES RAPEES FIF 180g
3560071429973	Fruits Vegetables Medium	CAROTTES RAPEES 350g
3280222411144	Fruits Vegetables Medium	Wok fondant de légumes Florette barquette 300g
3280220106172	Fruits Vegetables Medium	Wok maraîcher Fraîcheur Florette baquette 300g
3248340054070	Milk	LT 1/2E.C'EST QUI PATRON 6X1L
3256224234562	Milk	LAIT UHT 1/2 EC.U BIO BLE 6X1L
3256225426775	Juices	PJ DE POMMES DOUCES U PET 1L
3270190025337	Milk	1L BLE LAIT 1/2 ECREME CRF BIO
3276554163158	Milk	BP 1L LAIT 1/2ECREME CRF
3560070275267	Juices	1L PET PUR JUS POMME CRF EXTRA
3560070561186	Prepared Salads Bowl	SALADE JAMBON EMMENTAL
3560070561216	Prepared Salads Bowl	SALADE FROMAGÈRE
3560070708833	Prepared Salads Bowl	SALADE POULET PATE MIMOLETTE
3560070717712	Juices	PET 1L PJ ORANGE 3% PULPE CRF
3560070823246	Juices	PET 1L PJ ORAN S/PULPE CRF EXT
3256224231462	Cheese	POT_U_LEGER_15%_50cl
3256224231523	Cheese	8598 U CREME FRAICHE 30% 50CL
3265266075019	Juices, Milk*	Sirop de grenadine la Maison GUIOT 70cl
3265266075026	Juices, Milk*	Sirop de menthe verte la maison GUIOT 70cl
3560071318796	Savory Biscuits Bucket	Minis GF Choco 168g
3256225041404	Savory Biscuits Bucket	Minis GF Choco 168g
3560070484225	Savory Biscuits Big	Minis Safari nappés chocolat lait 160g
3256229922990	Savory Biscuits Big	Minis Safari nappés chocolat lait 160g
3560071265199	Savory Biscuits Big	Tourtes fourrées cacao noisettes 240g
3256229545298	Savory Biscuits Big	Tourtes fourrées cacao noisettes 240g
3560070316243	Savory Biscuits Big	Minis tartelettes fourées lait 225g

Table 8 Product - Product Category association

The subset of components (i.e raw materials) that compose a reusable packaging $m \in \mathrm{MP} \subset M$, consider all the reusable packaging manufactured by the Packaging producers and coupling with the products packaged and sold by the Food packagers. The available alternatives are countless and differ in material, size and volume occupied. The available materials for the reusable containers proposed are the following:

- PET - Polyethylene Terephthalate
- PP - Polypropylene
- PCN - Polychlorinated Naphthalene
- Glass
- SS - stainless steel

The different configurations of the reusable package could join a broad set of products. This wide range of alternatives would enhance the model complexity. For this reason, a packaging clusterization into typologies/categories could come to hand. Deliverable WP3.1 outlines the classification of reusable packaging (Packaging category in Table 9) based on the Packaging producers offer and the Food Categories needs.

Packaging Category	Volume Capacity $[mL]$
Small size plastic packaging	250 - 250
Medium size prepared fruits & vegetables	650 - 750
Big size non-liquid products	1200
Medium size dairy products	500 - 600
Big size plastic «bucket»	1000
Extreme big size salty snacks	> 2000
Glass bowl and paver	1200
Glass jar	1000
Liquid products	1000
Stainless steel paver and bowl	300 – 500 - 1000

Table 9 Packaging Categories

Since the definitive reusable packaging characteristics and attributes have yet to be defined, these Packaging categories are used in the model to define the subset of $m \in \mathrm{MP} \subset M$ of reusable packaging alternatives. The Packaging producers' offer has been analyzed and each Packaging category has been associated with a list of Packaging producers able to manufacture containers in compliance with the category definition. Table 10 links every Packaging Category with the list of its eligible Packaging producers. The subset $(p, m) \in \mathrm{PM} \subset P \times MP$ represents such links.

Packaging Category	Packaging producer	Material
SMALL SIZE PLASTIC PACKAGING	ALLINPACKAGING Pot PET rond	PET
	GUILLIN - ALPHA FORM Crudipack (thicker prototype)	PET
	GUILLIN - ALPHA FORM Prestipack	PP
	BERRY SUPERFOS UniPak Round 3	PP
	BERRY SUPERFOS Superlock 95	PP
	FIRPLAST R'box	NCP
	MONBENTO mb DELIGHT	NCP
	FIRPLAST R'box small box	NCP

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MEDIUM SIZE PREPARED FRUITS AND VEGETABLES	KNAUF INDUSTRIES Kary fresh	PET
	GUILLIN - ALPHA FORM Freshipack	PET
	GUILLIN-ALPHA FORM Sekipack	PET
	SABERT Fast Pac	PP
	PKG FOODS Square bowl	PP
	REUSABOL Big one	PP
	SABERT Fast Pac	PP
	ARC Luminarc Pure Box Active	GLASS
	BORMIOLI ROCCO Frigoverre evolution sqare tall	GLASS
	ARC Luminarc salad bowl	GLASS
	ARC Luminarc Keep'n box	GLASS
	DURALEX Freshbox square	GLASS
BIG SIZE NON-LIQUID PRODUCTS	GUILLIN-ALPHA FORM Multipack	PET
	PETAINER Straight cyclindrical	PET
	BERRY SUPERFOS Unicpak square 1	PP
	GUILLIN-ALPHA FORM Alphacell	PP
	MONBENTO MB jar	NCP
	FIRPLAST R'box medium box	NCP
MEDIUM SIZE DAIRY PRODUCTS	REUSABOL Small one	PP
	JOKEY Jetb 550	PP
	BERRY SUPERFOS UniPak round 2	PP
	REUSABOL Bowl	NCP
	BORMIOLI ROCCO frigoverre evolution round	GLASS
	TICORBRAUN Glass straight side jacr 82-2040	GLASS
BIG SIZE PLASTIC (BUCKET)	PETAINER Straight cyclindrical	PET
	GUILLIN-ALPHA FORM Tusipack	PP
	JOKEY Jetb 10	PP
	MEPAL Multi-fonction bol Cirqula high	PP
	ECOBOX Bowl	NCP
	MONBENTO MB jar	NCP
EXTREME BIG SIZE SALTY SNACKS	JOKEY Jet 23	PP
	BERRY SUPERFOS	PP
	GEFU Muovo	SS
GLASS BOWL AND PAVER	ARC Luminarc Keep'n box	GLASS
	DURALEX Freshbox square	GLASS
LIQUID PRODUCTS	PETAINER Plastic 38mm bottle	PET
	FRAPAK Milk bottle	PET
	Square bottle	PET
	LE PARFAIT	GLASS
STAINLESS STEEL PAVER AND BOWL	CUITISAN Food box rectangle	SS
	BERNY/GUELT Small box	SS
	TIFFIN Bol	SS
	CUITISAN Food box round	SS

Table 10 Packaging Category - Packaging producer association

An association between Packaging categories (Table 10) and products (Table 8) must be performed to define the subset of $(a, m) \in B \subset A \times M$. Such connections must take into consideration a series of physical and safety constraints such as:

- Packaging material - food compatibility
- Packaging volume and sizes
- Food nature (liquid, humid, dry, …)
- Refrigerated storage

Based on these constraints, Packaging Categories and Product Categories have been associated as shown in Table 11 below.

Product Category	Packaging Category
CHEESE	STAINLESS STEEL PAVER AND BOWL
CHIPS	EXTREME BIG SIZE SALTY SNACKS
JUICES	LIQUID PRODUCTS
MILK	LIQUID PRODUCTS
PREPAREDSALADS_BIG	BIG SIZE NON-LIQUID PRODUCTS
PREPAREDSALADS_BOWL	GLASS BOWL AND PAVER
SAVORYBISCUITS_BIG	BIG SIZE NON-LIQUID PRODUCTS
SAVORYBISCUITS_BUCKET	BIG SIZE PLASTIC (BUCKET)
SAVORYBISCUITS_EXTREME	EXTREME BIG SIZE SALTY SNACKS
SOUPS	LIQUID PRODUCTS
FRUITSVEGETABLES_SMALL	SMALL SIZE PLASTIC PACKAGING
FRUITSVEGETABLES_MEDIUM	MEDIUM SIZE PREPARED FRUITS AND VEGETABLES
YOGHURT_MEDIUM	MEDIUM SIZE DAIRY PRODUCTS
YOGHURT_BIG	BIG SIZE PLASTIC (BUCKET)
SOURCREAM	MEDIUM SIZE DAIRY PRODUCTS

Table 11 Packaging Category - Food Category association

Once that each Food Category has been associated with a set of eligible Packaging Categories, each product $a \in A$ (identified with a unique EAN code) can be

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associated with a feasible Packaging Category through the associated Food Category.

Packaging Category	Packaging producer	Material	Volume [mm³]	Cheese	Juices	Milk	Soups	Prepared salads	Savory biscuits	Chips	Yogurt	Sour cream	Prepared fruits and vegetables
SMALL SIZE PLASTIC PACKAGING	ALLINPACKAGING Pot PET rond	PET	307380										✓
	GUILLIN - ALPHA FORM Crudipack (thicker prototype)	PET	1152000										✓
	GUILLIN - ALPHA FORM Prestipack	PP	643072										✓
	BERRY SUPERFOS UniPak Round 3	PP	573961										✓
	BERRY SUPERFOS Superlock 95	PP	276223										✓
	FIRPLAST R'box	NCP	715331										✓
	MONBENTO mb DELIGHT	NCP	319259										✓
	FIRPLAST R'box small box	NCP	332212										✓
MEDIUM SIZE PREPARED FRUITS AND VEGETABLES	KNAUF INDUSTRIES Kary fresh	PET	1215500										✓
	GUILLIN - ALPHA FORM Freshipack	PET	1458000										✓
	GUILLIN-ALPHA FORM Sekipack	PET	2283859										✓
	SABERT Fast Pac	PP	1536000										✓
	PKG FOODS Square bowl	PP	1536000										✓
	REUSABOL Big one	PP											✓
	SABERT Fast Pac	PP	1564000										✓
	ARC Luminarc Pure Box Active	GLASS	1597956										✓
	BORMIOLI ROCCO Frigoverre evolution sqare tall	GLASS	1584000										✓
	ARC Luminarc salad bowl	GLASS	953932										✓
	ARC Luminarc Keep'n box	GLASS	1309859										✓

	DURALEX Freshbox square	GLASS	1136800									✓
BIG SIZE NON-LIQUID PRODUCTS	GUILLIN-ALPHA FORM Multipack	PET	1689600				✓					
	PETAINER Straight cyclindrical	PET	1642499					✓				
	BERRY SUPERFOS Unicpak square 1	PP	1788276				✓	✓				
	GUILLIN-ALPHA FORM Alphacell	PP	2008950				✓	✓				
	MONBENTO MB jar	NCP	1311640				✓	✓				
	FIRPLAST R'box medium box	NCP	1058223				✓	✓				
MEDIUM SIZE DAIRY PRODUCTS	REUSABOL Small one	PP								✓	✓	
	JOKEY Jetb 550	PP	655820							✓	✓	
	BERRY SUPERFOS UniPak round 2	PP	870813							✓	✓	
	REUSABOL Bowl	NCP								✓	✓	
	BORMIOLI ROCCO frigoverre evolution round	GLASS	1000090							✓	✓	
	TICORBRAUN Glass straight side jacr 82-2040	GLASS	605070							✓	✓	
BIG SIZE PLASTIC (BUCKET)	PETAINER Straight cyclindrical	PET	1642499					✓		✓	✓	
	GUILLIN-ALPHA FORM Tusipack	PP	1588388					✓		✓	✓	
	JOKEY Jetb 10	PP	1296782					✓		✓	✓	
	MEPAL Multi-fonction bol Cirqula high	PP	2137162					✓		✓	✓	
	ECOBOX Bowl	NCP						✓		✓	✓	
	MONBENTO MB jar	NCP	1311640					✓		✓	✓	
EXTREME BIG SIZE SALTY SNACKS	JOKEY Jet 23	PP	3166150					✓	✓			
	BERRY SUPERFOS	PP	3471034					✓	✓			
	GEFU Muovo	SS	4144800					✓	✓			
GLASS BOWL AND PAVER	ARC Luminarc Keep'n box	GLASS	1882979				✓					
	DURALEX Freshbox square	GLASS	1965200				✓					
LIQUID PRODUCTS	PETAINER Plastic 38mm bottle	PET	1269440	✓	✓	✓						

	FRAPAK Milk bottle	PET	0		✓	✓	✓
	Square bottle	PET	0		✓	✓	✓
	LE PARFAIT	GLASS	0		✓	✓	✓
STAINLESS STEEL PAVER AND BOWL	CUITISAN Food box rectangle	SS	750000	✓			
	BERNY/GUELT Small box	SS	788100	✓			
	TIFFIN Bol	SS	1307810	✓			
	CUITISAN Food box round	SS	854865	✓			

Table 12 Packaging Category - Product Category association

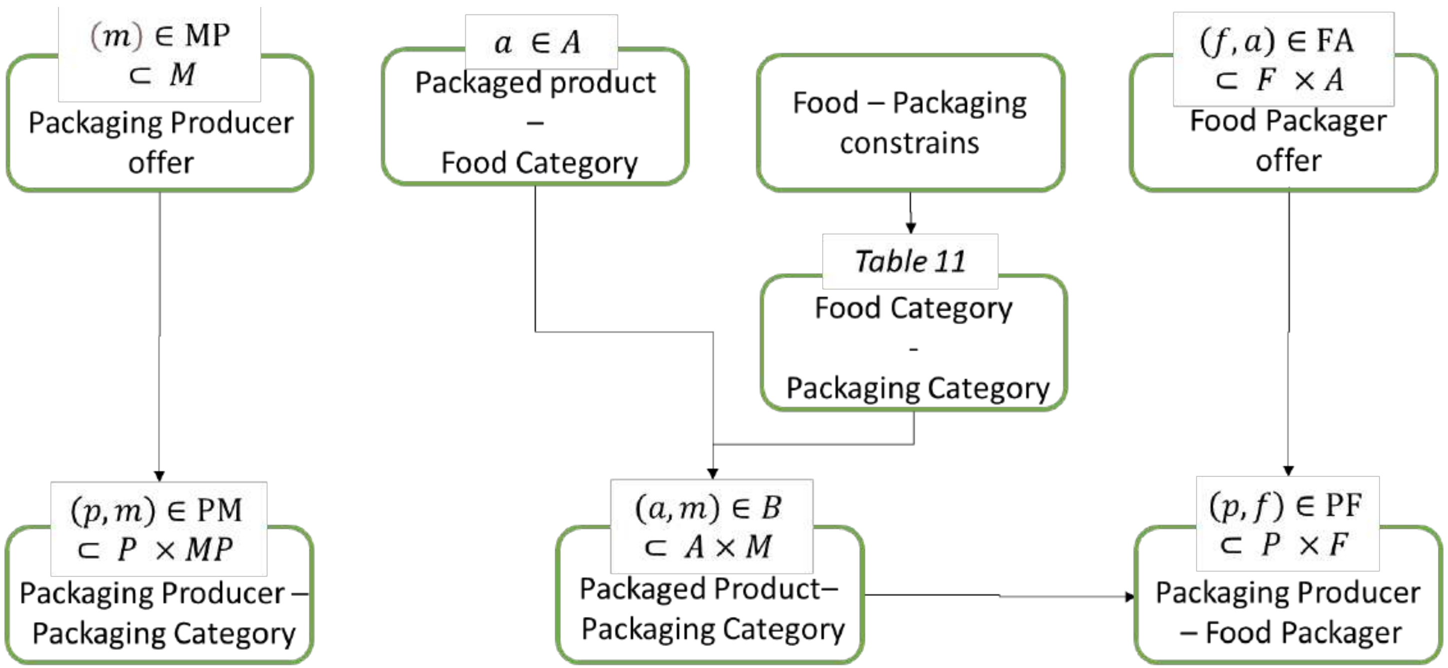

Figure 7 Logical steps for some model subset valorization

2.2 Network connections

2.2.1 Products distribution paths

The retailer marketing choices, the Packaged products nature, and the Packaging handling constraints drive the definition of the eligible connections among the network facilities.

The subset $(p,f) \in \mathrm{PF} \subset P \times F$ represent the possible couples of Packaging producers and Food packagers. The association between a Packaging producer and a Food packager is feasible when the packaging required by the Food packager belongs to the Packager producer's offer (see Table 12).

The marketing choices of the two retailers of the project (Carrefour and SystemeU), define their set of suppliers of Packaged products ($(f,d) \in \mathrm{FD} \subset F \times D$). It Is assumed that each unique EAN-code defined product can be sold by both retailers, except for those retail-branded. Carrefour-branded products and SystemeU-branded products can be sent only by, respectively, Carrefour's and SystemeU's Distribution Centers.

From the Distribution centers to the stores, the possible connections $(d,s) \in \mathrm{DS} \subset D \times S$ are driven by the retailer brand. With the purpose to narrow down the computational complexity of the instance, each shops is served from one or multiple distribution centers within a travelling distance of 120km.

2.2.2 Reverse Logistics of Reusable Packaging

After consumption, reusable containers may be returned to RVMs. Several types of RVMs exist on the market, each one with specifics on capacity, packaging material, and packaging size. Table 13 summarizes the main features of the RVMs considered in the analysis, highlighting the fitting materials and the capacity (size o throughput) of the system. According to the RVMs' technological constraints, a list of acceptable reusable packaging $(rvm,m) \in \mathrm{RVMM} \subset RVM \times MP$ is set.

RVM brand	Picture	Compatible materials	Capacity [pieces]	Features
LEMONTRI		• Glass bottles • Plastic bottles	200	CDI
NoWW		• Glass bottles • Plastic bottles	300	-
CUPLOOP		• Glass bottles • Plastic bottles	300	CDI
TOMRA_T9		• Glass bottles • Plastic bottles	400	CDI, Sorting

RVMx3	RVM X3		• Glass bottles	200	CDI, Sorting
RVMx30	RVM X30		• Glass bottles	200	CDI, Sorting
TOMRA_T90	TOMRA T90		• Glass bottles	300	CDI, Sorting

Table 13 RVMs technical features. Legend: CDI: Customer Digital Interface

The RVMs can be installed in Stores and Dweller districts. The consumer willingness to return the packaging in the store or dweller district is modeled with a probability parameter. The set of RVMs in the Stores and Dweller districts depend on the space available in such locations and the technological constraints. For the performed analysis, it has been considered that all the RVMs shown in Table 13 could be placed in every location. This rule defines the sets $(s, rvm) \in \mathrm{RS} \subset S \times RVM$ and $(dd, rvm) \in RDD \subset DD \times RVM$.

From RVMs the used packaging must reach the washers facilities. The consolidation of returned packaging at the retailers distribution center is suggested by the capillarity of the RVMs placed in the shops or the dweller districts which will confer small quantities of package each. Consolidating the dirty packaging in a centralized warehouse before shipping to a possible washing facility is a valuable practice. In the current model formulation, the packaging consolidation is supposed in the Distribution center but it could be reasonably redefinied to incorporate municipal waste collection options (i.e. whether the source is an RVM in a dweller district). The reusable packaging accepted at each Distribution centers $(d, m) \in \mathrm{DM} \subset D \times MP$ are those handled as Packaged products in the forward distribution. The subset of the possible collecting connection $(dd, d) \in \mathrm{DDD} \subset DD \times D$ between Dweller districts to Distribution centers is defined over a maximum distance rule: a Dweller district can reach each Distribution center within a 120 km radius. From Distribution centers, dirty containers may be sorted, and then reach the washer facilities. The Distribution center has visibility over all the set of Washers $(d, w) \in \mathrm{DW} \subset D \times W$). The model will activate packaging flow only when a Washer is able to handle and wash the specific material and shape of the packaging shipped. Table 14 summarizes the specific washing and handling capabilities of each washer company. From such constraints the subset $(w, m) \in \mathrm{WM} \subset W \times MP$ of acceptable packaging from each washer facility has been defined. From Washer plants, the clean containers are sent to the Food packagers ($(w, f) \in \mathrm{WF} \subset W \times F$). Every connection is possible, the model will decide the optimal to activate based on the Packaging Category selected in the Food packager.

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Washer	Reusable Packaging specifics
Options solutions	Collection and washing of reusable containers
Impact group	Collection and washing of reusable containers
Eternity systems	Local industrial washing centers handling glass, stainless steel, and plastic containers
Uzaje	Washing of reusable containers
Bring back	Washing and return logistics service
Haut la consigne	Collection point for empty used bottles
Boutin service	Washing, bottling, labelling of glass bottles
Oc'consigne	Collection point for empty used bottles
Ma bouteille s'appelle revient	Washing by immersion and spray drying. All kinds of containers' shapes
Serge cheveau	Washing of glass bottles
Bout à bout	Collection and washing of reusable bottles
Luz	Collection and washing of reusable bottles
Univerre	Washing of bottles

Table 14 Washer facilities - reusable packaging constraints

2.3 Model parameters

2.3.1 Capacity parameters

Production line throughput, as well as inbound and outbound storage areas at each facility are the capacity parameters which constraint the problem. Such parameters limit the maximum material flow the network can through the closed-loop supply chain. Considering the lack of awareness of the most partners has on the values of capacity for their facilities and operations, we discharged this aspect at this stage relaxing the capacity constraints. As a result, the scope of the model is to find the optimal logistics network for a fully-operational scenario without boundaries on the capacity and considering the logistic distances as the main driver. Moreover, the target demand to satisfy with the new packaging derives from the actual sales forecast and concerns product volumes already handled by the retailers network.

2.3.2 Packaging return and losses parameters

The parameters that define the likelihood of citizens returning reusable packaging at RVMs are defined a priori. The consumers willingness to return the used packaging result from WP2. There are multiple factors influencing such behavior, such as the age, the welfare state, the economic condition. There are also external factors, such as the characteristics and spread of the neighbourhood. Rural and city areas may present different access to the grocery, influencing the carrying capacity of people. Urbanization also impacts the size of the store and distribution pattern. Varying the values of return rates can aid estimating the impact of consumers beheviour on logistic performance and impacts. For this deliverable, a return value of 68% Is considered. In particular, each RVM has been considered equally preferable by the consumers. The parameters valorization has been the following:

- $\%s_m$ - likelihood of returning the container In a store 60%
- $\%dd_m$ likelihood of returning the container in a Dweller district 8%
- $\%not_m$ likelihood of not returning the container 32%

The $\%not_m$ rate requires the introduction of new packaging to meet demand. Packaging losses are also due to the $ScrapRate_{mpw}$, accounting for the breakage and wear of packaging. This parameter has been set to **5%** of the packaging flow reaching the washers.

2.3.3 Cost parameters

Because of their sensitivity in industry, the exact values of the cost parameters are unknown and not shared. Therefore, a cost estimation has been carried to valorize them. For each cost category, an order of magnitude has been established, following typical industry values. From this first evaluation, a customized entity or process cost has been found using allocation criteria.

Cost variability is sensitive to the complexity of handling, production, storage, and washing activities, as well as the size and material of reusable components. For example, refrigerated process and facilities will face higher costs than non-refrigerated ones, due to the cold-chain energy and infrastructural costs. Figure 8 summarize the allocation criteria used for the cost parameters valorization.

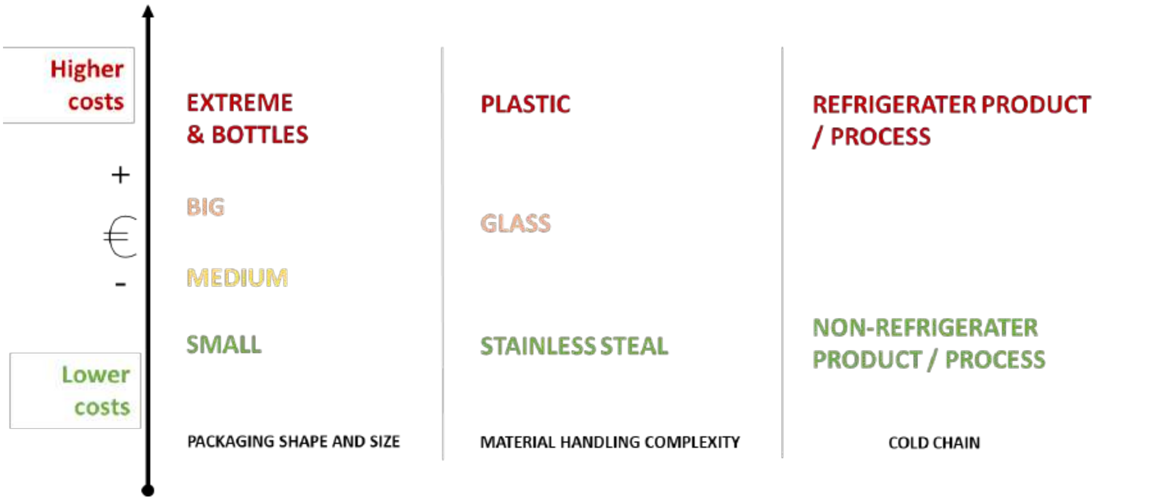

Figure 8 Allocation costs criteria

Cost parameters are classified in two categories: fixed cost and variable costs. Fixed cost represents investments costs for opening a facility, a production line, a washing line, or installing an RVM. These cost items are una tantum in the lifetime of a plant or facility. Indeed, in the OF they are linked with the binary variables for the network functions activation decisions. Variable costs vary with the handled quantity of products and are related to the flow of product through a facilty or between two facilities. These are paid each time a product travels across a plant or is shipped in the network and are linked to the continuous variables, namely the flow variables. Table 15 outlines the allocation rule to define the investment costs, while Table 16 illustrates the criteria followed for the variable cost items valorization.

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Facility	Param.	Allocation base	Criteria
Packaging producer	fc_p	150 000€	An average coefficient (≥1) for each Packager facility has been defined taking into consideration the complexities of the Packaging Categories produced in the plants.
Food packager	fc_f	150 000€	An average coefficient (≥1) increases the cost based on: • The potential total handled flow • The quantity of refrigerated products packaged • The potential packaging's handling complexity
Distribution center	fc_d	50 000€	Considering the total potential quantity of products handled in each Distribution center, the base cost has been increased with an average coefficient (≥1) based on: • The total potential quantity of goods handled • The quantity of refrigerated products • The packaging handling complexity of the handled products
Washer	fc_w	50 000€	An average ≥1 coefficient is defined for each Washer based on: • The packaging handled complexity (shape and material) • The washing complexity of the handled packaging's material
RVM	fc_{rvm}	5000 - 10000 €	The RVM complexity has been hypothesized based on the available functions of the machines: • 5000 - 7000 € RVMs without sorter • 7000 – 10000€ RVMs with sorter In addition, the RVM installation cost increases with the RVM capacity.

Table 15 Valorization criteria of investment cost parameters

Facility	Param.	Allocation base	Criteria
Packaging producer	cp_{pm}	0.3 $\frac{€}{kg\ of\ m}$	For each feasible couple of Packaging producer - Packaging Category (p,m), a ≥1 parameter multiplies the allocation base and increases following the handling complexity of the • packaging shape • packaging size • packaging material
Food packager	c_{fa}	0.3 $\frac{€}{piece\ of\ a}$	For each feasible couple of Food packager - Packaged product (f,a), a ≥1 parameter multiplies the allocation base considering the handling and packaging activities complexity linked to • packaging shape • packaging size • packaging material Moreover, the multiplier parameter differs among

			• refrigerated or non-refrigerated Packaged products
Distribution center	hc_{da}	0.02 $\frac{€}{piece\ of\ a}$	For each feasible couple of Distribution center - Packaged product (d, a), a ≥1 parameter multiplies the allocation base considering the handling and packaging activities complexity linked to • packaging shape • packaging size • packaging material Moreover, the multiplier parameter differs among • refrigerated or non-refrigerated Packaged products
	hc_{dm}	0.025 $\frac{€}{kg\ of\ m}$	For each feasible couple of Distribution center - Packaging Category (d, m), a ≥1 parameter multiplies the allocation base considering the handling and packaging activities complexity linked to • packaging shape • packaging size • packaging material
RVM	c_{rvm}	0.3 – 1.2 $\frac{€}{kg\ of\ m}$	The variable cost of RVM operational activities depends on whether the sorting mechanism is present. If the mechanism is already present inside the machine, no labor is needed, and the handling variable costs are lower. The RVM variable cost increases with: • the absence of a sorting function
Washer	c_{wm}	0.3 $\frac{€}{kg\ of\ m}$	For each feasible couple of Washer - Packaging Category (w, m), a ≥1 parameter multiplies the allocation base considering the handling and packaging activities complexity linked to • packaging shape • packaging size • packaging material
Truck	dc_t	1.3 $\frac{€}{km*truck}$	Even though the model is able to handle more transportation means, the evaluated scenario only includes one truck typology. This is the most common 40-pallet truck used in organized distribution services (cap_t=40 pallet)

Table 16 Valorization criteria of variable cost parameters

2.3.4 Demand parameters

Demand data comes directly from the two retailer companies' sales forecasts. For each Packaged product in Table 8, a sale forecast is given for the different categories of stores' sizes. The stores' sizes classification is the following:

- Hyper store represent the biggest shops
- Super store represent stores of medium size
- Proxi store are local shops, typically of small dimension and with a reduced offer

The demand parameter dem_{sa} assessment involves the average demand forecast, different for the two retailer's brands, and evaluate each shop demand based on the percentage that is typically sold in a shop of such size.

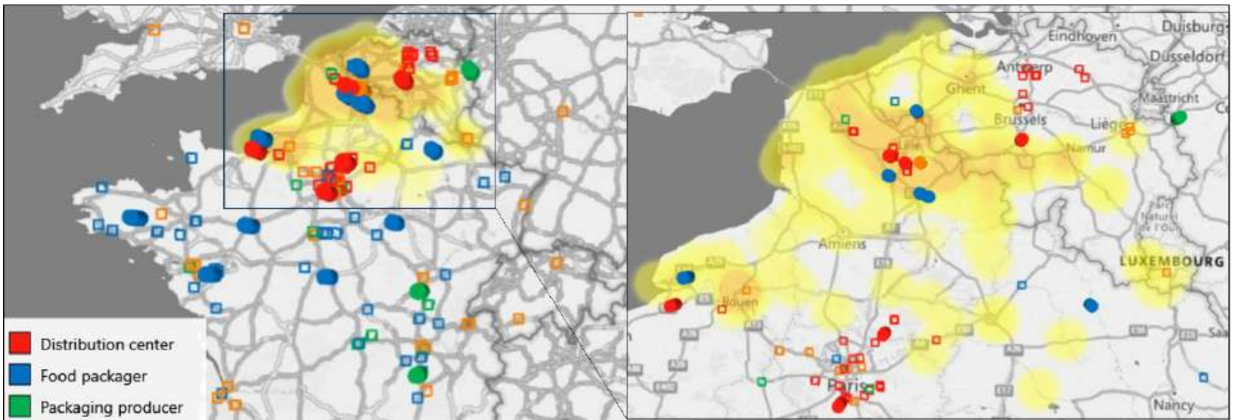
3. RESULTS AND DISCUSSION

The optimization model presented in Section 1 has been run with the input data showed in Section 2. Despite the high complexity of the model formulation, and the large dimension of the input data, the model was able to find the optimal solution.

Some maps showing the model decisions will now be presented and discussed. Then, some more detailed analysis on the logistics Implications and main outcomes will be presented.

3.1 Facilities opening decisions

One first decision the model delivers, is which facilities to activate in the Reuse network to deal with the new reusable containers. To know which facilities have been selected in the optimal configuration, the variables "y" have been analyzed. Figure 9 shows, on the left, the map of all interested areas and, on the right, a close up on the north of France. The activated facilities are highlighted with a solid circle, while the empty squares show the location of the non-activated facilities. The heat map under the Facilities represents the demand areas, with the warmer colors meaning peaks of demand. The facilities typologies shown are the Packaging producers, the Food packagers, the Distribution centers, and the Washers. For the same facility types, in the table in Figure 9 are shown some average values of the solution. The result suggests the centralization of activities helps to reduce the costs. Only one washer is selected to take care of the whole network's needs, and only 3 packaging producers over 13 should be employed for manufacturing new containers.



Facility type	Total	Activated	Avg Pkgd Product / Facility [pieces]	Avg Pkging/ Facility [kg]
Distribution center	43	6	168457	42891
Food packager	51	11	91886	23395
Packaging producer	13	3	0	30367
Washer	51	1	0	166244

Figure 9 Model output: Logistic network

The lack of capacity constraints allows the model to enforce the centralization of the network. Distribution centers play a dual role: the distribution of packaged product from food packager to the shops, and the collection of dirty containers from shops and dweller district to send to washers. Given their pivotal role, the optimal configuration involves the activation of 6 Distribution centers all in the North

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of the country out of 43. Figure 10 shows how the Packaged products is distributed among the six activated Distribution centers according to their Packaging Category.

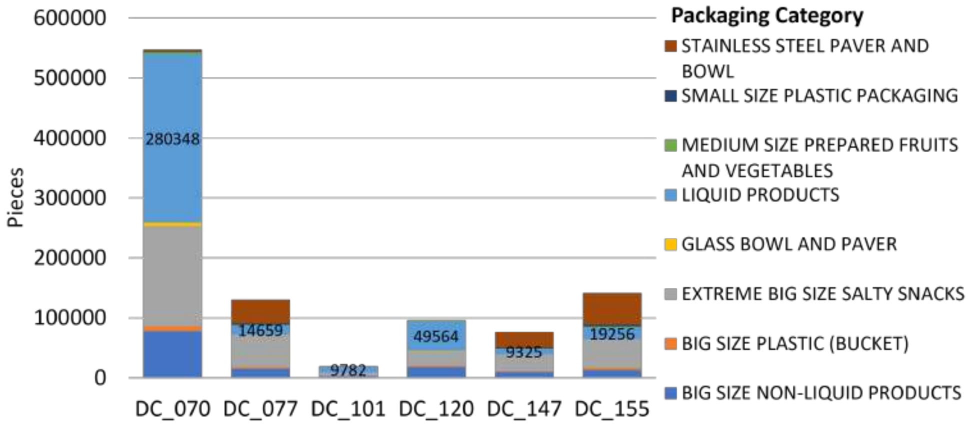

Figure 10 Activated Distribution centers

3.2 Products and Packaging flow

Figure 11 illustrates the number of shipments for each route within each packaging category. Whilst considering the assumption of non-stackability for reusable packages, it's crucial to emphasize that the process goes beyond mere aggregation. Aggregating shipment counts at various supply chain stages oversimplify the complexities involved. For instance, the shipment numbers between food packagers and distribution centers are consistent across all packaging categories. However, these counts undergo changes in subsequent stages, particularly in the initial two steps of the reverse phase. It's worth noting that the return of empty containers from RVMs to stores and dwellers, destined for distribution centers, closely mirrors the flow between distribution centers and stores. These adjustments account for variables like packaging return and losses parameters (%s_m;%dd_m;%not_m), which consider specific loss percentages and non-return factors. Furthermore, the continuity of flows between washers and food packaging nodes is influenced by the failure rate of each packaging category (ScrapRate_mpw) during the washing processes. This factor adds complexity to the flow dynamics. In conclusion, the cycle of primary packaging reuse is a multifaceted process that involves not only shipments but also considerations of loss, damage, and dynamic adjustments based on specific packaging categories. This complexity underscores the need for a holistic approach when modeling and optimizing the supply chain for reusable packaging.

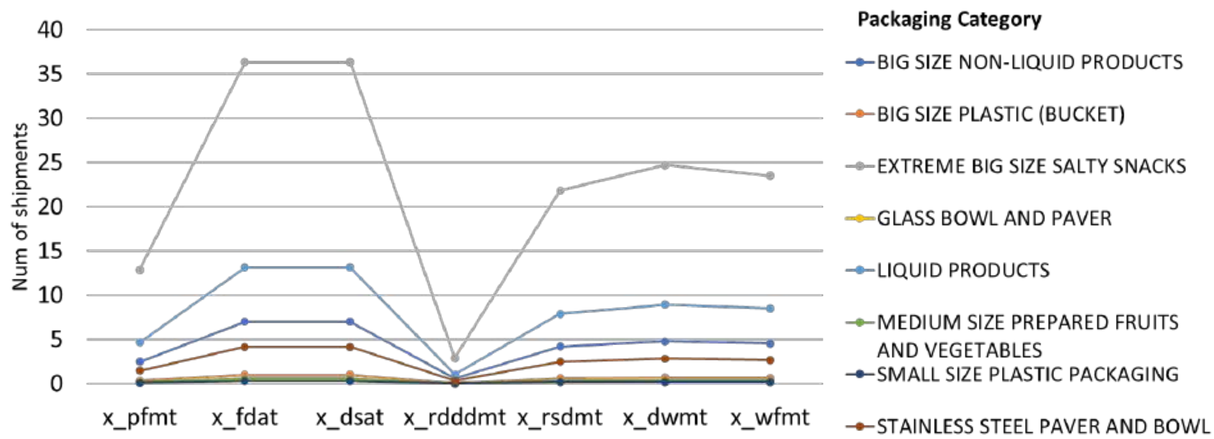

Figure 11 Num of shipments per route type

Figure 12 shows the average travelled distance for every possible supply chain stage (connection among two sequent facilities). The most intensive and expensive connection is experienced between the Packaging producer and the Food packager. This is caused by the few alternatives of packaging producers available throughout the network. The selected Washing facility has a favourable logistics because of its baricentral location. Again, the fact that only one washer has been selected result from the relaxation of all the facilities' capacities. The connections between distribution center and Washer and between Washer and Food packager are, with a few exeptions, highly convenient in comparison with other stages because of their geographic location. This suggests that, given the aforementioned assumptions, the more reuse cycles the containers carry out before recycling, the lower the impact associated with the entire circular network will be.

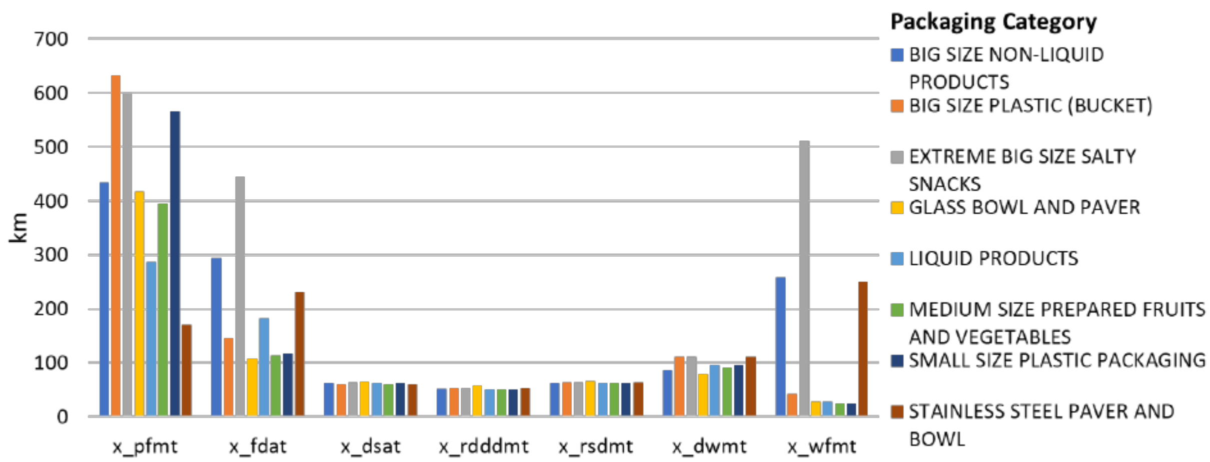

Figure 12 Average route distance per flow type

Figure 13 illustrates the packaging flows generated to meet the consumers demand of packaged food items. These flows move through the stages of the supply chain (depicted by the blue line), starting from the production of packaging at nodes referred to as "package producers" (i.e., blue nodes) and extending to the widespread distribution of the finished product. These flows are normalized with respect to the maximum flow observed through the different stages within the supply chain. The flow, quantified in units of pieces, enhances while moving toward the supply chain upstream, attaining its maximum intensity when the food Items couple with the primary packaging. This convergence is tracked at the 'food packager' nodes, coloured In green in the Figure.

The phases of the supply chain encompassing the collection, washing, and redistribution of reusable packaging are depicted in Figure 14. In the figure, emphasis is given to the reverse logistics (indicated by the red line), which plays a pivotal role in the circularity of the packages. During this phase, the downstream section of the supply chain reconnects with the upstream through the washers (i.e., orange points). These nodes serve as pivotal facilities receiving the flows from the RVMs, optimally allocated by the model in various shops and dwellers districts (black nodes) for collection. In Appendix A, both the forward and reverse phases are illustrated for each package category. Each of these phases is intricately associated with the nodes and flows pertaining to the optimal network topology configuration.

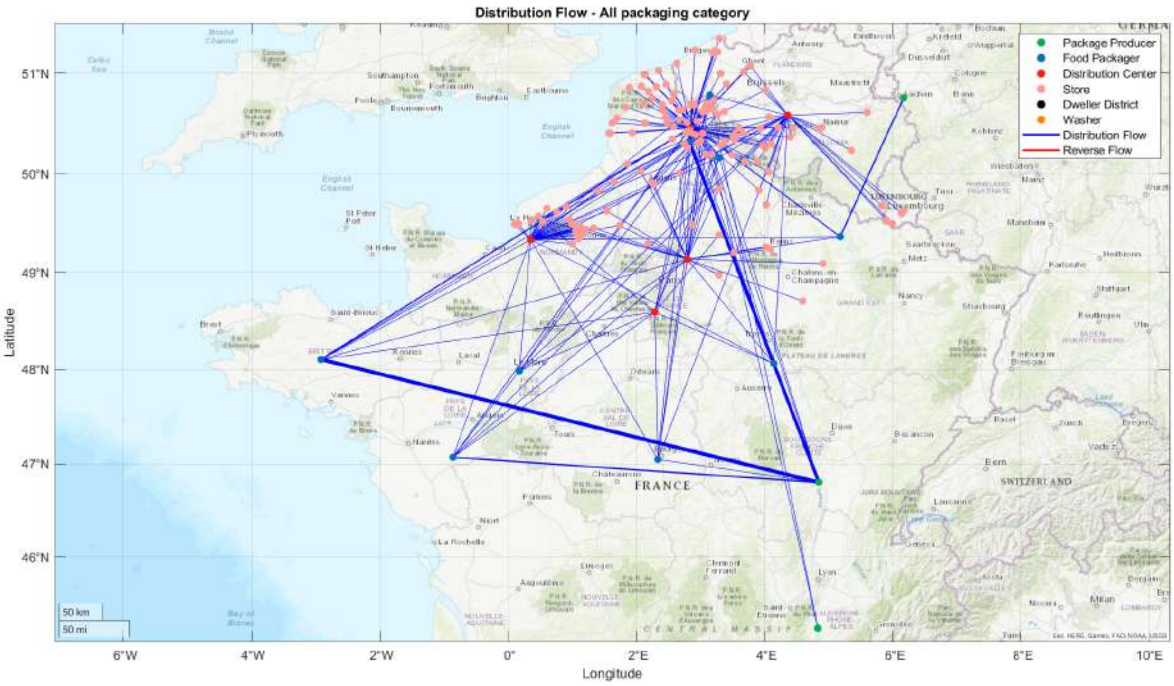

Figure 13 - Total flow for distribution phase

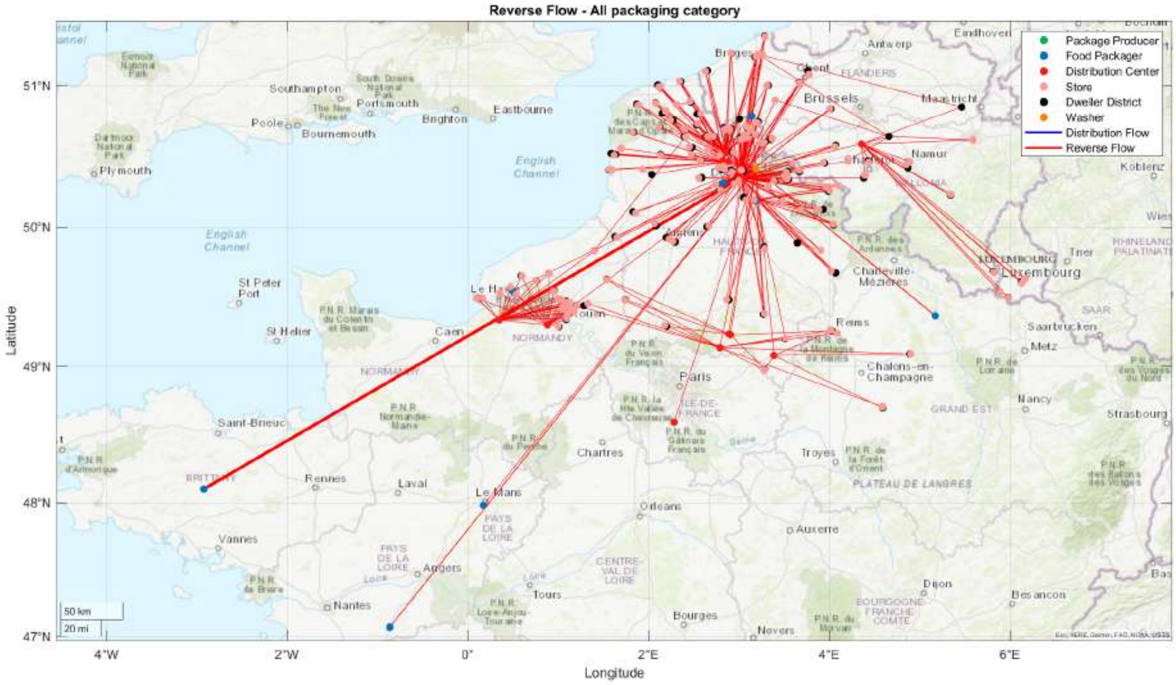

Figure 14 - Total flow for reverse phase

3.3 Reuse logistic implications

The logistic convenience of the reuse cycle is influenced by the network topology. Given the assumptions made, the results suggest the reuse cycle shipments are overall shorter than the production-and-disposal cycle. To explore such implication, the logistic impact of the reuse scenario has been compared with a business-as-usual (BAU) 0% reuse scenario. Without reuse, the packaging production facilities must provide a containers' flow equal to the demand. Figure 15 outlines the differences in these two configurations on the number of shipments and on the total traveled distance for each route type. The traveled distance has been evaluated as following:

$$TraveledDistance = numOfFullTrucks * Distance * SatIndex$$

$SatIndex$ represents the truck volume utilization index, namely the percentage of the truck capacity occupied by pallets of goods. Each model's flow variable accounts for a specific product, while shipments are usually composed of multiple items. To make a realistic assumption, $SatIndex$ is set to 80% for every shipment. Whith this assumption, and with the assumptions of overall return rate of 68% ($\%s_m$ + $\%dd_m$) and $ScrapRate_{mpw}$ = 5% for every Packaging Category, the yearly number of shipments is higher for the reuse scenario, but the total travelling is lower. Such a reduced traveled distance is a marker of a lower logistic cost.

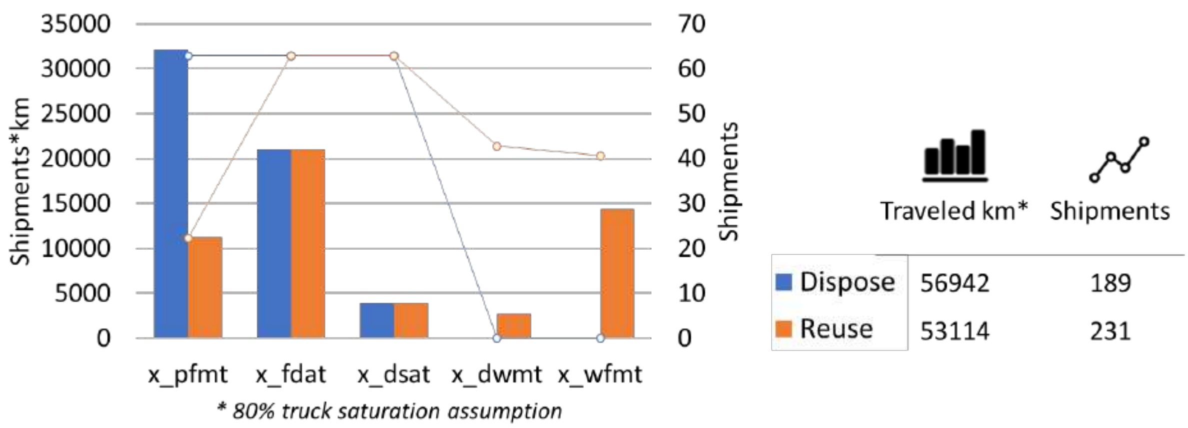

*Figure 15 Reuse vs Dispose num of shipments*distance [km]*

With the assumptions made on the packaging return and losses parameters, the yearly average usage cycles (*UC*) are evaluated as follows:

$$UC = \frac{Produced\ Containers}{Retailer\ Demand} = \frac{\sum_{\substack{f\ in\ F, p\ in\ P, t\ in\ T, m\ in\ MP:\\ (p,m)\ in\ PM\ and\ (p,f) in\ PF}} x_{pfmt}}{\sum_{(s,a) in\ SA} dem_{sa}}$$

For the examined scenario, UC is equal to 2.82. It means that on average, each container is placed on a store's shelf 2.82 times. Figure 16 compares the containers' manufactured according to the Reuse and Disposal scenario respectively over time. In the Dispose scenario, the yearly Produced Containers number is equal to the yearly Retailer Demand (represented by the horizontal dashed line), hence UC = 1. In the Reuse case, the produced containers' equalizes the yearly Retailer Demand in 33 months, as drawn in the graph by the intersection between these two lines.

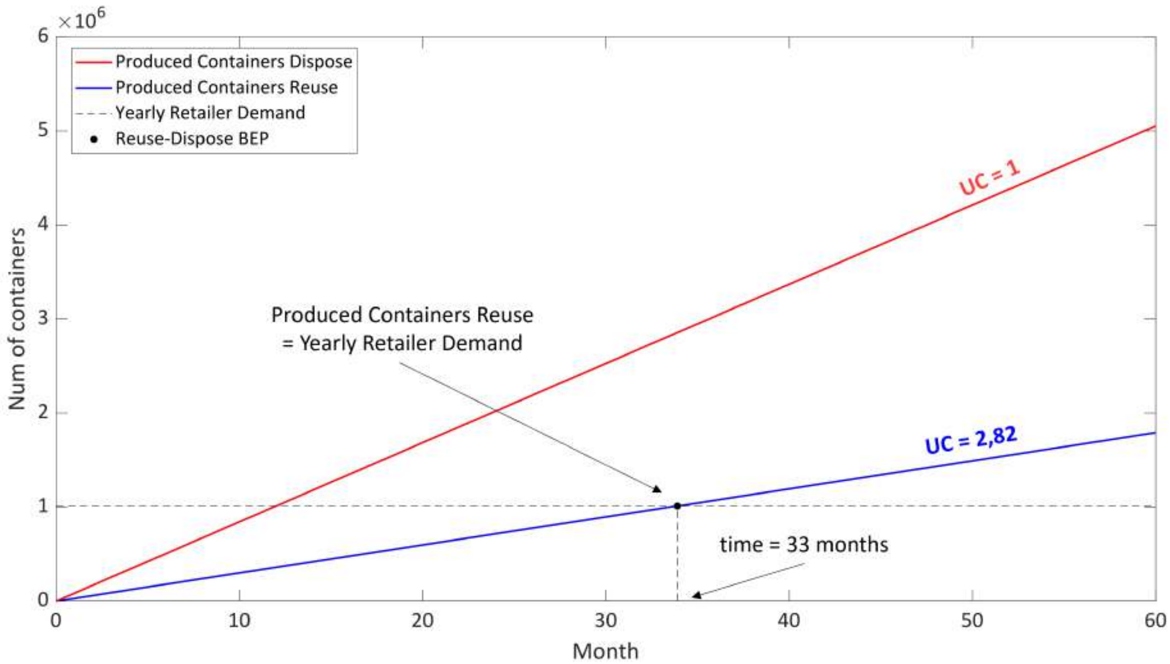

Figure 16 Reuse-Dispose containers production over time. BEP: Break Even Point

Since UC value was expected to be higher than 2.82, a sensitivity analysis on how **return and losses parameters** influence UC value is performed. Figure 17 shows the 3D graph of the UC (vertical axes) as function of $Scrap\%$ and $Reuse\%$ ($\%s_m$ + $\%dd_m$). $Scrap\%$ varies between 1% and 25%, while $Reuse\%$ ranges between 40% and 95%. High values for UC are only found in a small portion of the chart domain. A chart section for UC=10 is shown below. To reach 10 reuse cycles, $Scrap\%$ must be below 10%, and $Reuse\%$ above 90%. Such rate is far from the 60-70% ideal reuse rate suggested by other R3PACK partners. With low UC, containers production impact spreads over fewer uses and has a greater weight in the cost function. In such Reuse scenario, packaging production processes' efficiency becomes more strategic than material resistance. A future discussion on the reusable container alternatives within the R3PACK consortium should take such insight into consideration.

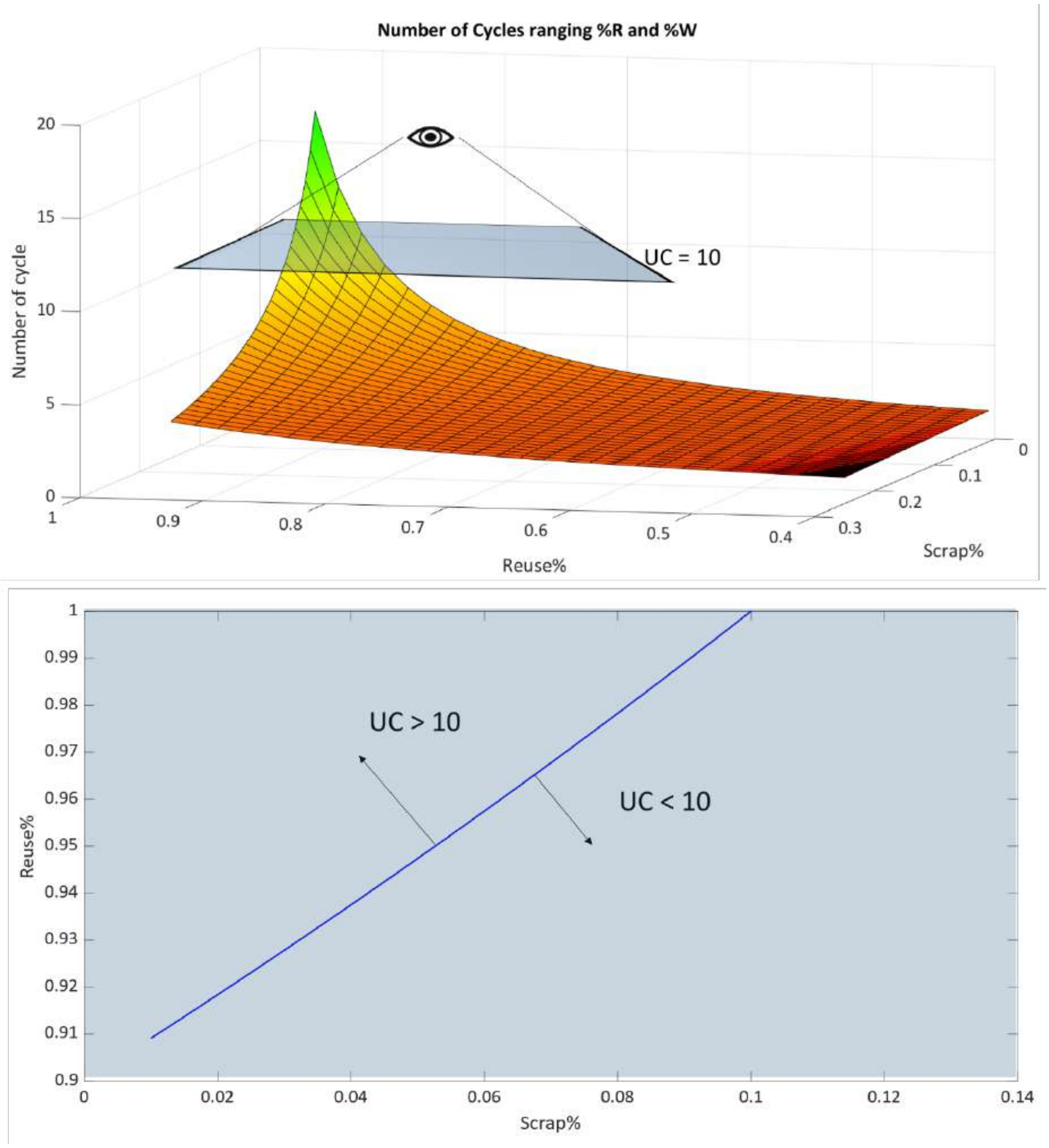

Figure 17 UC values varying Reuse% and Scrap%

3.4 Conclusions & Future steps

This deliverable introduces and illustrates a novel decision-support strategic optimization model intended for design and planning of the reuse logistic network of food primary packaging in the retailer supply chain. The optimization model bases upon the peculiar problem entities, like products and packages, components and materials, facilities, RVMs and collecting bins, logistic connections, resulting into a set of parameters (inputs) and variables (unknowns, outputs) which linearly combines (i.e. linear combinations) into an overall network cost objective function. This function, reported In Table 3, accounts the total investment for facilities activation, for RVMs establishment, for packaging manufacturing and washing, and for material flow handling and transportation. Optimizing the reuse logistic network means to search and find the values of the unknowns which minimize the value of this function. The model has been written in the high-level mathematical language (AMPL) and solved using a commercial open solver (i.e. gurobi). The mathematical formulation of the model provided could be easily written in other languages and solved using other solver.

The proposed model has been tested and validated with an instance (Input dataset) coming from the R3Pack demonstrator. While the geography of the network (facilities addresses) was easy to share and collect from the consortium, some other parameters required by the models (facilities capacities and costs) were considered sensitive and not provided properly. As a consequence, the insights from the model are promising but partial so far, and represent only a first step toward a more comprehensive and collaborating data collection phase.

Furthermore, the model has been formulated considering high flexibility in the choices and strategy opted for by the actors involved through the closed-loop supply chain network. Specific constraints and forbidden options (e.g., logistic connections or flows) can be easily forced in the Input dataset for a given Instance (like the demonstrator) and relaxed in other context to enable applicability and replicability of this support-decision optimization model.

As future developments (expected in the next two WP3 deliverables), the model will incorporate a new leading function based on environmental Impacts resulting from logistic decisions and reuse options. A Multi-Objective Optimization problem (MOOP) will be then formulated and solved to bring out the trade-off and thresholds of economic and environmental benefits associated with food packaging reuse and recycling.

Lastly, an extended data collection integrated with the results coming from other tasks and WPs will aid multi-scenario what-If analyses obtained by solving the model with different Inputs (based on the same network). Examples of different inputs include ranging demand, different facilities capacities, different scrap and returning rates together with different consumers behaviours. The manipulation and discussion of the different network configurations' results will support sensitivity and risk analysis for the long term sustainability of the designed reuse network.

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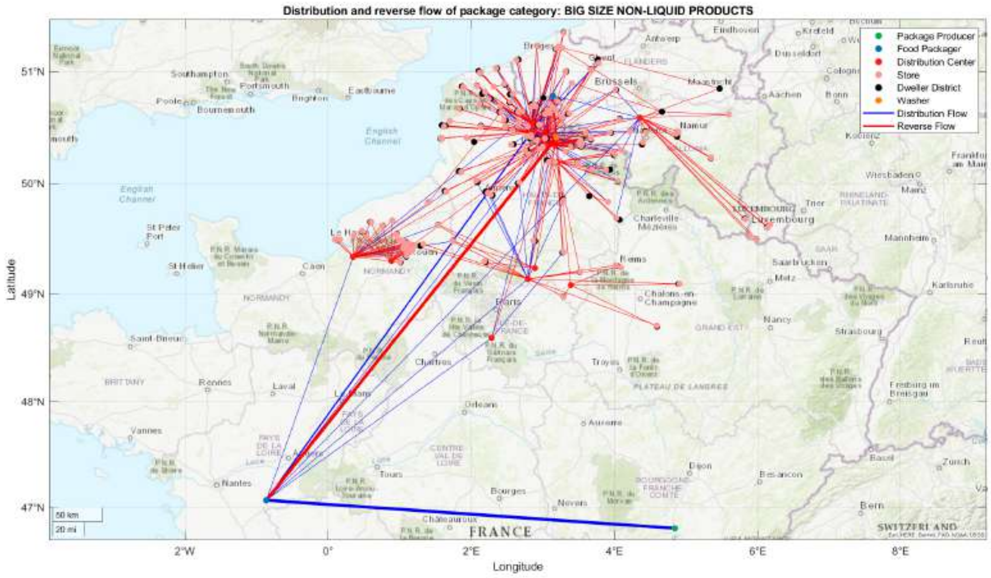
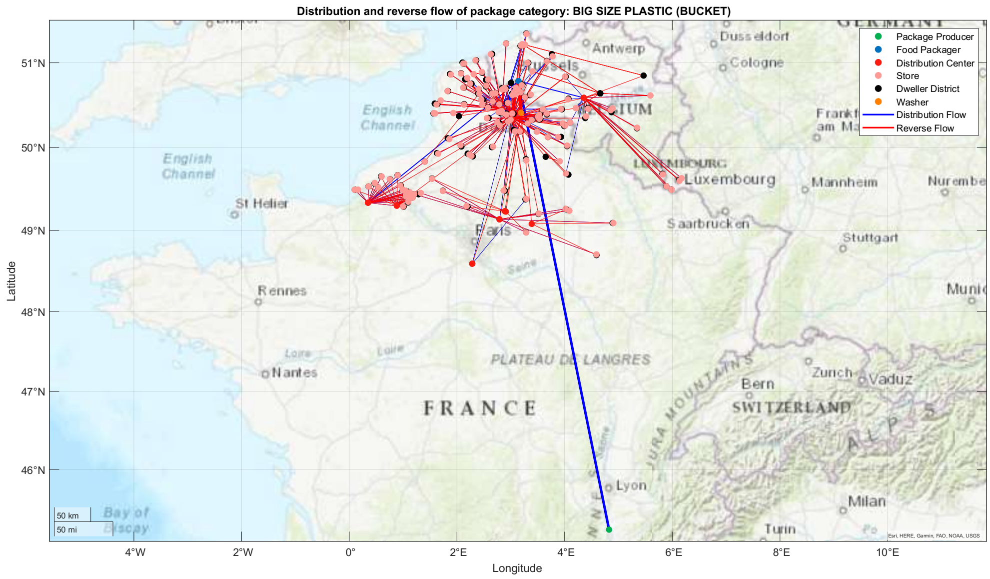
APPENDIX A - Network Map Configuration per Packaging Category





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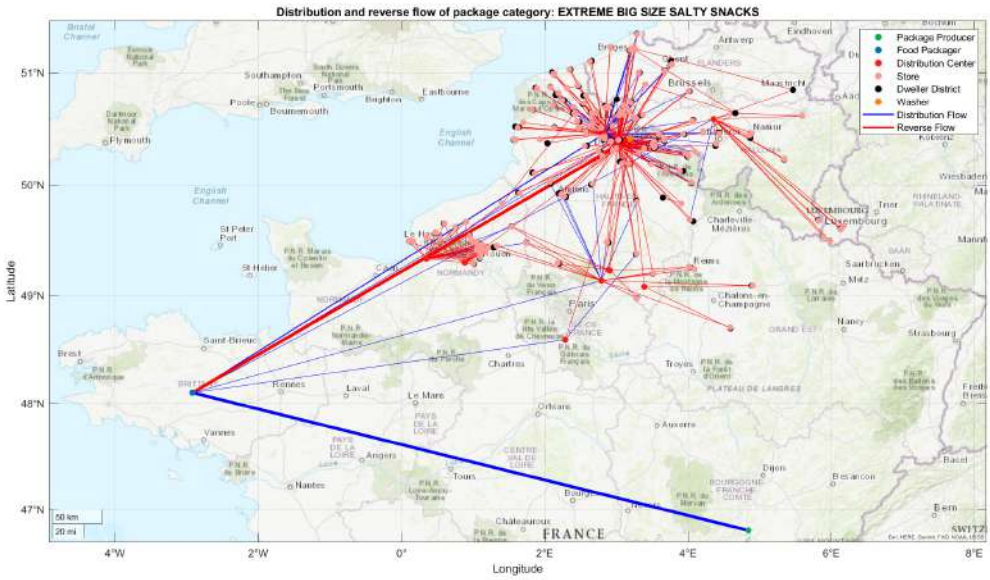
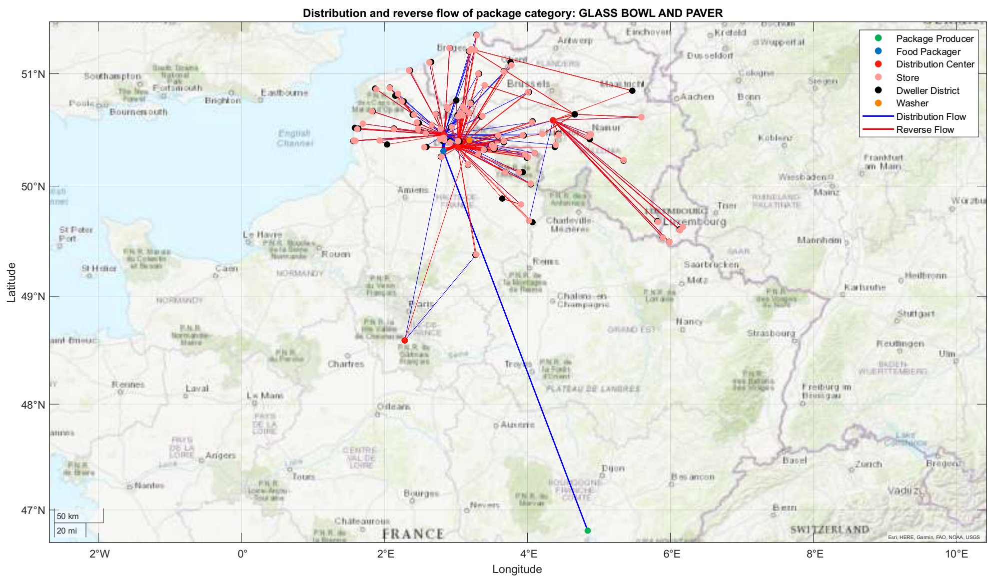
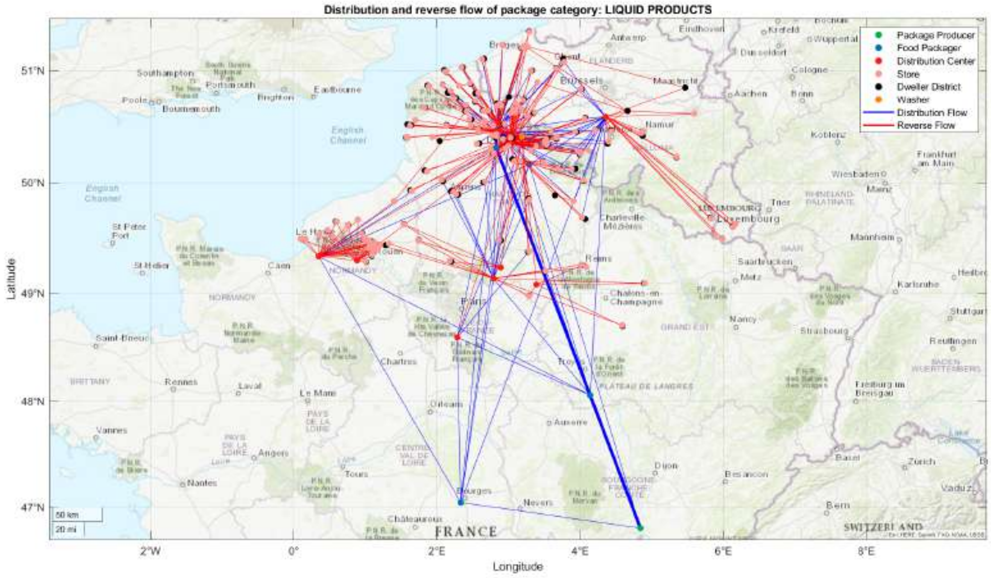
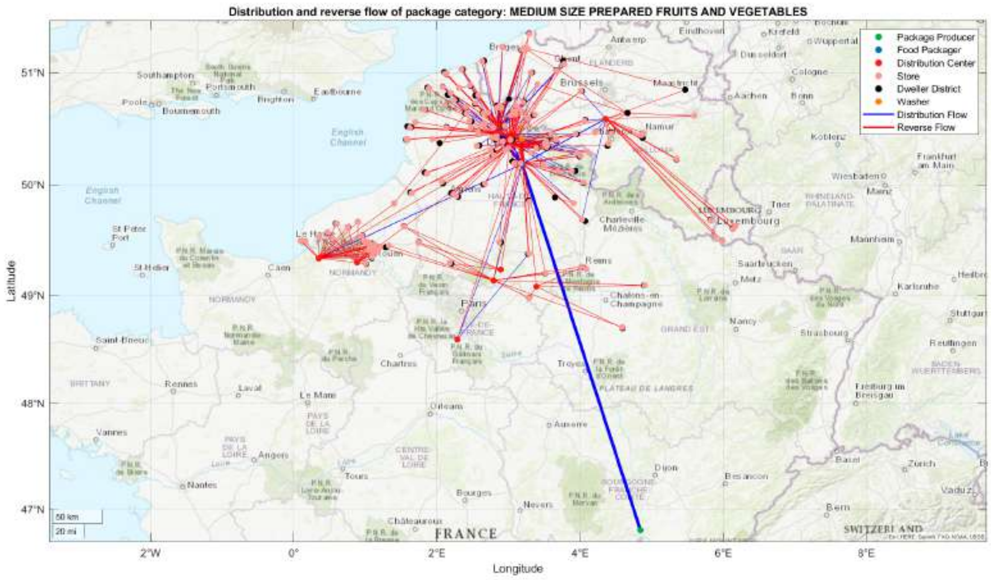
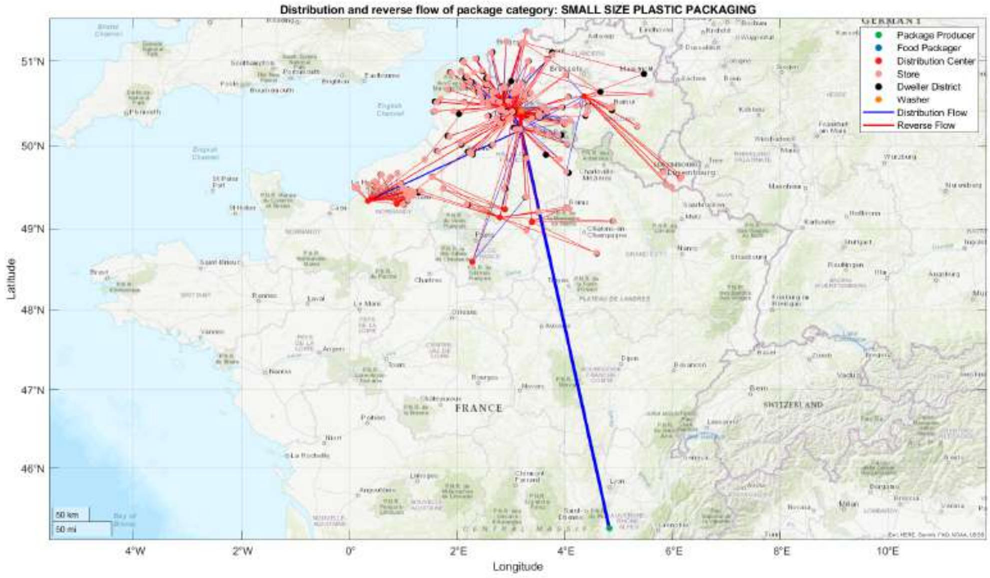
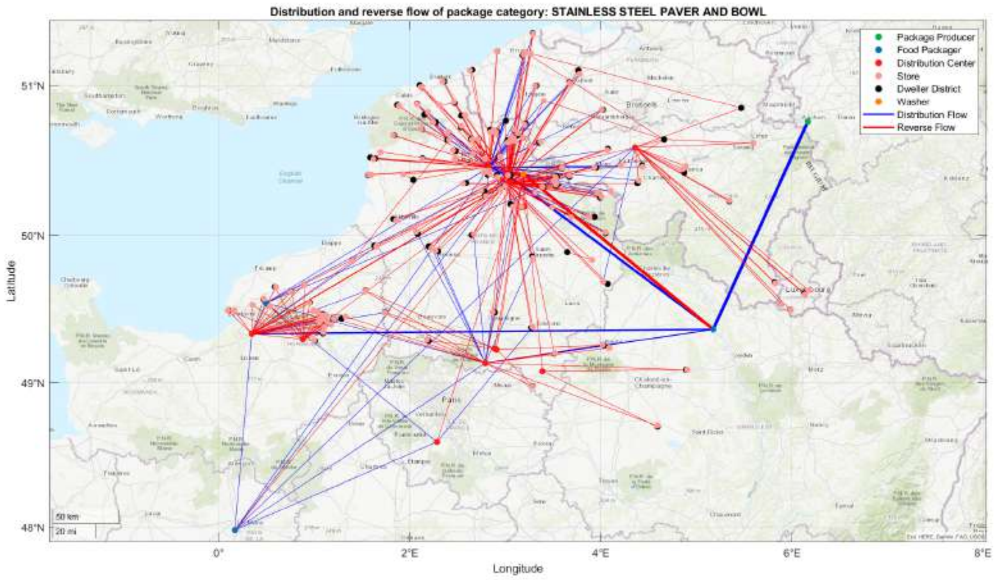

Distribution and reverse flow of package category: EXTREME BIG SIZE SALTY SNACKS
Package Producer
Food Packager
Distribution Center
Store
Dweller District
Washer
Distribution Flow
Reverse Flow
Latitude
Longitude
51°N
50°N
49°N
48°N
47°N
4°W
2°W
0°
2°E
4°E
6°E
8°E
50 km
20 mi


Distribution and reverse flow of package category: GLASS BOWL AND PAVER
Package Producer
Food Packager
Distribution Center
Store
Dweller District
Washer
Distribution Flow
Reverse Flow
Latitude
Longitude
51°N
50°N
49°N
48°N
47°N
2°W
0°
2°E
4°E
6°E
8°E
10°E
50 km
20 mi


Distribution and reverse flow of package category: LIQUID PRODUCTS
Package Producer
Food Packager
Distribution Center
Store
Dweller District
Washer
Distribution Flow
Reverse Flow
Latitude
Longitude
51°N
50°N
49°N
48°N
47°N
2°W
0°
2°E
4°E
6°E
8°E
FRANCE


Distribution and reverse flow of package category: MEDIUM SIZE PREPARED FRUITS AND VEGETABLES
Package Producer
Food Packager
Distribution Center
Store
Dweller District
Washer
Distribution Flow
Reverse Flow
Latitude
Longitude
51°N
50°N
49°N
48°N
47°N
2°W
0°
2°E
4°E
6°E
8°E
FRANCE


Distribution and reverse flow of package category: SMALL SIZE PLASTIC PACKAGING
Package Producer
Food Packager
Distribution Center
Store
Dweller District
Washer
Distribution Flow
Reverse Flow
Latitude
Longitude
FRANCE


Distribution and reverse flow of package category: STAINLESS STEEL PAVER AND BOWL
Package Producer
Food Packager
Distribution Center
Store
Dweller District
Washer
Distribution Flow
Reverse Flow
Latitude
Longitude