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

Grant Agreement No. 101060806

Work package: WP3 - Reuse

Task: 3.3 - Reuse Logistic Network Modelling

Deliverable: 3.5 - Sensitivity Analysis and Multi-Scenario Network Optimization with Guidelines about Risk Hotspots

Dissemination level: Public

Issue date: 31st of July 2024

Lead beneficiary: UNIBO - University of Bologna

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DOCUMENT INFORMATION

HISTORY OF CHANGES		
Version	**Publication date**	**Changes**
1.0	29.07.2024	Draft send to (RE)SET
2.0	31.07.2024	Deliverable

ADDITIONAL AUTHOR(S) CONTRIBUTION	
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DOCUMENT DISTRIBUTION		
Issue	**Date**	**Distributed to**
V1	31.07.2024	European Commission

VERIFICATION AND APPROVAL		
	Date	**Distributed to**

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TABLE OF CONTENT

Funded by the European Union

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LIST OF FIGURES

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Nomenclature

The following abbreviations will be used throughout the document to reduce unnecessary repetitions.

Abbreviation	Definition
PP	Packaging producer facility
FP	Food packager facility
DC	Distribution center
ST	Store
W	Washing facility
SO	Sorting facility
RVM	Reusable Vending Machine
RP	Reusable Packaging
PDF	Probability Distribution Functions

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1. CONTEXT AND MOTIVATION

As global awareness of environmental sustainability grows, the food sector is seeing increasing attention towards reusable packaging to mitigate the adverse impacts of single-use materials. However, the transition to reuse brings inherent challenges and risks that must be carefully managed to ensure both economic viability and environmental sustainability. Logistical complexities in managing reverse supply chains for used packaging can escalate costs and operational inefficiencies if not optimized effectively. The uncertainty on the return rate of the packaging from the consumers exacerbates production and distribution risks. Another critical point involves the hygiene and safety of reused packaging, especially in food and beverage sectors where stringent health regulations apply. Contamination, improper cleaning, or material degradation could compromise product quality and consumer safety, leading to legal liabilities and reputational damage for businesses. Addressing these issues requires comprehensive risk assessment frameworks that encompass strategic and operational dimensions. By identifying and studying potential risk hotspots, the food sector can enhance its resilience in packaging reuse initiatives. This proactive approach not only safeguards consumer trust and brand reputation but also aligns with global sustainability goals by reducing plastic waste generation and resource consumption throughout the product lifecycle. Thus, emphasizing risk reduction in packaging reuse processes is not merely a compliance requirement but a strategic imperative for fostering sustainable business practices in a circular economy paradigm.

In this document, risk analysis focuses on evaluating optimal network configurations and decision-making strategies. To achieve this, we compare the outcomes of different reuse systems by varying key parameters within the system, which are sources of uncertainty. This approach allows us to identify how changes in these critical factors impact the overall performance and reliability of the network, ensuring a thorough understanding of potential risks and their implications.

Building on the model introduced in *Deliverable 3.4*, it is expanded to include the environmental impact assessment of the reuse system. This model is applied to the different scenarios in the sensitivity analysis, exploring trade-offs between economic viability and environmental sustainability. The goal is to make data-driven decisions regarding packaging selection and logistics configurations according to the uncertainty level of the system. Ultimately, this approach aims to foster a robust circular economy framework where uncertainty is addressed through a detailed analysis of possible outcomes.

To illustrate the analysis' environment, Figure 1 schematically represents the reusable supply chain and its various actors and stakeholders. The scheme in Figure 1 underlines the main difference between a business-as-usual (BAU) packaging system scenario, primarily built on recycling, and the Reuse mechanism this proposal attempts to plan and design. Green arrows identify the logistical flow involved in a closed-loop reuse scenario. The inevitable waste of packaging (e.g., citizens throwing the packaging away, packaging breakage during operations) triggers the production of new packaging to maintain the needed quantity within the network.

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The BAU scenario relies on municipal solid waste collection and private or public recycling supply chains responsible for producing secondary material for the same or, more likely, other industries. Indeed, the tight safety standards and control required by food packaging often prevent the adoption of secondary material when sources are not certified and trusted.

Conversely, the packaging returns from the consumers trigger a set of reverse flows of packaging material to be managed through Reusable Vending Machines (RVMs), Distribution Centers (DCs), or dedicated facilities (i.e., Sorter - SO) committed to reusable packaging sorting and washing systems. After a certain number of cycles, the packages might be damaged, thus requiring disposal and recycling. In such a case, new virgin or certified recycled material is used to produce new packages that will replace the overall containers inventory serving the forward production and distribution operations.

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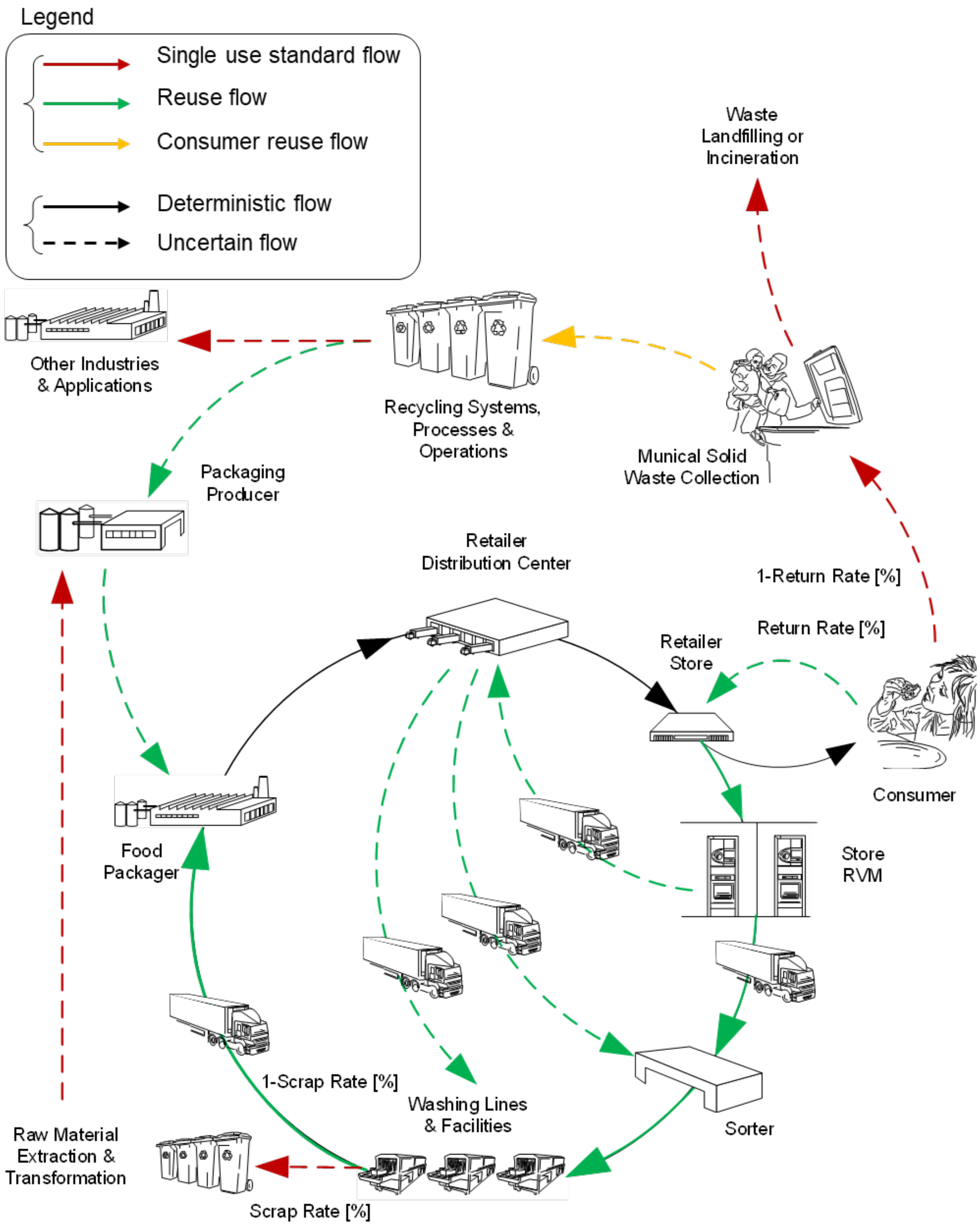

Figure 1 Reuse network and uncertainty aspects

Within this system, uncertainty sources exist and impact the reverse flows of the reuse network, resulting in significant logistics costs and environmental benefits and impacts. The reduced amount of virgin material is a clear benefit, whilst the increased efforts of transportation, sorting, and washing activities bear economic and environmental burdens worth investigating.

Costs and impacts mainly depend on the strategic design of the reuse network made of RVMs, sorting (within current DCs or devoted facilities), and washing facilities. The decision-support optimization model proposed and illustrated in Deliverable 3.4 aimed at identifying the optimal locations of such entities and allocating the forward

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and reverse material flows throughout the circular network to minimize total logistic costs.

The risk analysis here conducted exploits the decision-support model (D3.4) run under uncertain scrap and return rates to investigate how such parameters affect the economic and environmental sustainability of the reuse system.

The risk analysis is carried out with a sensitivity analysis primarily focused on two critical aspects: the scrap rate of reusable packaging and the return rate. The return rate represents the percentage of purchased products that consumers actually decide to return for reuse within the logistics system. If consumers choose to retain or discard the packaging, it cannot be reintegrated into the reuse cycle, necessitating the production of new packaging to replace it. Meanwhile, the scrap rate denotes the percentage of circulating packaging within the network that is discarded. The reasons for discarding packaging are multifaceted and warrant careful study to optimize the network effectively. Packaging may be discarded due to breakage during transportation, washing, or filling stages. Additionally, previous use may have caused visible damage, such as scratches, making the packaging visually unappealing to consumers. Furthermore, packaging may be discarded if it cannot be effectively cleaned and sanitized, leaving food residues that compromise its suitability for containing consumable products and requiring its disposal. Addressing these factors through rigorous sensitivity analysis not only enhances operational efficiency but also ensures the sustainability and economic viability of packaging reuse initiatives.

Studying the network's reaction to varying levels of these parameters provides valuable insights. It supports stakeholders' and practitioners' understanding of uncertainty's consequences. By analyzing the network's performance under different risk scenarios, food industry actors can develop more resilient and adaptable strategies. This, in turn, reduces environmental impact and optimizes resource utilization in the circular economy framework.

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2. METHODOLOGY

In this section, we will detail the primary parameters and decision variables analyzed in this report. The parameters represent characteristic values related to production and distribution phases, costs, and impacts involving one or more stakeholders. Many parameters are known and derived from the actual characteristics of the supply chain and the products under consideration. Others have been hypothesized based on available information and industry reference values. Some parameters introduce uncertainty into the system, making them the focus of our sensitivity analysis.

The decision variables, on the other hand, are the outputs of the developed optimization tool. These variables represent the strategic choices that various stakeholders must make to minimize overall supply chain costs and environmental impacts. By understanding these variables and their interactions with the parameters, we can develop robust strategies that enhance efficiency and sustainability.

2.1 Parameters

We will now discuss the primary parameters. For each modeled entity, we will identify the most important parameters and their characteristics. For products, significant parameters include weight, volumetric saturation during transport, and the number of product pieces that can be transported on a full pallet. For packaging, critical parameters are weight, material (which impacts the feasible washing facilities), volume, and stackability. The combination of volume and stackability determines how many empty packages can be neatly arranged on a pallet. Higher stackability increases volumetric saturation, reducing transportation and handling costs and impacts.

Critical parameters shared across the entire network include transportation-related factors. Specifically, these encompass the distances between various pairs of actors where logistical flows can occur, the available transportation modes, as well as the costs and environmental impacts associated with transportation. These parameters have been gathered from standard cost and impact databases.

Each entity within the network possesses specific throughput and capacity parameters that reflect its core activities. For instance, for Packaging Producers (PPs) these parameters relate to the production of reusable packaging, while Food Packagers (FPs) focus on filling, sealing, and labeling. Warehouses have throughput and capacity parameters for handling, storage, and distribution of products, while retail shops' demand correlates with their size and customer attraction capacity. RVMs are characterized by parameters such as volumetric capacity and the maximum weight of packaging they can accept. Sorters (SOs) and Washers (Ws) are characterized by capacities, throughputs, and acceptable packaging types (some handle only plastic, others only glass).

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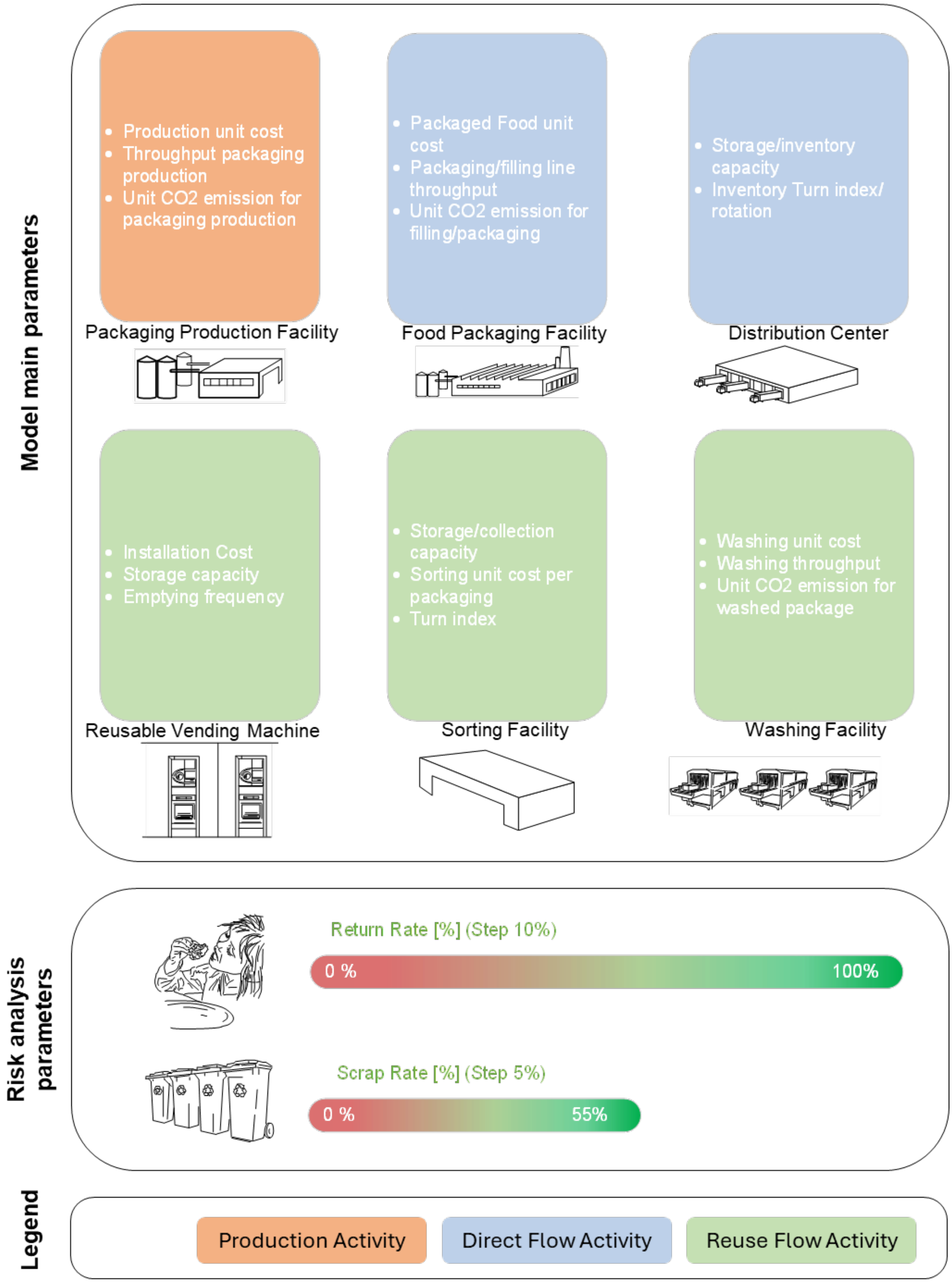

Figure 2 Main parameters per each step per actor and sensitivity analysis domain

Another crucial category is cost parameters, divided into investment cost (i.e., opening cost) and unit costs. Opening costs represent initial investments to expand production capacities, such as installing new machinery in plants or setting up RVMs. Not all actors incur these costs; for instance, DCs and shops may not. These costs

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are depreciated over time for analysis, considering their multi-year lifespan and the one-year analytical horizon used in this report. Unit costs, on the other hand, encompass operational costs per unit of product or packaging, including production, filling, handling, washing, and sorting. Both types of costs are evaluated based on data provided by industrial partners or, in the absence of specific data, industry-standard values.

Another critical parameter category is environmental impacts, assessed as unit costs and covering all actors' activities. These parameters are part of a specific WP within the project but are temporarily substituted with reference values from environmental impact analysis databases due to data collection delays. Once data provided by project partners become available, they will be integrated into the model for a more precise and updated analysis of the environmental impact of different processes and packaging types.

Finally, there are parameters that introduce uncertainty within the production and distribution network: the scrap rate and the return rate of the packaging. The sensitivity analysis will focus on these two parameters, varying their values to observe how the network configuration and flows adjust. This analysis will help identify the most efficient configuration for each different value of these parameters, ensuring that the system remains optimized despite fluctuations in these critical factors.

Figure 2 illustrates the key parameters for each stakeholder in the supply chain, highlighting the differences compared to a non-reusable supply chain. The colors in the figure denote the nature of the activities conducted by each stakeholder: red signifies production and transformation activities, blue indicates distribution activities, and green represents activities associated with the reuse supply chain flows. At the bottom of Figure 2, the variation ranges for the two parameters under risk analysis are depicted. The combination of these ranges defines the entire domain of the sensitivity analysis. For the *ReuseRate*, all possibilities from 0% to an ideal 100% were tested. However, for the *ScrapRate*, the maximum value was set at 55% because a higher breakage rate was considered unrealistic. This decision was based on the commitment and results achieved by other project partners in studying materials and improving the handling and washing processes of the new packaging.

2.2. Variables

The variables involved can be categorized into two types. The first type includes the installation decisions, such as the RVM deployment variables, which represent the number of RVMs that need to be installed at each retail location to ensure sufficient capacity for the return flow of packaging from consumers. The second type encompasses the flow variables, which govern all the movements of finished products and packaging, whether dirty or ready for reuse, among the supply chain actors.

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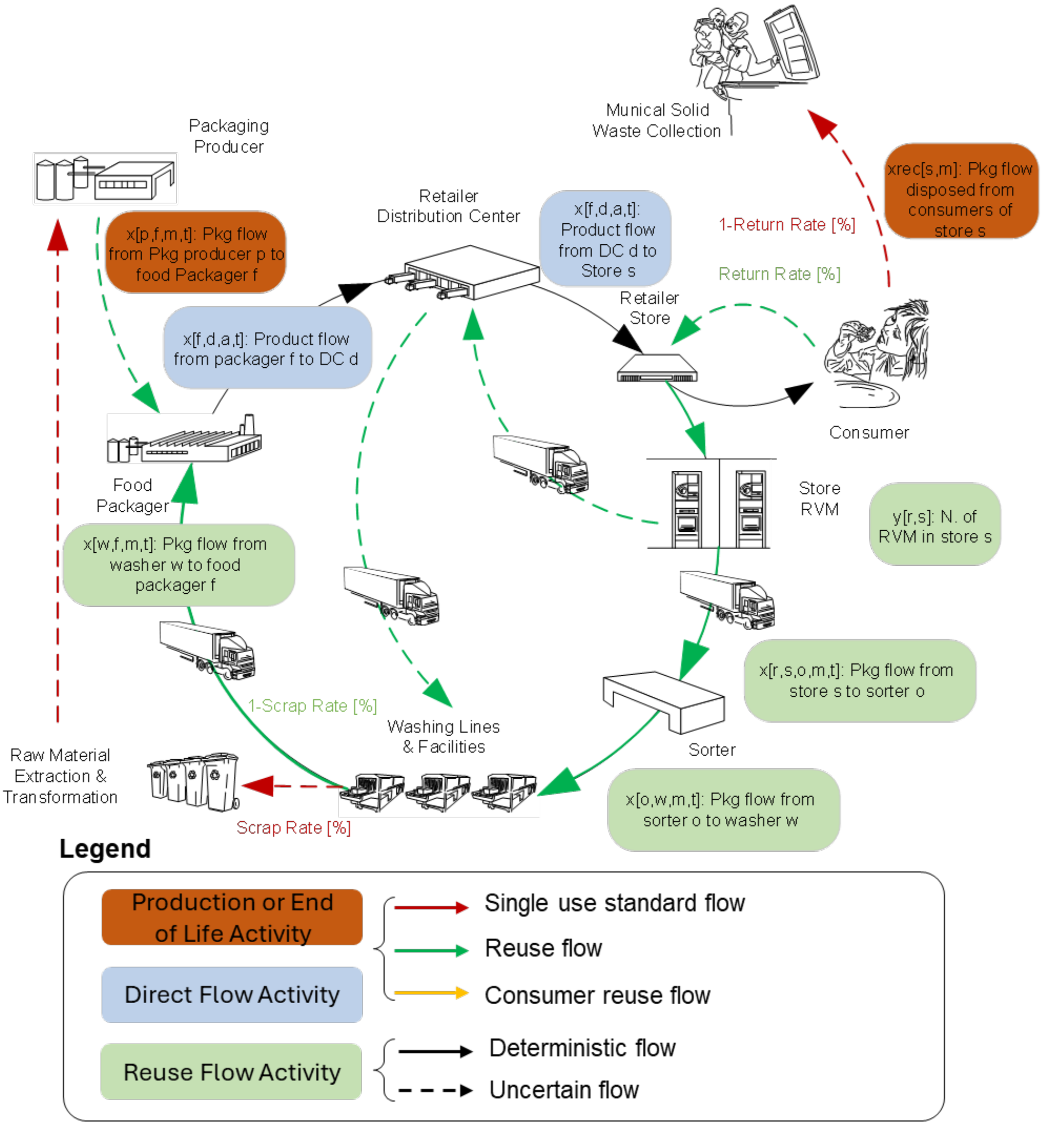

Figure 3 Main model variables

Figure 3 illustrates the key model variables associated with each activity or stakeholder. As in Figure 2 the colors red, blue, and green indicate the nature of the activities: red represents production, blue indicates distribution, and green signifies reuse management. For each pair of stakeholders where a logistic flow is possible, a decision variable has been defined. In contrast, the variables for installing Reverse Vending Machines (RVMs) in Stores (STs) focus on determining the ideal investment level rather than on logistic flows. These variables' values represent the decisions suggested by the model to stakeholders, aiming to minimize the overall supply chain cost.

For a more detailed definition of parameters, variables, and the functioning of the model, please refer to *Deliverable 3.4*.

2.4 Environmental footprint evaluation

To evaluate the overall performance of the network across the different scenarios analyzed, a function to assess the environmental impact of the network has been

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defined. This function follows the cost function described in Deliverable 3.4 but accounts for emissions, expressed in kg CO_2eq, instead of costs expressed in euros. The function aggregates all emissions produced by the supply chain's daily operations. Specifically, it considers emissions from the production and transformation of reusable packaging, emissions from food and packaging distribution activities, and emissions from handling, sorting, and washing of packaging. The valuation of the environmental impact of the new reusable packaging is covered in another project deliverable. Currently, precise values for the R3PACK case study are not available. To provide a benchmark, reference values from scientifically validated databases have been used. Although these reference values are precisely calculated, they represent an average and may differ significantly from the actual parameters for the R3PACK case. Therefore, the absolute values of the emission function should not be considered as an objective reference. Instead, they should be used to understand the general direction of the network, the relationships between the different tested scenarios, and the relative relationship between costs and emissions.

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3. SENSITIVITY ANALYSIS ON AN EXTENDED GEOGRAPHICAL SCOPE

The case study is developed across the entire territories of France, Belgium, and Luxembourg. This area is significantly larger than the predefined area for the pilot demonstration phase of the project, which involves only a few provinces in northern France, Belgium, and Luxembourg. The reason for this broader scope is that a sensitivity analysis on uncertainty factors needs to be applied to a realistic and fully operational system to be reliable. This approach ensures that the analysis accurately reflects the complexities and challenges of a real-world network.

Working with industrial and food distribution partners based throughout France, we decided to apply the optimization tool to the most extensive known territory. By doing so, the volume of flows increases substantially, and the number of actors involved grows significantly. Consequently, the range of possible decisions expands, increasing the complexity of the analysis. This complexity is essential to accurately reflect the challenges that may arise in a real-world reusable packaging network.

3.1. Network entities selection and assumptions

Several assumptions and hypotheses were made to derive the final set of actors and their potential interactions throughout the supply chain. To illustrate the geographical distribution and interaction of the various stakeholders, the following maps will show the locations of the different actors involved in the network. These representations aid the understanding of the scale and complexity of this supply chain.

3.1.1. Packaging producers

Figure 4 Packaging producers' map

The PPs included in the map (Figure 4) are those offering a range of reusable packaging. Some of these producers are the same entities that previously manufactured the non-reusable versions of the packaging for the same products.

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Others are new players who have entered the market to replace versions of packaging made by different producers that could not convert their packaging into reusable formats. This difference often depends on the material of the packaging. Products originally contained in glass can generally continue to be packaged in identical or very similar glass containers, produced by the same manufacturers, with a few additional precautions. In contrast, the original plastic containers are often unsuitable for reuse, necessitating the involvement of new industrial partners to create reusable alternatives in plastic or other materials.

3.1.2. Food packagers

Figure 5 Food packagers map

All food producers within the three selected states are included, as illustrated inFigure 5, encompassing brands that produce products packaged in reusable containers. We have assumed that these products can be packaged in reusable containers not only at the facilities currently involved in the pilot demonstration phase but also at other facilities owned by these same manufacturers located throughout the country. This strategic decision has significant economic implications, particularly concerning investments in new production lines, which will be further explored and detailed in the following sections.

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3.1.3. Distribution centers

Figure 6 Distribution centers map

Regarding the set of DCs, the assumptions mirror those made for food producers. Specifically, all warehouses within the selected countries of the project's two retail partners, Carrefour and Cooperative U, have been included. This approach allows the model to freely select distribution hubs that are strategically advantageous for capillary distribution to points of demand, as illustrated inFigure 6.

3.1.4. Shops

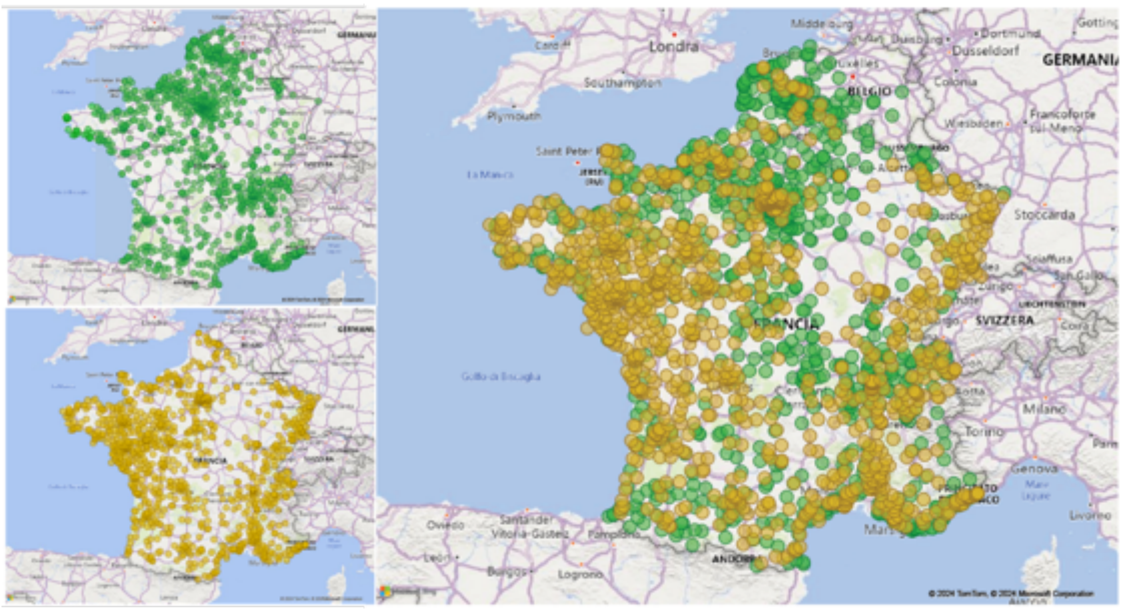

Figure 7 Shops map

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The retail shops encompass all points of demand operated by the two partner retailers within the selected countries for the case study (Figure 7). This comprehensive approach ensures that the model's strategic decisions are based on a realistic and extensive coverage of consumer demand across the region. In Figure 7, yellow dots represent CoopérativeU STs, while green dots represent Carrefour STs.

3.1.5. Reusable Vending Machines (RVM)

RVMs, while not classified as facilities, are treated as nodes within the model as they support the flow of packaging in the network. These machines are installed within the shops, enabling consumers to return used and dirty packaging in exchange for a deposit refund. The deposit is a financial amount collected from consumers at the time of purchase (akin to a surcharge) to incentivize the return of packaging after product consumption. It is assumed that such machines can be installed in any retail location, and their collection capacity scales with the number of machines deployed. Therefore, the model not only decides whether to utilize a potential location for packaging return but also determines the optimal number of machines to install for effective operation.

3.1.6. Sorting facilities

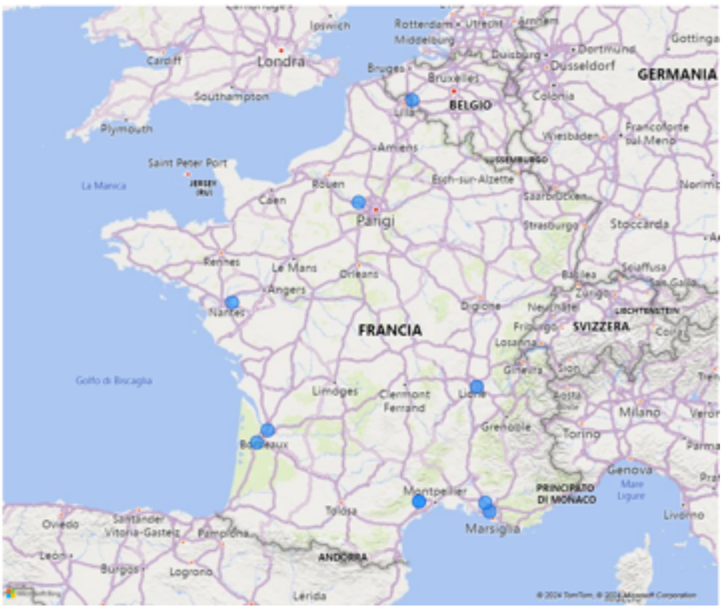

Figure 8 Sorting facilities map

SO facilities locations are illustrated in the map in Figure 8. Sorting centers play a crucial role in the reusable packaging network by receiving and organizing the mixed packaging collected from RVMs. This separation is essential for the subsequent washing and sanitization processes, as washing facilities (Ws) are often specialized by material type—some handle only glass packaging, while others manage plastic. Therefore, it is necessary to route the dirty packaging through sorting centers to direct it to the appropriate Ws based on the material. The location of sorting centers posed significant challenges. Currently, the only operational facility capable of handling the selected types of packaging for this project is a partner-operated plant (Loop) in northern France, used for the Demonstrator. For the national-scale case study, additional centers were needed, especially to manage flows from southern

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France. Without alternative centers, packaging from all three countries would have to be transported to this single location, then redistributed after cleaning and refilling. This would lead to excessive economic and environmental costs due to the long distances involved, making it an impractical and inefficient logistical solution. To address this limitation, we assumed the establishment of new sorting centers. These new possible locations were strategically placed at existing DCs and Ws.

DCs are typically located in logistically advantageous positions, near urban areas but in commercial-industrial zones, ensuring easy access to various transportation modes. This makes them suitable locations for potential new sorting centers, as they are likely to have the necessary space and infrastructure. Only the largest and most logistically central DCs were selected to ensure optimal positioning. Moreover, alternative locations for sorting centers were considered among the principal Ws. This alternative, currently under discussion within the consortium, would involve expanding some Ws to also serve as sorting centers. This would eliminate the need for an intermediate transport step, as the packaging would be sent directly from the shops to a combined sorting and W. Naturally, this would require significant investments to expand the washing facilities, which are currently hypothetical. The selected Ws to serve as potential sorting centers are those that already have a widespread network in the target countries and are flexible enough to handle different types of packaging. To evaluate the best option, the model is fed with both the most important DCs and some of the principal Ws as potential sorting center locations. The optimization model will then determine which of these two alternatives is the more efficient, selecting the best locations to enhance the system's economic and environmental efficiency.

3.1.7. Washing facilities

Figure 9 Washing facilities map

As previously mentioned, the washing facilities specialize in different materials. The network of washing facilities includes structures that belong to the logistical networks of the project's partners (Figure 9). Although they are currently operational within the designated territory, the volume of packaging these centers currently handle may be

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less than what would be required for a national reuse network. Nevertheless, these locations are all viable options within the system.

3.2. Products and packaging selection

The sensitivity analysis applied to this extensive and complex network provides reliable insights to reduce costs and minimize the environmental impact of the packaging reuse system. Now that the network is defined, the final products selected for the reuse system and the selected reusable packaging alternatives will be presented.

InFigure 10, we present the final list of products selected for the reuse network within the project, along with their respective manufacturers. As shown, some products share the same packaging, which helps reduce operational complexities related to washing and transporting the packaging. At the time of writing this report, some of these products are already being produced and sold within the Demonstrator's points of sale. Therefore, their final appearance, including the packaging and modified labels, is already known. For other products, while the packaging has been defined, they have not yet entered the production phase. Consequently, definitive images of their final appearance are not available. The figure includes images of the products as they are currently known, along with data on weights and manufacturers. The product EAN codes have been generated arbitrarily for use within the model.

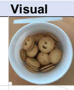
FoodItemID	FoodItem	FoodPackager	Weight	UoM	Visual	FoodItemID	FoodItem	FoodPackager	Weight	UoM	Visual
EAN_01	prepared salad and cut vegetable	LSDH	250	g		EAN_12	Biscuits Mini GF choco_3256225130955	BISCUITSBOUVARDS	350	g	
EAN_02	prepared salad and cut vegetable	SODEBO	250	g		EAN_13					
EAN_03	prepared salad and cut vegetable	FLOREALE	250	g		EAN_14	Fromage blanc 2 kg_3184670001707	RIANS	2000	g	
EAN_04	Fromage blanc and fresh cream 500 g	YOPLAIT	500	g		EAN_15	Sirup of Mint_3265261638813	MONIN	437,8	g	
EAN_05	Fromage blanc and fresh cream 500 g	SCHREIBER	500	g		EAN_16	Sirup of grenadine_3265261638820	MONIN	437,8	g	
EAN_06	Fromage blanc and fresh cream 500 g	EURIAL	500	g		EAN_17	mayonnaise_3265470135271	LESIEUR	239	g	
EAN_08	Peanut curl MDD U_3256225135424	ALTHO	250	g		EAN_18	Olive Oil Puget_3265470135257	LESIEUR	230	g	
EAN_09	Bret's_3497917003793	ALTHO	250	g		EAN_19	Brut cider_3013060118711	ECLOR	790	g	
EAN_10	Mix party_3256225109531	EUROPESNACKS	100	g		EAN_20	Fruity cider_3013060118629	ECLOR	790	g	
EAN_11	Orange Juice_3256225036004	LSDH	1000	g			Lemonade	LORINA	750	g	

Figure 10 Products details and visuals

Table 1 illustrates the match between products and their corresponding reusable packaging. This product-packaging association, provided as input to the model, accurately reflects the industrial decisions made to ensure the results align with the

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actual choices implemented so far. The table includes the weights of both the food products and their packaging, as well as the total weight of the finished products. It also highlights the packaging materials, which are crucial for sorting processes, and the food categories to which the products belong.

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Table 1 Products considered in the reuse network optimization

Product_Pack	Product	Description	FoodPackager	Weight_Food	FoodCategory	Pack_ID	PackagingDescription	PackagingProducer	MaterialType	WeightPack	Weight_Total
EAN_01_PKG_01	EAN_01	prepared salad and cut vegetable	LSDH	250	Prepared salads	PKG_01	PP Salad Tray 261 mL	KNAUFINDUSTRIES	PP	44,1	294,1
EAN_02_PKG_01	EAN_02	prepared salad and cut vegetable	SODEBO	250	Prepared salads	PKG_01	PP Salad Tray 261 mL	KNAUFINDUSTRIES	PP	44,1	294,1
EAN_03_PKG_01	EAN_03	prepared salad and cut vegetable	FLOREALE	250	Prepared salads	PKG_01	PP Salad Tray 261 mL	KNAUFINDUSTRIES	PP	44,1	294,1
EAN_04_PKG_02	EAN_04	Fromage blanc and fresh cream 500 g	YOPLAIT	500	Yoghurt	PKG_02	PP Pot 610ml	BERRYSUPERFOS	PP	17,3	517,3
EAN_05_PKG_02	EAN_05	Fromage blanc and fresh cream 500 g	SCHREIBER	500	Yoghurt	PKG_02	PP Pot 610ml	BERRYSUPERFOS	PP	17,3	517,3
EAN_06_PKG_02	EAN_06	Fromage blanc and fresh cream 500 g	EURIAL	500	Yoghurt	PKG_02	PP Pot 610ml	BERRYSUPERFOS	PP	17,3	517,3
EAN_08_PKG_03	EAN_08	Peanut curl MDD U_3256225135424	ALTHO	250	Chips	PKG_03	PP Bucket 3,5L	BERRYSUPERFOS	PP	108	358
EAN_09_PKG_03	EAN_09	Bret's_3497917003793	ALTHO	250	Chips	PKG_03	PP Bucket 3,5L	BERRYSUPERFOS	PP	108	358
EAN_10_PKG_04	EAN_10	Mix party_3256225109531	EUROPESNACKS	100	Savory biscuits	PKG_04	PP Bucket 1L	BERRYSUPERFOS	PP	37	137
EAN_11_PKG_05	EAN_11	Orange Juice_3256225036004	LSDH	1000	Juice	PKG_05	Glass bottle 1L	VIDRALA	Glass	375	1375
EAN_12_PKG_04	EAN_12	Biscuits Mini GF choco_3256225130955	BISCUITSBOUVARDS	350	Sweet biscuits	PKG_04	PP Bucket 1L	BERRYSUPERFOS	PP	37	387
EAN_13_PKG_06	EAN_13	Fromage blanc 2 kg_3184670001707	RIANS	2000	Yoghurts	PKG_06	PP Bucket 2L	BERRYSUPERFOS	PP	70,9	2070,9
EAN_14_PKG_07	EAN_14	Sirup of Mint_3265261638813	MONIN	437,76	Boissons	PKG_07	Glass bottle 70cl	VERRALLIA	Glass	460	897,76
EAN_15_PKG_07	EAN_15	Sirup of grenadine 3265261638820	MONIN	437,76	Boissons	PKG_07	Glass bottle 70cl	VERALLIA	Glass	460	897,76
EAN_16_PKG_08	EAN_16	mayonnaise_3265470135271	LESIEUR	239	Condiments	PKG_08	Glass jar 475g	ARDAGH GROUP	Glass	230	469
EAN_17_PKG_09	EAN_17	Olive Oil Puget_3265470135257	LESIEUR	230	Oil	PKG_09	Glass bottle 25cl	VERALLIA	Glass	160	390
EAN_18_PKG_10	EAN_18	Brut cider_3013060118711	ECLOR	790	Beverages	PKG_10	Glass bottle 75 cl	VERALLIA	Glass	560	1350
EAN_19_PKG_10	EAN_19	Fruity cider_3013060118629	ECLOR	790	Beverages	PKG_10	Glass bottle 75 cl	VERALLIA	Glass	560	1350
EAN_20_PKG_11	EAN_20	Lemonade	LORINA	750	Beverages	PKG_11	Glass bottle 75 cl	VERALLIA	Glass	560	1310

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Table 2 Industrial partners involved in the reuse network

Industrial Partner	Entity type	N° of Facilities
Carrefour	*DC*	114
Système U	*DC*	31
Altho	*FP*	2
Biscuits Bouvards	*FP*	11
Eclor	*FP*	1
Eurial	*FP*	5
Europesnacks	*FP*	3
Floreale	*FP*	7
Florette	*FP*	1
Lesieur	*FP*	1
Lorina	*FP*	1
Lsdh	*FP*	9
Monin	*FP*	1
Rians	*FP*	1
Schreiber	*FP*	1
Sodebo	*FP*	1
Yoplait	*FP*	2
Carrefour	*SO*	114
Loop	*SO*	1
Options Solutions	*SO*	5
Système U -DC	*SO*	31
Ardaghgroup	*PP*	3
Berry Superfos	*PP*	3
Knaufindustries	*PP*	15
Verallia	*PP*	7
Vidrala	*PP*	1
Carrefour	*ST*	1213
Coopérative U	*ST*	1153
Aquarys	*W*	1
Bocaux & Co	*W*	1
Boutin Services	*W*	1
Ma bouteille s’appelle reviens (Locaverre)	*W*	1
Distro	*W*	1
Eco In Pack	*W*	1
Eternity Systems	*W*	1
Fraiche Cancan	*W*	1
France Consigne | Bout' À Bout'	*W*	1
France Consigne | Oc'Consigne	*W*	1
France Consigne | Haut La Consigne	*W*	1
Idverre	*W*	1
J'Aime Mes Bocaux (Alternativ 7)	*W*	1
La Plonge S'Adapte	*W*	1
La Station (La Feuille D'Erable)	*W*	1
Les Retournées	*W*	1
Naowash	*W*	1
Oeco (Villette Emploi Service)	*W*	1
Options Solutions	*W*	6
Pop	*W*	1
Reconcil	*W*	1
Reutiliz	*W*	1
Reuz	*W*	1

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Reuz Le Boulou	W	1
Reuz Bordeaux	W	1
Reuz Santeny	W	1
Reverredire / L'Attache Rapide	W	1
Serge Cheveau	W	1
Uzaje	W	2

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4. RESULTS AND DISCUSSION

In this section, we present the results obtained from the optimization model and discuss the sensitivity analysis conducted on two critical parameters: the scrap rate and the return rate. The scrap rate ranges from 0.05 to 0.55 in increments of 0.05, while the return rate varies from 0 to 1 in increments of 0.1. By exploring all combinations of these increments, we created a comprehensive set of scenarios for evaluation with the model. Table 3 shows all the different values for the *ScrapRate* and the *ReturnRate* used for the scenarios' generation. The list of all the scenarios generated by combining such values is available in Appendix A.

Table 3 Levels of ScarRate and ReuseRate used in the sensitivity analysis

ScrapRate_Scenario	ScrapRate	Return_Scenario	ReturnRate
1	0,05	1	0
2	0,1	2	0,1
3	0,15	3	0,2
4	0,2	4	0,3
5	0,25	5	0,4
6	0,3	6	0,5
7	0,35	7	0,6
8	0,4	8	0,7
9	0,45	9	0,8
10	0,5	10	0,9
11	0,55	11	1

Our model employs a dual objective function designed to minimize both costs and emissions. However, due to the uncertainty in the exact impact values of some packaging processes, we prioritized economic efficiency. This decision was based on the availability of more reliable cost data and the natural alignment between cost reduction and emission reduction. Specifically, minimizing costs often leads to shorter transportation distances and more efficient logistics, which in turn reduce emissions. Therefore, while the primary focus was on economic efficiency, the model also accounts for the environmental benefits of the decisions.

The results are presented in graphical form, highlighting key system parameters to illustrate the effects of varying the scrap rate and return rate. These graphs show how changes in these two parameters impact logistics, costs, emissions, and the return flow operations. By examining these trends, we can gain insights into the influence of these uncertainties on the overall efficiency and sustainability of the system.

4.1 Prediction of ReturnRate's logistic impact

In this analysis, we focused on understanding how the distances traveled between various pairs of actors in the network are distributed. To achieve this, we analyzed all possible flows between pairs of actors and created frequency graphs to illustrate how often different distances occur. This allowed us to derive the Probability Distribution Functions (PDF) for each pair of actors.

For this analysis, we maintained a fixed *ScrapRate* of 15%, which means that 15% of the packaging was assumed to be unusable or discarded. On the other hand, the *ReturnRate* of the packaging by citizens ranged from 0% to 100%. The

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presented results compare 4 levels of *ReturnRate*, as outlined in Table 4 (0%, 40%, 70%, and 100%). The goal of this analysis was to understand how fluctuations in the return rate affect the distribution of distances between different network actors. This understanding helps identify patterns in the logistics network and highlights areas where efficiencies or inefficiencies might arise based on different return rates.

Table 4 List of scenarios analyzed in the PDF of distances

Case	ReturnRate %	ScrapRate %
Case 1	0%	15%
Case 2	40%	15%
Case 3	70%	15%
Case 4	100%	15%

Table 5 Main statistical features of the analyzed scenarios: Scale Factor and Shape Factor relates to the extrapolated Weibull distribution. Mean, Variance and Median values are evaluated over the real data points distributions

Case ID	RouteType	Scale Factor	Shape Factor	Mean	Variance	Median
Case 1	PP-FP	452.082	1.838	401.651	51330.430	370.357
Case 1	FP-DC	427.642	1.567	384.178	62768.584	338.468
Case 1	DC-ST	65.511	1.262	60.883	2358.490	49.000
Case 1	ST-SO	N.A.	N.A.	N.A.	N.A.	N.A.
Case 1	SO-W	N.A.	N.A.	N.A.	N.A.	N.A.
Case 1	W-FP	N.A.	N.A.	N.A.	N.A.	N.A.
Case 2	PP-FP	413.495	1.819	367.539	43818.553	338.023
Case 2	FP-DC	428.467	1.570	384.855	62797.886	339.254
Case 2	DC-ST	65.784	1.262	61.138	2378.407	49.205
Case 2	ST-SO	300.354	1.492	271.331	34294.613	234.917
Case 2	SO-W	55.025	0.988	55.317	3136.311	37.968
Case 2	W-FP	297.508	1.280	275.642	47058.586	223.443
Case 3	PP-FP	375.085	1.885	332.926	33711.538	308.793
Case 3	FP-DC	428.449	1.568	384.895	62978.761	339.124
Case 3	DC-ST	66.183	1.257	61.567	2431.363	49.442
Case 3	ST-SO	290.982	1.514	262.397	31211.714	228.409
Case 3	SO-W	54.068	1.033	53.370	2672.582	37.912
Case 3	W-FP	289.746	1.313	267.071	42118.374	219.178
Case 4	PP-FP	308.126	2.266	272.932	16263.109	262.113
Case 4	FP-DC	427.767	1.561	384.444	63311.320	338.255
Case 4	DC-ST	66.558	1.258	61.902	2453.150	49.737
Case 4	ST-SO	297.569	1.504	268.539	33073.442	233.221
Case 4	SO-W	54.294	1.048	53.298	2590.050	38.266
Case 4	W-FP	290.731	1.318	267.768	42016.395	220.172

In the following graphs, the histograms represent the frequency distributions of distances traveled (counted as the number of full truckloads) between every possible pair of actors. Based on this distribution, a Weibull function (red line) has been extracted, representing a continuous PDF. This function can be used to predict the likelihood of certain distances being traveled between network actors.

The Weibull distribution is characterized by two main parameters: the shape factor and the scale factor. Depending on the combination of these two factors, the Weibull distribution can take on various forms often found in complex

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systems, such as Gaussian, Poisson, and negative exponential distributions. Table 5 contains the parameters that reproduce all the Weibull functions present in the graphs below (Figure 11,Figure 12,Figure 13,Figure 14).

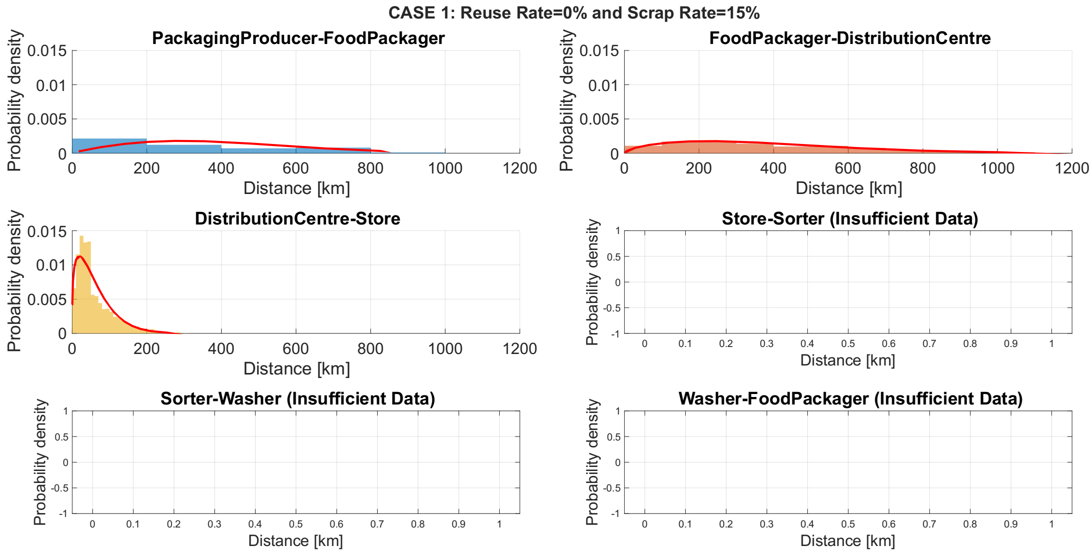

Figure 11 Case1 - distances' PDFs

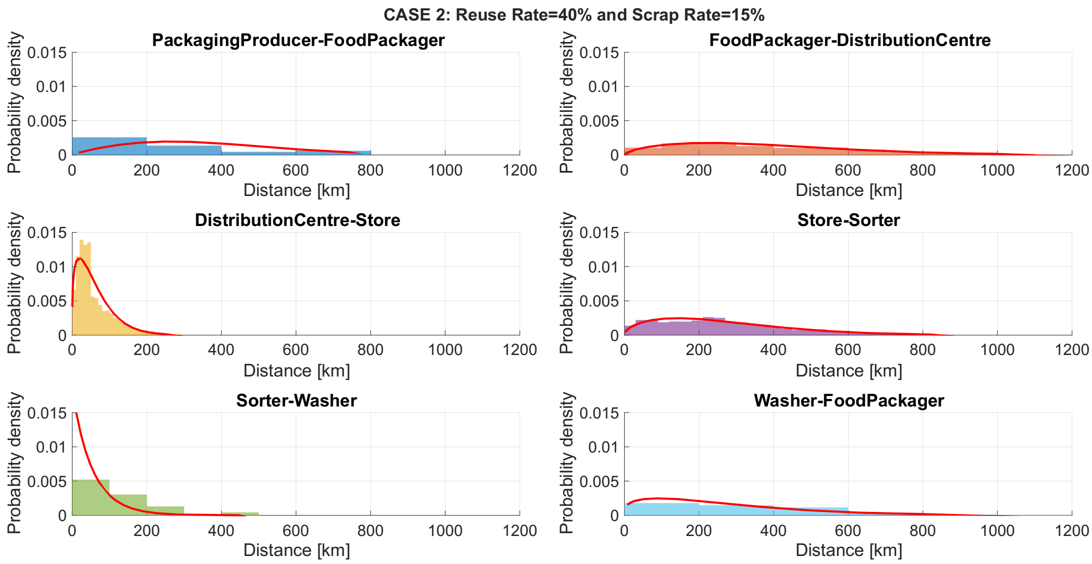

Figure 12 Case2 - distances' PDFs

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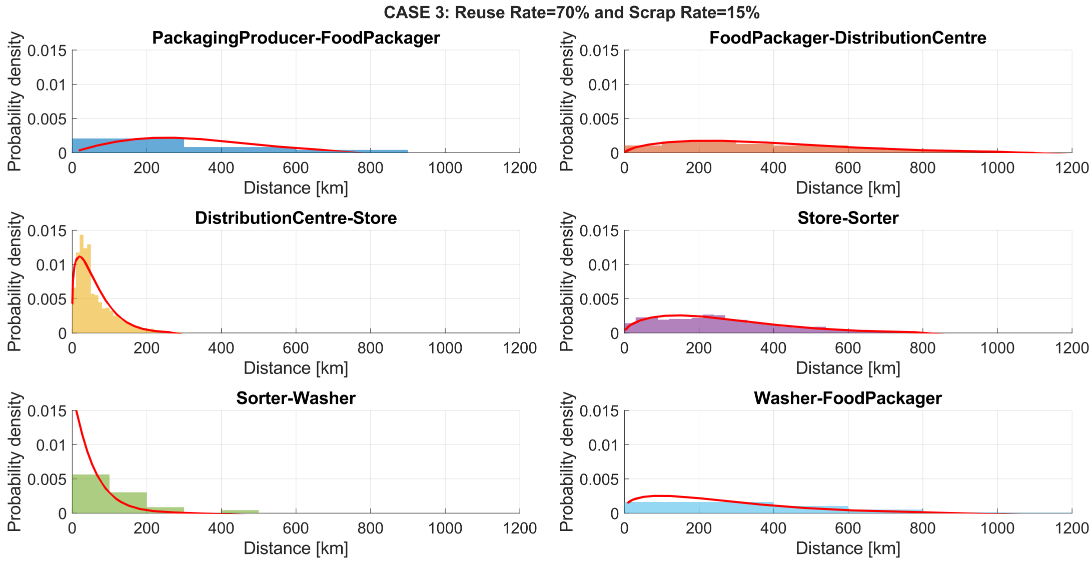

Figure 13 Case3 - distances' PDFs

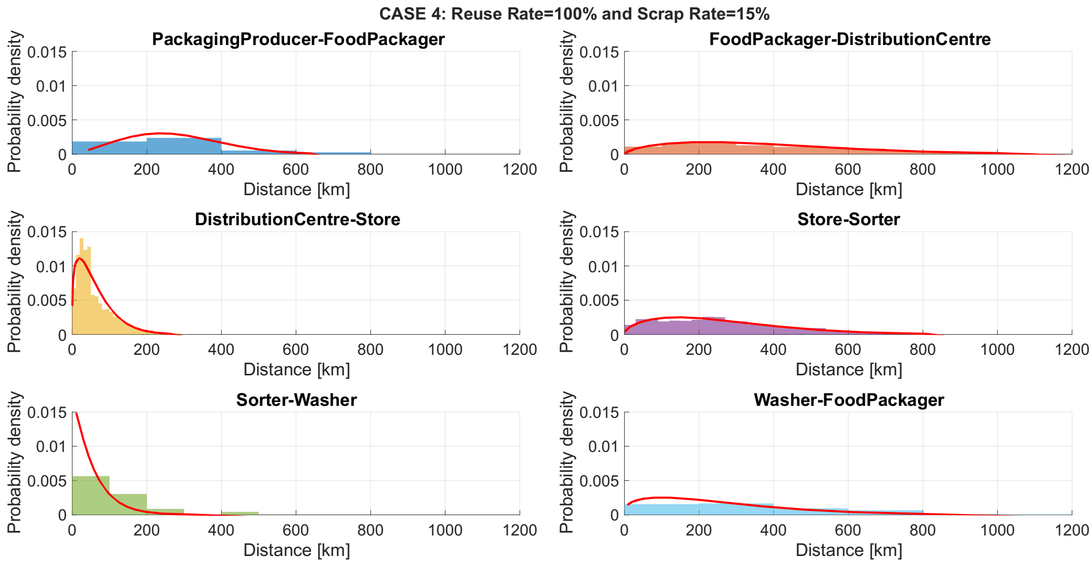

Figure 14 Case4 - distances' PDFs

These distributions provide insight into how likely it is for a particular distance to occur between two actors. A flatter curve indicates higher uncertainty regarding the logistical impact of a given route, meaning there is greater variability in the distances observed. Conversely, a pronounced peak in the curve suggests lower variability, indicating that distances between the actors are more consistent.

In Case1, where the *ReturnRate* is set to 0%, we are examining a supply chain where packaging is not reused. In this scenario, all demand is met through the production of new packaging. Consequently, there are no data points available to generate probability distributions for interactions involving actors engaged in the reuse process, such as Ws and SOs. This is because, with no return or reuse of packaging, these actors do not participate in the logistics of handling used packaging. In contrast, for scenarios where the return rate is greater than 0%, all probability distributions are populated.

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Below are some general observations drawn from these graphs:

- The DC-ST distances PDF exhibits a Poisson-like shape, characterized by a narrow spread with a pronounced peak at around 50 kilometers. This distinct pattern is influenced by two primary factors: firstly, retailers strategically position DCs and STs to minimize travel distances. This optimization is intentional, aiming to enhance logistical efficiency and reduce transportation costs and impacts. By carefully selecting locations, retailers can ensure that the distances their goods need to travel are as short as possible, which is reflected in the sharp peak around the 50-kilometer mark in the distribution graph. Secondly, the model itself, which prioritizes economic efficiency, further minimizes these distances. Given the numerous flows involved—one for each store (ST) —each flow carries transportation costs and environmental impacts. Consequently, the model strives to reduce the traveled DC-ST distance to the minimum necessary. This dual influence of strategic planning and model optimization results in a highly efficient and predictable logistical network between DCs and STs.
- The SO-W distance probability distribution clearly follows a negative exponential pattern. This shape indicates that the reuse network has significant potential for efficiency and distance reduction. In practical terms, a negative exponential distribution suggests that most of the distances are short, with a rapidly decreasing probability of longer distances. This distribution pattern implies that, within the reuse network, SOs and Ws are typically located relatively close to each other. Consequently, the logistical efforts and associated costs for transporting packaging between these two types of facilities can be minimized. The presence of this distribution highlights the inherent efficiency of the reuse network. It shows that, even as *ReturnRates* vary, the system tends to maintain shorter transportation routes between sorting centers and washers. This efficiency is crucial for achieving both economic and environmental benefits, as it reduces fuel consumption, emissions, and transportation costs.
- The other distributions, in contrast, are represented by very flat Gaussian curves. Despite the model's aim to find the most efficient solution, these distributions indicate significant uncertainty and variability in the distances between certain pairs of actors. This high variability in distances suggests that the network for these actors is not efficient and could benefit from redesigning. Additionally, the high variability could also be attributed to the limited number of nodes available in the network for these functions. With few alternatives, there is less room for optimizing distances. To address this inefficiency, the network should be redesigned by establishing new key facilities in more strategic locations. Specifically, relocation of PP and FP facilities would certainly reduce logistics costs and related emissions. These new nodes should be positioned to provide better accessibility from various points within the network, thus reducing the traveled distances. This redesign would help create a more balanced and efficient network, where distances between all pairs of actors are minimized, leading to improved overall system performance.

Comparing the four different analyzed cases, we can make some observations:

- The FP-DC flows, as well as DC-ST flows, remain consistent regardless of the packaging *ReturnRate*. This consistency is due to the constant total demand, which must pass through both FPs and DCs, whether it is managed with washed or newly produced packaging. As expected, the

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graphs show no variations in the distribution of distances between these pairs of actors at different *ReturnRates*.

- In contrast, the ST-SO, SO-W, and W-FP flow rates vary across different scenarios. However, these variations do not significantly affect the distribution patterns. This is likely due to the limited number of facilities available for these functions, meaning that the return paths for packaging remain fixed regardless of the flow volume. Consequently, the destinations for return flows remain proportionally the same, even as the quantity of flow changes.
- A notable observation is a reduction in the variability and average PP-FP traveled distance as the *ReturnRate* increases. When the *ReturnRate* is low, a significant flow of new packaging is required, forcing the model to utilize less logistically convenient production facilities, leading to a less efficient overall distribution. Conversely, when the demand for new packaging is low, the capacity of the more logistically convenient PP centers is sufficient to meet the demand. As a result, the average distance traveled and its variability decrease.

Overall, the consistent flow patterns between FPs and DCs, as well as between DCs and STs, highlight the stable nature of these connections, driven by constant demand. The variability in flows among other actor pairs emphasizes the need for a more optimized network with strategically placed facilities to improve efficiency and reduce distances. The observed trends underscore the importance of optimizing the locations and capacities of facilities within the network to achieve better logistical efficiency and sustainability. Additionally, the significant variability may also be due to the limited number of available nodes for these functions, limiting the optimization of distances.

4.2 Environmental impact of the cost-optimized network

In this section, we evaluate the environmental impact of the economically optimized logistics network, specifically focusing on the carbon footprint of production and distribution activities. This is achieved by using a secondary objective function within the model that quantifies the CO2 equivalent emissions resulting from the model's economic optimization decisions.

It is crucial to clarify that the specific environmental impact parameters for the R3PACK project operations are still under investigation and quantification. Therefore, the parameters used in this analysis are extracted from established databases as average values. While these database values are validated, they may not represent the case study's reality. Environmental impact can vary significantly based on several factors, including energy sources, transportation modes, and regional practices.

Even though the average values used may not capture all specific nuances, they provide a solid foundation for understanding the potential environmental implications of cost-saving strategies in the logistics network. The primary objective remains to minimize costs, but the secondary function offers valuable insights into the environmental consequences of these economic decisions.

As more accurate and specific data become available, they will be incorporated into the model. This will enable a more refined analysis, balancing both economic efficiency and environmental sustainability. Thus, while current results offer a preliminary benchmark, they pave the way for future, more detailed assessments that will better inform decision-making in optimizing both economic and environmental outcomes.

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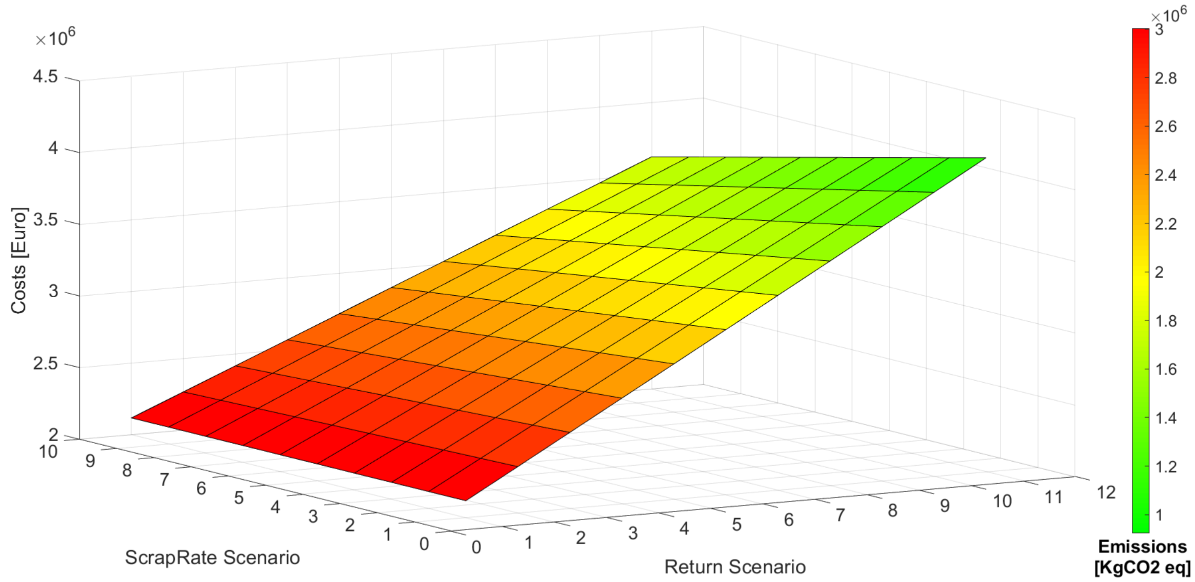

Figure 15 Cost-Emissions relationship

In Figure 15, the relationship between cost and emissions objective functions is presented. The horizontal plane identifies all the scenarios analyzed (as detailed in Appendix A). Each rectangular section of the curve represents the outcome of one of the analyzed scenarios, identified by the *ScrapRate* and *ReturnRate* values on the horizontal plane. These values indicate the scenario ID and correspond to the parameter values presented in Table 3The vertical axis shows the cost function value, while the plane's color indicates the impact function value, with greener colors representing lower environmental impact scenarios.

Analyzing the curve, the following observations can be made:

- Higher *ReturnRate* results in lower environmental impact but higher costs.
- Higher *ScrapRate* results in lower costs and greater environmental impact.
- Variations in the *ReturnRate* impact costs significantly more than equivalent variations in the *ScrapRate*, as evidenced by the differing slopes of the plane.
- Similarly, emissions are more affected by the *ReturnRate* levels than the *ScrapRate*.
  Across the sensitivity analysis domain, costs range from just over 200,000 to over 400,000 euros. This value represents the estimated total operational costs within the supply chain and the amortized annual share of investment costs.
- Emissions range from a minimum of approximately 1 million kg CO2 equivalent at the maximum cost value to about 3 million kg CO2 equivalent at the minimum cost value.

Regarding the relationship between costs and emissions, the following observations can be made:

- Overall, costs and emissions have an inversely proportional relationship. This means that the lowest emissions correspond to the highest cost values and vice versa.
- Within the analyzed domain, doubling the total operational costs results in a 67% reduction in emissions.

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Several considerations can be drawn regarding the reasons for this behavior. Economically optimizing a logistics network often leads to reduced environmental impacts since both objectives aim to minimize distances traveled. However, in this case, other factors play a significant role, outweighing the distribution-related factors. These factors pertain to the processing and handling operations of reusable packaging. Such activities are only present if the consumer returns the packaging. Otherwise, their cost and impact are neglected.

In a closed-loop reuse network, new actors facilitate the effective reuse of packaging, with their operations carrying a cost and an environmental impact. As *ReturnRate* increases, the use of sorting and washing facilities increases, consequently raising the overall logistical flow and impact of related operations. This additional impact of reusable packaging transportation, sorting, and washing evidently outweighs the cost savings from avoiding new packaging production, but suggests a lower environmental footprint of the overall system.

These results are influenced by multiple factors. Firstly, using average values can negatively impact the analysis because these values are based on real cases that have been scientifically quantified. Given that large-scale reuse systems, like the R3PACK one, are rare, the referenced cases are likely from prototype contexts or systems limited in geographical scope or managed quantity. Therefore, economies of scale and technological efficiencies typical of established systems are likely not present in these cases. It is reasonable to expect that if such a large-scale reuse system were implemented, optimizations and technological efficiencies in the sorting and washing processes would develop over time. These improvements (e.g., energy and water use reduction, higher throughput, new materials, and new technologies) would reduce both costs and environmental impacts per single-use cycle of the packaging, suggesting that the current cost observed is likely higher than what would be seen in a fully optimized, operational reuse network.

Furthermore, besides the nature of the actors' activities, logistics can also have a negative impact in the analyzed network. While the pool of available PP locations is already established in the non-reusable network, the positions of SO and W facilities have not been optimized for this project's purposes but chosen among industrial partners that must adapt their old business to the retailer distribution network. Thus, their locations may be logistically inconvenient.

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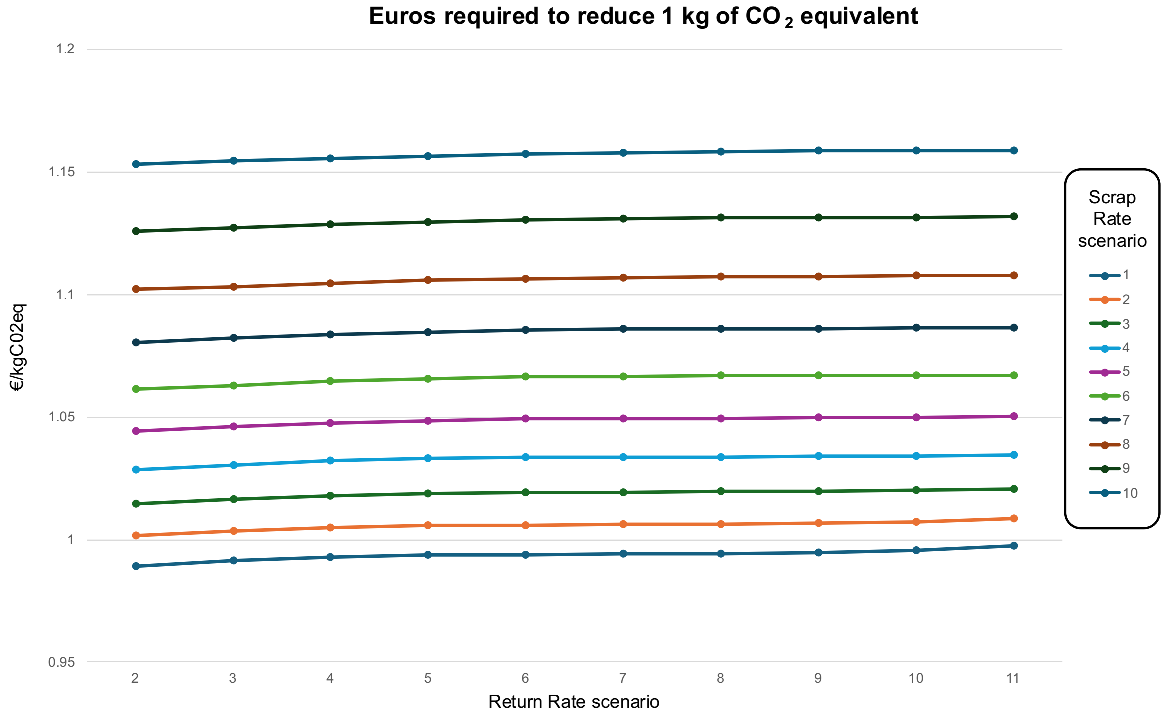

Figure 16 Incremental cost of environmental impact reduction

When examining the relationship between costs and environmental impacts, it is crucial to consider not only the absolute values of these functions but also the potential improvements relative to the baseline scenario. The baseline here is the scenario with no reuse (*ReturnRate* equal to 0%), which inherently carries a certain level of costs and impacts.

Figure 16 illustrates the cost in euros for each kilogram of CO2 saved compared to the baseline scenario of a 0% *ReturnRate* (Scenario 1). Starting from the costs and impacts of the 0% *ReturnRate* case, each line on the graph represents the cost in €/kgCO2eq saved for each subsequent scenario with *ReturnRates* greater than 0% and for each level of *ScrapRate*.

From the graph, it is evident that the cost per kilogram of CO2 saved does not vary significantly between different scenarios and is generally above 1€. However, it can be observed that reducing the *ScrapRate* has a more pronounced impact on the €/kgCO2eq saved than increasing the *ReturnRate*. This indicates that optimizing the network to ensure that packaging does not break, that it can be cleaned effectively, and developing more durable materials, yields a proportionally greater benefit than merely increasing the rate at which consumers return used packaging.

In conclusion, while the current analysis shows higher cost for higher *ReuseRate*, this should not discourage the adoption of reusable systems. Instead, it highlights the need for strategic planning in the reuse supply chain, especially regarding the positioning of new actors, such as sorting and washing facilities. Moreover, while both reducing the *ScrapRate* and increasing the *ReturnRate* contribute to reducing costs and environmental impacts, efforts focused on enhancing packaging durability and efficiency in the washing process have a more substantial effect in the cost of environmental impact reduction. This highlights the importance of technological advancements and logistical optimizations in achieving significant environmental benefits in reusable

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packaging systems. Over time, as technologies and processes improve and the network becomes more optimized, the operational costs are likely to decrease, making reusable packaging a more viable and sustainable option. The role of logistics in achieving these efficiencies is crucial, as suboptimal facility positioning can undermine efforts to improve the efficiency of the processes involved.

4.3 Network node utilization analysis

This section presents the decisions regarding the use of supply chain nodes by different network stakeholders under varying uncertainty parameters. For this analysis, eight reference scenarios have been selected from the tested scenarios. Specifically, the *ScrapRate* is evaluated at 5% and 15%, while the *ReturnRate* is examined at 0%, 40%, 70%, and 100%. In the following figures, the bubble size represents the flow amount managed by each node. Such flow has been evaluated as the number of packaging units.

Key observations include:

- Location Selection - The sites are chosen at central points where STs demand is most concentrated. The goal is to centralize flows, reducing the number of trips and distance traveled.
- PPs: Figure 17- As the return rate of packaging increases, the number of required sites decreases, which aligns with the model's expectations. For a 70% *ReturnRate*, as the *ScrapRate* increases from 5% to 15%, the number of necessary PPs also increases. This is consistent with the need to introduce more packaging into the network to compensate for higher *ScrapRates*.
- FPs: Figure 18 - Variations are minimal due to limited flexibility in location choice. The food product's nature and the plant's filling capacity drive the FP choices toward few alternatives. The decision to open a facility also depends on the locations chosen for washers in the reverse logistics chain.
- DCs: Figure 19 - Changes are minimal. DCs locations are optimized by retailers for logistics and transportation. Indeed, they are located near points of demand (STs). Consequently, their selection is not influenced by parameter variations.
- SOs: Figure 20 - No variations are observed for sorters. Strategic positions for SOs' facilities are determined for the whole French territory. Since SOs represent potential facilities yet to be built, there is no capacity constraint. Thus, the decision to open sorters is not influenced by the flow volume to be managed. The stability of chosen positions demonstrates the resilience of sorters to parameter variations, indicating that the positions identified are strategically optimized and logistically efficient.
- W: Figure 21- W are given a substantial capacity to simulate functional plants. With these given capacity constraints, no significant variations are noted.

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Figure 17 PPs' locations throughout different scenarios

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Figure 18 FPs' locations throughout different scenarios

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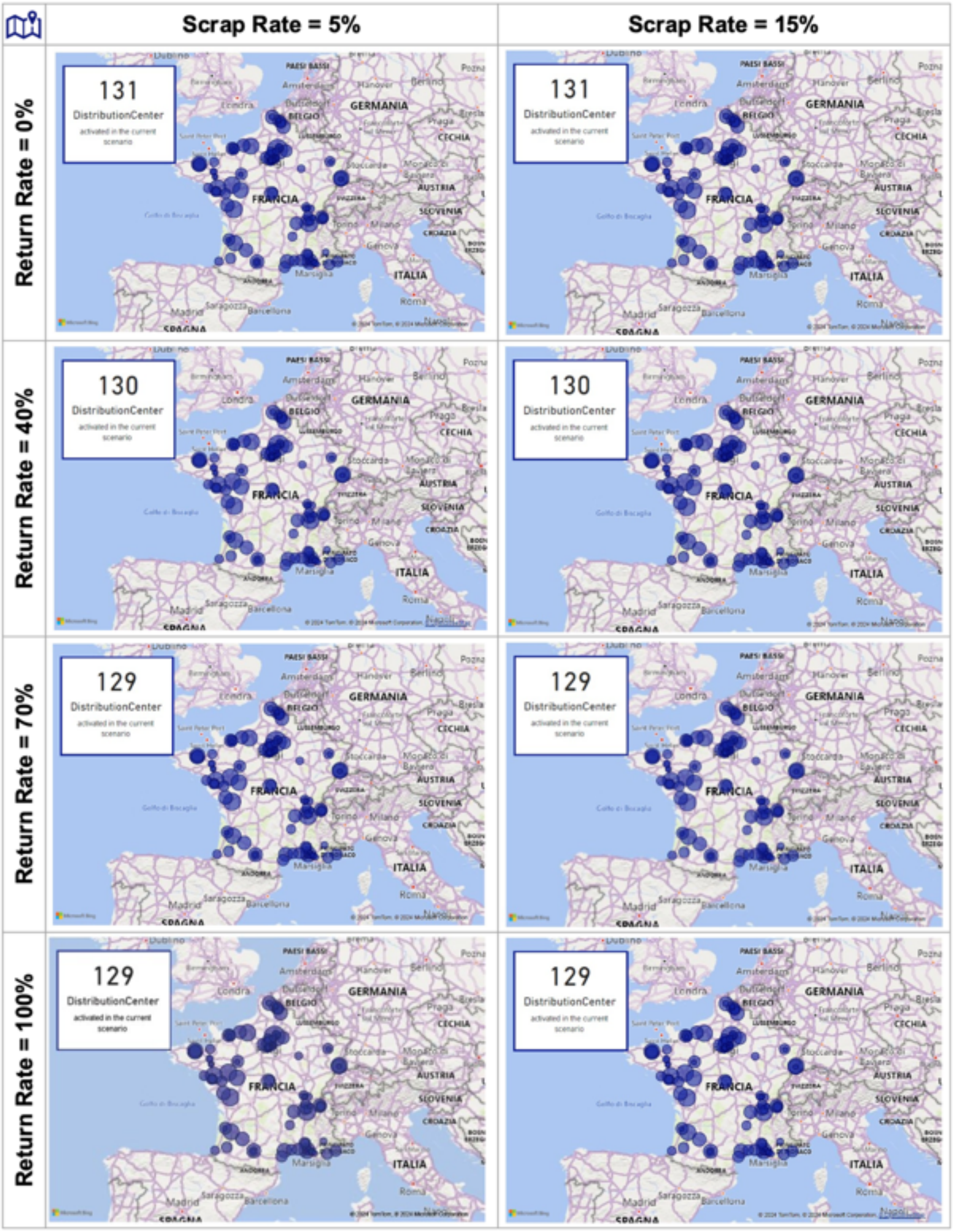

Figure 19 DCs' locations throughout different scenarios

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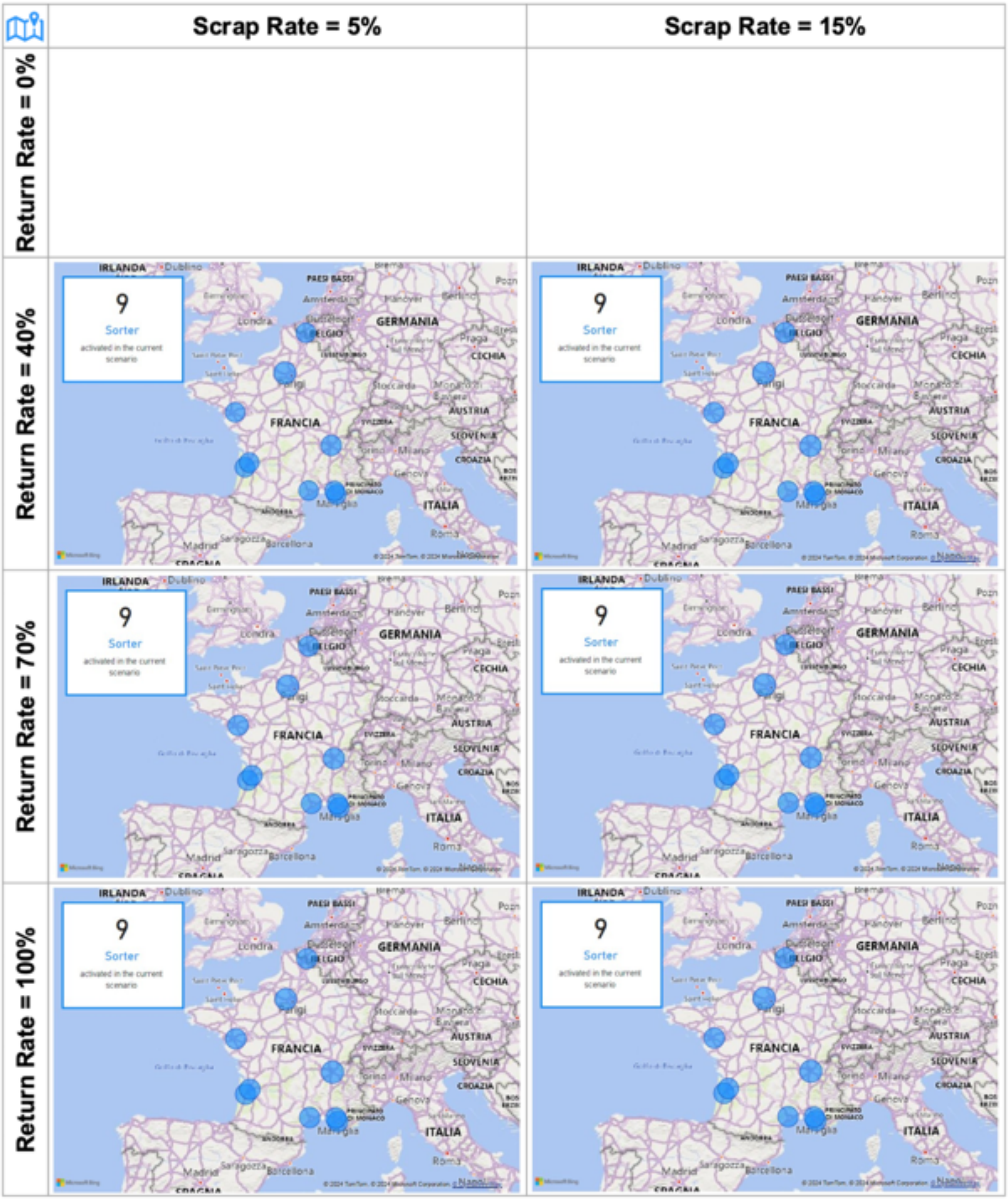

Figure 20 SOs' locations throughout different scenarios

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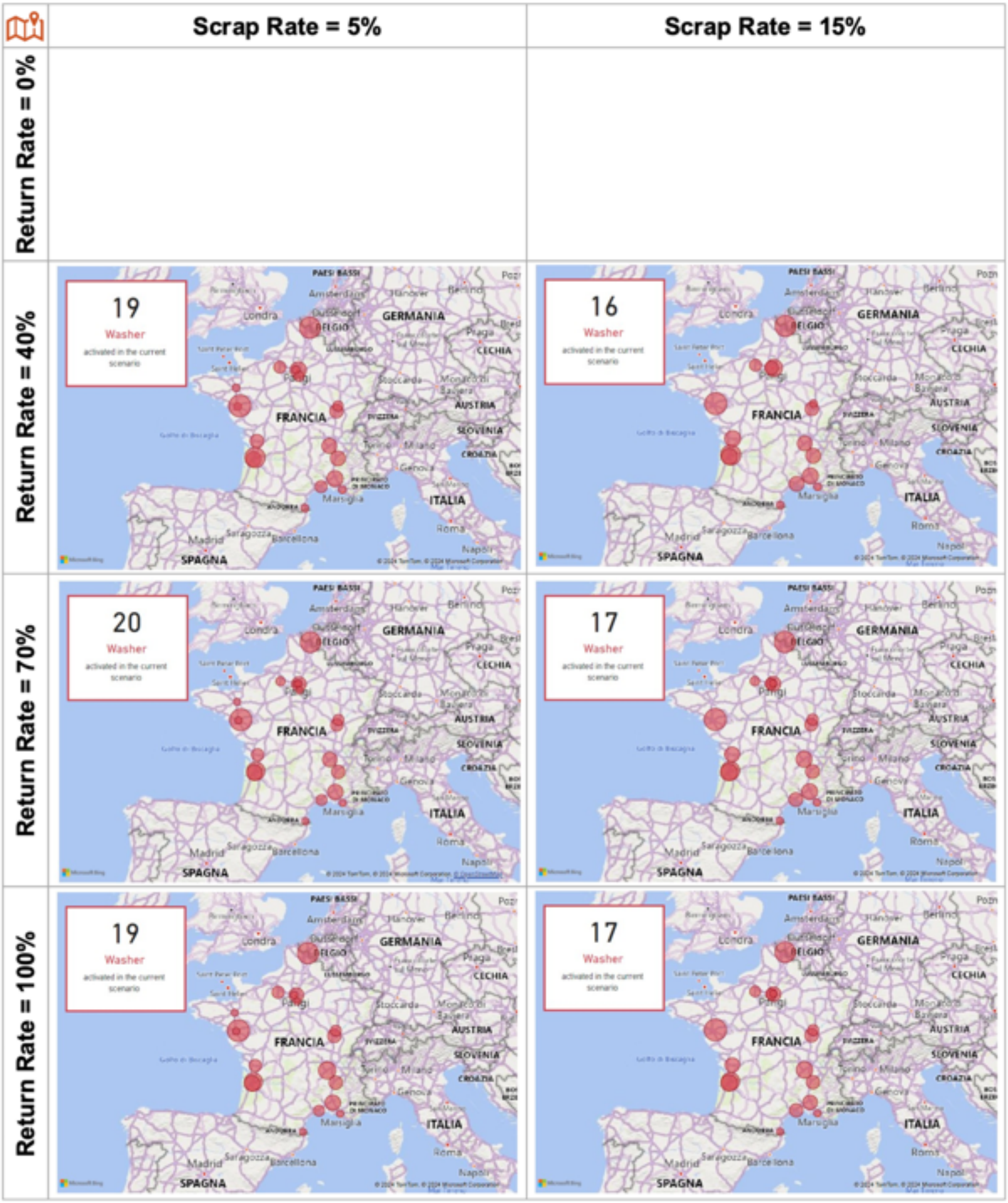

Figure 21 Ws' locations throughout different scenarios

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4.4 Impact of Sensitivity Parameters on Packaging Reuse and Return Patterns

The analysis presented in this section aims to evaluate the impacts of consumer choices on packaging management within the supply chain post-purchase. For each scenario examined, the model identifies the optimal consumer decisions that can enhance the efficiency of the entire supply chain. Specifically, this analysis examines the percentages of packaging that are recycled, returned to the original store of purchase, and returned to a different store, for each kind of packaging. Figure 22 outlines different scenario results.

Once the consumer buys a product with reusable packaging, its options are the following:

- Case 1: Packaging Not Returned - The packaging may be recycled, discarded by the consumer, or kept at home without being returned. This scenario is represented by the blue bars in the histogram.
- Case 2: Packaging Returned to the Same Store of Purchase - The packaging is brought back to the ST where the product was purchased. This scenario is represented by the orange bars in the histogram.
- Case 3: Packaging Returned to a Different Store - The packaging is returned to a store located within a 5 km radius of the original purchase store, and of the same brand. This scenario is represented by the yellow bars in the histogram.

Case 3 decision depends on the consumer's behavior and attitude. When the model assumes such a consumer behavior, it means such a tendency would be more economical for the entire supply chain. However, evaluating incentive systems to encourage this behavior is beyond the scope of this analysis.

By varying the *ReturnRate*, each scenario defines the percentages of packaging returned and not returned. The model can identify RVMs placed in strategic stores for the supply chain and suggest the quantity of packaging to be returned to a different ST from the one where it was purchased, aiming to optimize the supply chain.

From the overall sensitivity analysis conducted, it is observed that the *ScrapRate* does not influence the quantities managed in the various return scenarios. Therefore, the analysis was performed by fixing a *ScrapRate* value of 0%.

The histograms in Figure 22 illustrate the optimal decisions as the *ReturnRate* varies for each packaging (see Table 1 for product-packaging associations). For each type of packaging, the quantity expressed in pieces of packaging for each consumer alternative (Case 1, Case 2, or Case 3) is expressed in the y-axis. The varying total volumes among the different packaging are due to the varying overall demand for that packaging, which is linked to the demand volume of the associated product.
Some practical observations are the following:

- As expected, as the *ReturnRate* increases, the volume returned to the stores (whether the same as or different from the purchase store)

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increases, and the volume not returned by consumers decreases accordingly.

- The model favors returning to the same purchase store over a different one, thus suggesting the installation of an RVM in every store.
- If installing RVMs in every store was not possible, the stores chosen by consumers who purchased products elsewhere (yellow bars) represent efficient packaging collection points and should be prioritized for RVM installation. The map of such strategic locations is shown in Figure 23 (yellow dots for Coopérative U stores, green dots for Carrefour).

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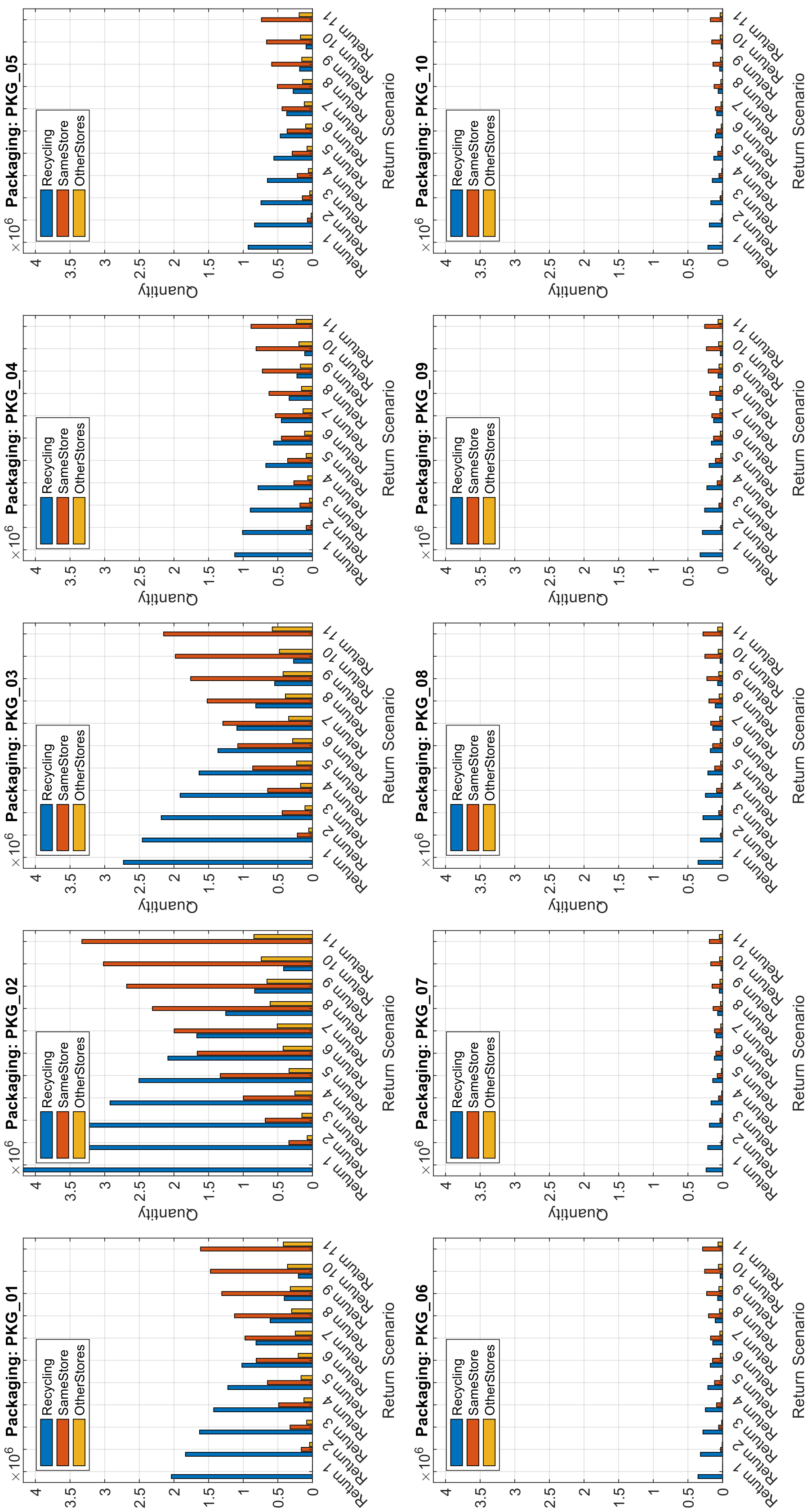

Figure 22 Return Patterns

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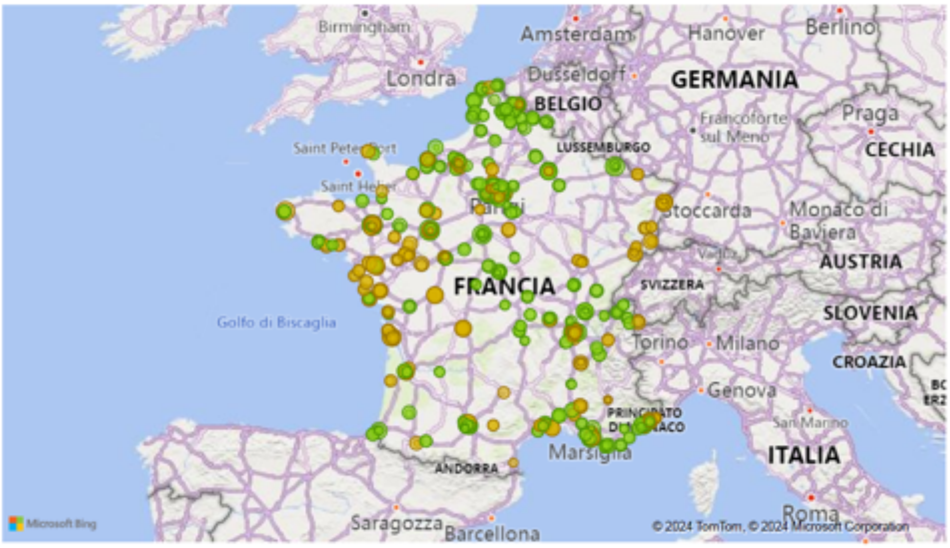

Figure 23 Strategic packaging collection points

4.5 Differential costs analysis

In this section, we examine how the costs within the supply chain vary based on different parameters analyzed in the sensitivity analysis. The goal is to understand the impact of varying *ReturnRates* and *ScrapRates* on the differential costs introduced by implementing reusable packaging. By comparing several scenarios, we aim to highlight the cost implications of transitioning from a non-reusable to a reusable packaging system. This analysis provides valuable insights into which factors most significantly affect cost efficiency and helps identify areas for potential optimization.

The graph in Figure 24 evaluates the variation in supply chain costs as the parameters analyzed in the sensitivity analysis change. Specifically, the graph illustrates scenarios identified by the matrix header in the image, which include *ReturnRates* of 0%, 40%, 70%, and 100%, and *ScrapRates* of 5% and 15%. These scenarios were selected as examples, summarizing the supply chain's cost behavior.

The costs analyzed here do not represent the total costs incurred but rather the differential costs compared to the case of non-reusable packaging. Therefore, the included costs are those for the production of the packaging (PP), the installation of RVMs at points of demand (ST), the washing and sanitization costs of reusable packaging (W), and the sorting operations costs (SO). The costs related to DCs and FPs were excluded as they are assumed as not differential compared to the disposable packaging scenario.

To evaluate the reusable packaging alternative against non-reusable packaging, the costs described here should be compared to the differential costs in the case of non-reusable packaging. These costs consist only of the procurement of virgin or secondary raw materials for the packaging material, the production of primary packaging, and the disposal costs of the packaging once discarded.

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Each cell of Figure 24 represents a scenario containing two pie charts. The top pie chart shows the breakdown of operational costs by node type. The bottom chart represents the breakdown of transportation costs by route type (PP-FP, FP-DC, DC-ST, ST-SO, SO-W, W-FP). From the analysis of these charts, the following observations can be made:

- Scenario with 0% *ReturnRate*: in this case, the only differential costs are borne by the PP, as the reverse supply chain is not present. Consequently, transportation costs are quantified only for the direct supply chain routes.
- Increasing *ReturnRate*: As the *ReturnRate* increases, there is a significant reduction in PP costs since the production of new packaging is replaced by returned packaging. Simultaneously, costs for actors involved in the reverse supply chain, particularly W and SO, increase.
- RVM installation Costs: The cost of installing RVMs accounts for about 5-6% of the total differential operational costs. Although this cost item has a directly proportional relationship with the *ReturnRate*, its increase with rising *ReturnRate* is not particularly impactful on the total differential costs. This is because, with adjustments made to the frequency of emptying the RVMs, a single or few RVMs can be installed in each ST.
- Transportation Costs: The most impactful cost segment in terms of transportation is the ST-SO route. This is due to the significantly higher number of STs compared to SOs, leading to centralization at SOs with longer travel distances. The second most impactful segment is the FP-DC route, as there is limited flexibility in the placement of logistic nodes, with each FP managing specific food products and having capacity constraints. Consistent with the distance analysis, the most optimized part of the supply chain is the DC-ST segment. Despite a high number of STs, DCs are strategically located near STs, optimizing the logistics chain.
- Impact of Parameter Variation: The distribution of transportation costs does not change significantly with parameter variation. Specifically, as the *ScrapRate* increases, costs for the ST-SO route slightly decrease, while costs for the FP-DC route increase, balancing the overall network optimization.

For each scenario, the costs represented and quantified in the figure represent the optimal supply chain configuration. The model aims to optimize the costs of the entire supply chain. Consequently, if a particular cost item is notably high in some scenarios, it indicates that synergies and balancing with other areas of the supply chain lead to an overall reduction of costs.

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Figure 24 Differential costs analysis

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5. CONCLUSIONS

This report provides a thorough examination of the impacts associated with the adoption of reusable packaging systems in the food sector, focusing on both logistical efficiency and environmental sustainability. Our analysis reveals that the effectiveness of these systems is significantly influenced by the *ReturnRate* and *ScrapRate* of the packaging.

A key finding is the crucial role that *ReturnRate* plays in determining the overall efficiency and sustainability of reusable packaging networks. Higher *ReturnRate* generally leads to reduced environmental impacts and packaging production costs, but increased operational costs, as more packaging is reused rather than disposed of. Indeed, achieving higher *ReturnRates* requires substantial investment in SO and W facilities. This balance underscores the need for careful management of logistics and infrastructure to fully capitalize on the environmental benefits of increased reuse rates.

The *ScrapRate* also has a substantial impact on both cost and environmental performance. A higher *ScrapRate* results in lower costs but higher environmental impacts due to the need for additional packaging production and disposal. However, waste reduction from both the consumer and supply chain sides is thus essential to minimize economic and environmental burdens, highlighting the importance of optimizing packaging lifecycle management as well as consumer awareness.

Our investigation into logistical efficiency highlights a trade-off between cost and environmental impact. Higher *ReturnRate* can lead to lower environmental impacts but may increase operational costs due to the complexities involved. On the other hand, lower *ReturnRate* tends to reduce operational costs but results in higher environmental impacts due to increased production of new packaging. This trade-off emphasizes the need for a balanced approach to managing costs and environmental goals.

In terms of recommendations, it is evident that strategic placement of SO and W facilities is crucial for reducing transportation distances and associated costs. Investing in technologies that improve packaging durability and washing efficiency will also be vital for minimizing both costs and environmental impacts. Additionally, encouraging higher *ReturnRates* through incentives and better placement of RVMs can lead to significant improvements in sustainability and cost-effectiveness.

Looking forward, it is clear that ongoing research and optimization are essential for enhancing the efficiency and sustainability of reusable packaging systems. As technology evolves and processes improve, the benefits of these systems are expected to increase. Future studies should focus on refining environmental impact metrics, exploring technological advancements, and evaluating the long-term benefits of reusable packaging to support a more sustainable circular economy.

In conclusion, transitioning to reusable packaging systems presents both challenges and opportunities. While the shift requires careful planning and investment, it offers substantial benefits in terms of environmental sustainability and resource efficiency. By addressing the key factors identified and pursuing continuous improvement, we can enhance the effectiveness of reusable packaging systems and contribute to a more sustainable future.

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APPENDIX A: Complete list of optimized scenarios

Table 6 List of all the optimized scenarios in the sensitivity analysis

Scenario	Return_Scenario	ReturnRate	ScrapRate_Scenario	ScrapRate
s1_r1	1	0	1	0.05
s2_r1	2	0.1	1	0.05
s3_r1	3	0.2	1	0.05
s4_r1	4	0.3	1	0.05
s5_r1	5	0.4	1	0.05
s6_r1	6	0.5	1	0.05
s7_r1	7	0.6	1	0.05
s8_r1	8	0.7	1	0.05
s9_r1	9	0.8	1	0.05
s10_r1	10	0.9	1	0.05
s11_r1	11	1	1	0.05
s1_r2	1	0	2	0.1
s2_r2	2	0.1	2	0.1
s3_r2	3	0.2	2	0.1
s4_r2	4	0.3	2	0.1
s5_r2	5	0.4	2	0.1
s6_r2	6	0.5	2	0.1
s7_r2	7	0.6	2	0.1
s8_r2	8	0.7	2	0.1
s9_r2	9	0.8	2	0.1
s10_r2	10	0.9	2	0.1
s11_r2	11	1	2	0.1
s1_r3	1	0	3	0.15
s2_r3	2	0.1	3	0.15
s3_r3	3	0.2	3	0.15
s4_r3	4	0.3	3	0.15
s5_r3	5	0.4	3	0.15
s6_r3	6	0.5	3	0.15
s7_r3	7	0.6	3	0.15
s8_r3	8	0.7	3	0.15
s9_r3	9	0.8	3	0.15
s10_r3	10	0.9	3	0.15
s11_r3	11	1	3	0.15
s1_r4	1	0	4	0.2
s2_r4	2	0.1	4	0.2
s3_r4	3	0.2	4	0.2
s4_r4	4	0.3	4	0.2
s5_r4	5	0.4	4	0.2
s6_r4	6	0.5	4	0.2
s7_r4	7	0.6	4	0.2
s8_r4	8	0.7	4	0.2
s9_r4	9	0.8	4	0.2
s10_r4	10	0.9	4	0.2
s11_r4	11	1	4	0.2
s1_r5	1	0	5	0.25
s2_r5	2	0.1	5	0.25
s3_r5	3	0.2	5	0.25
s4_r5	4	0.3	5	0.25
s5_r5	5	0.4	5	0.25
s6_r5	6	0.5	5	0.25
s7_r5	7	0.6	5	0.25
s8_r5	8	0.7	5	0.25
s9_r5	9	0.8	5	0.25
s10_r5	10	0.9	5	0.25
s11_r5	11	1	5	0.25
s1_r6	1	0	6	0.3
s2_r6	2	0.1	6	0.3
s3_r6	3	0.2	6	0.3
s4_r6	4	0.3	6	0.3
s5_r6	5	0.4	6	0.3
s6_r6	6	0.5	6	0.3
s7_r6	7	0.6	6	0.3
s8_r6	8	0.7	6	0.3

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s9_r6	9	0.8	6	0.3
s10_r6	10	0.9	6	0.3
s11_r6	11	1	6	0.3
s1_r7	1	0	7	0.35
s2_r7	2	0.1	7	0.35
s3_r7	3	0.2	7	0.35
s4_r7	4	0.3	7	0.35
s5_r7	5	0.4	7	0.35
s6_r7	6	0.5	7	0.35
s7_r7	7	0.6	7	0.35
s8_r7	8	0.7	7	0.35
s9_r7	9	0.8	7	0.35
s10_r7	10	0.9	7	0.35
s11_r7	11	1	7	0.35
s1_r8	1	0	8	0.4
s2_r8	2	0.1	8	0.4
s3_r8	3	0.2	8	0.4
s4_r8	4	0.3	8	0.4
s5_r8	5	0.4	8	0.4
s6_r8	6	0.5	8	0.4
s7_r8	7	0.6	8	0.4
s8_r8	8	0.7	8	0.4
s9_r8	9	0.8	8	0.4
s10_r8	10	0.9	8	0.4
s11_r8	11	1	8	0.4
s1_r9	1	0	9	0.45
s2_r9	2	0.1	9	0.45
s3_r9	3	0.2	9	0.45
s4_r9	4	0.3	9	0.45
s5_r9	5	0.4	9	0.45
s6_r9	6	0.5	9	0.45
s7_r9	7	0.6	9	0.45
s8_r9	8	0.7	9	0.45
s9_r9	9	0.8	9	0.45
s10_r9	10	0.9	9	0.45
s11_r9	11	1	9	0.45
s1_r10	1	0	10	0.5
s2_r10	2	0.1	10	0.5
s3_r10	3	0.2	10	0.5
s4_r10	4	0.3	10	0.5
s5_r10	5	0.4	10	0.5
s6_r10	6	0.5	10	0.5
s7_r10	7	0.6	10	0.5
s8_r10	8	0.7	10	0.5
s9_r10	9	0.8	10	0.5
s10_r10	10	0.9	10	0.5
s11_r10	11	1	10	0.5
s1_r11	1	0	11	0.55
s2_r11	2	0.1	11	0.55
s3_r11	3	0.2	11	0.55
s4_r11	4	0.3	11	0.55
s5_r11	5	0.4	11	0.55
s6_r11	6	0.5	11	0.55
s7_r11	7	0.6	11	0.55
s8_r11	8	0.7	11	0.55
s9_r11	9	0.8	11	0.55
s10_r11	10	0.9	11	0.55
s11_r11	11	1	11	0.55

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APPENDIX B: Distances PDF of the overall network

In the following graphs the cumulated PDFs of the travelled distances of the overall network are presented. Refer to Table 4 for the four cases levels of *ReturnRate* and *ReuseRate*.

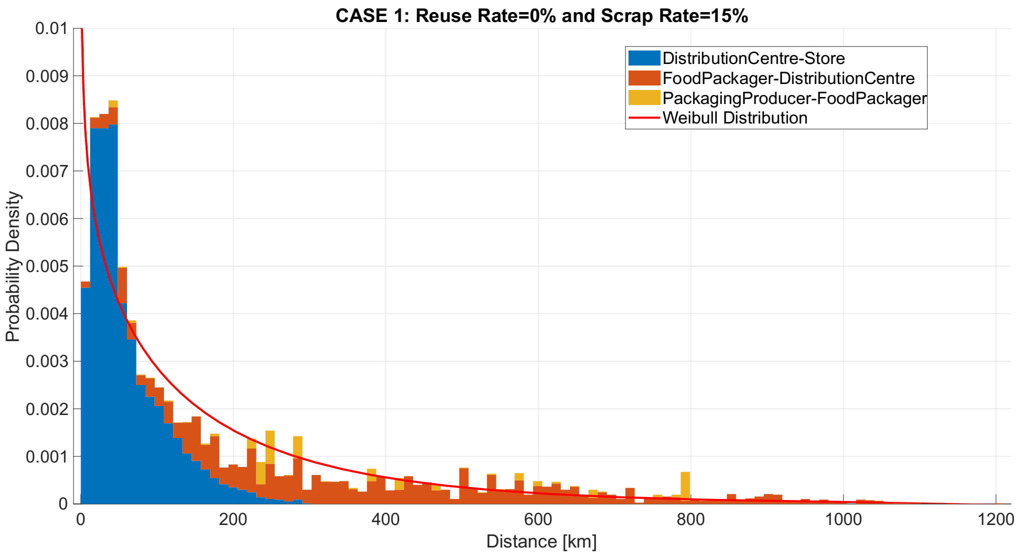

Figure 23 Distances PDF of the overall network - CASE 1

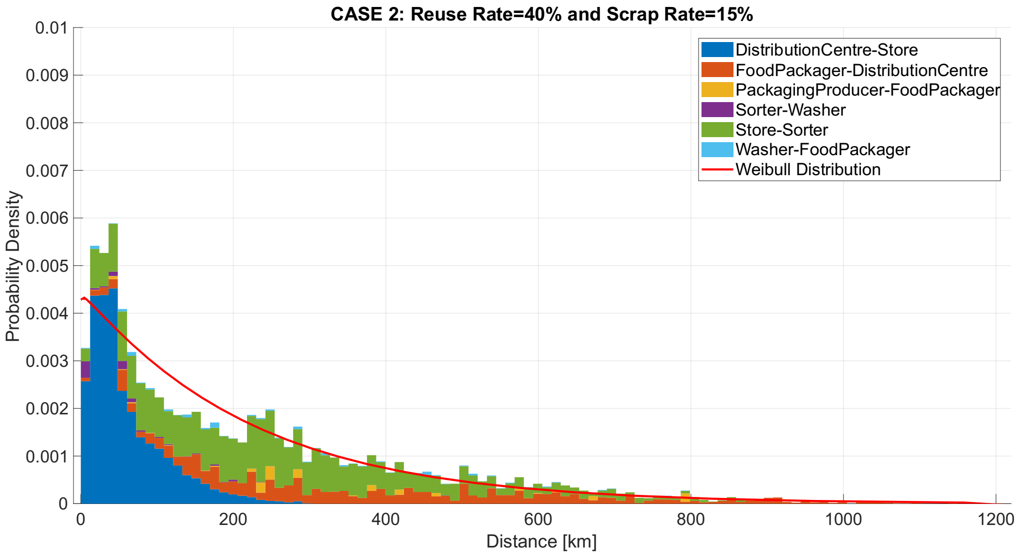

Figure 24 Distances PDF of the overall network-CASE 2

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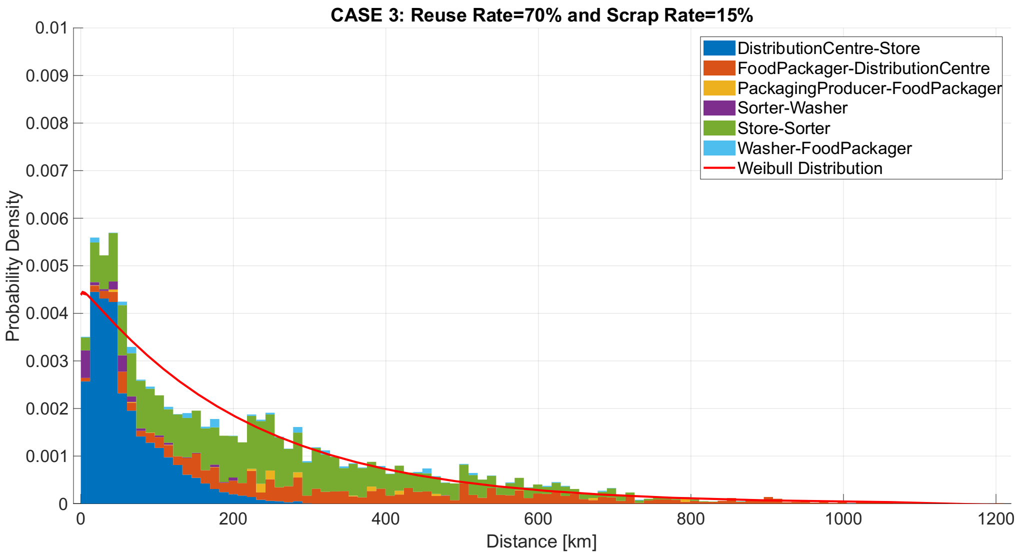

Figure 25 Distances PDF of the overall network CASE 3

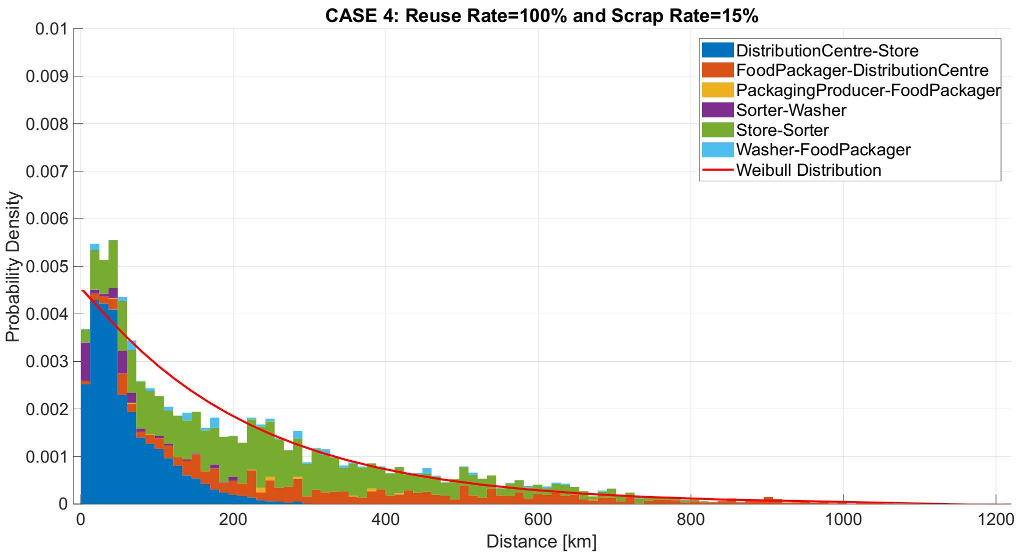

Figure 26 Distances PDF of the overall network CASE 4

Table 7 contains the statistical features of such PDFs.

Table 7 Main statistical features of the analyzed network scenarios: Scale Factor and Shape Factor relates to the extrapolated Weibull distribution. Mean, Variance and Median values are evaluated over the real data points distributions

Case ID	Scale Factor	Shape Factor	Mean	Variance	Median
Case 1	169.703	0.849	184.773	47784.480	110.203
Case 2	220.544	1.009	219.689	47374.978	153.389
Case 3	214.572	1.010	213.713	44805.775	149.252
Case 4	215.628	1.006	215.121	45761.347	149.769

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