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Augmented spatial LCA for comparing reusable and recyclable food packaging containers networks

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Abstract

Despite the benefits of reducing virgin plastic polymers in food packaging, the spread of reusable systems is limited by organizational and economic constraints, and reasonable doubts about their real environmental impacts still persist. Several studies have evaluated the environmental sustainability of reusable plastic containers (RPCs) compared to single-use systems; however, the trade-offs and benefits of reuse are not always clear. To model real-world network complexity with its bottlenecks and unbalanced infrastructural networks, primary data on travelled distances and flows collected throughout the logistics network must be included in the analysis. The material-driven characterization of the secondary package's logistic networks justifies the integration of Geographic Information Systems into LCA to overcome the limitations of using only secondary data, which is commonly done. This study evaluated alternative secondary packaging systems (SPSs) and associated material-driven networks using a spatial LCA approach augmented with a supply chain digital twin. The material-driven network flows were virtualized, and the resulting data on transportation emissions and fuel consumption represent the LCA input. The networks serve a countrywide FSC from growers to retailers, with up to 1600 nodes located in Italy over a 10-year time span. In this study, the LCEI of nine alternative SPSs differing in size and material-driven network, that is, reusable polypropylene (PP) crates, single-use corrugated cardboard boxes (CCBs), and single-use PP crates, were investigated. The novel contributions of the study lie in the *method*, *scale* of analysis, and *accuracy* of spatial data collection. The results show that the higher transportation emissions of RPCs (+23.80% compared with that of CCBs) are balanced by the reduced production and disposal impacts per use. After 10 years, the environmental impacts of the single-use SPSs are higher than those of the RPC SPSs in all the impact categories evaluated. Considering GWP_{20}, the RPCs are environmentally friendly after only 15 rotations. This study demonstrates the sensitivity of LCA results to transport parameters and highlights the importance of adopting supply chain digital twins to enhance the accuracy of the environmental profile of such complex logistic ecosystems.

Keywords: Life cycle assessment (LCA), Food packaging, Retailer distribution, Logistic networks, Reusable Plastic Crates (RPCs), Digital twin

1. Introduction

Global warming is today's *elephant in the room*. Ignoring the problem will permanently change the state of natural and anthropogenic ecosystems (Leisner, 2020; Godde et al., 2021). Researchers, practitioners, and policymakers must provide solutions that consider the industrial sectors that mainly affect climate change. Considering their demand volume and flow along with the impact of production and distribution processes, the food industry is a major contributor to climate change (Campbell et al., 2018). Owing to their crucial role in protecting and handling food throughout supply chain (SC) operations, packaging and containers are unavoidable despite being important environmental stressors and sources of waste (Gallego-Schmid et al., 2018).

Pathways exist to reduce such impacts and reusable packaging networks can provide timely answers (Sundqvist-Andberg and Åkerman, 2021). Regardless of the benefit of lowering virgin plastic polymers in food packaging, the spread of reusable systems is limited by organizational and economic issues (Greenwood et al., 2021) and reasonable doubts about their real environmental impacts still endure (Ertz et al., 2017). Remarkably, the impacts of the reverse logistics of reusable containers are under the lens of scholars, SC players, and policymakers, and the transportation phase might be up to tip the balance (Mahmoudi and Parviziomran, 2020). When comparing the environmental impacts of reusable and single-use packaging systems in the food supply chain (FSC), the trade-off between decreasing virgin materials and minimizing the backhauls of containers is ambiguous (Otto et al., 2021). Although packaging reuse is a fair strategy to prevent waste (Ross and Evans, 2003; Salhoder et al., 2008), the image becomes blurred in the FSC, and further assessment of transportation, handling, and washing processes is mandatory (Rigamonti et al., 2019). Countrywide regulations impose virgin material and tight washing standards to avoid microplastic leakage and microbial contamination and prevent early spoilage of food products (Matthews et al., 2021; Segura-Domingo et al., 2021; Jadhav et al., 2021). Together, these considerations underlie the environmental assessment of alternative packaging systems and logistic networks, aiding evidence-based decision making (Coelho et al., 2020).

Previous studies have evaluated the environmental preference of reusable plastic containers (RPCs) compared to single-use recyclable systems (Camps-Posino et al., 2021). In an FSC, the benefits of reuse are not always clear. Table 1 summarizes the main contributions to the secondary container LCA literature. Singh et al. (2006) and Albrecht et al. (2013) concluded that RPCs are generally preferable to Corrugated Cardboard Boxes (CCBs). Furthermore, Albrecht et al. (2013) discussed the impact of disposable wooden boxes, which perform almost like RPCs and better than CCBs in all impact categories. Levi et al. (2011) focused on the distribution of fresh fruits and vegetables and observed that the RPC system generally results in an environmentally preferable travel distance of less than 1200 km. This analysis highlights the sensitivity of the environmental impact of a packaging system to the transportation phase. Similarly, Koskela et al. (2014) argued that the impact of CCBs can be lower than that of RPCs used in bread deliveries in Finland.

	Containers type				Scenarios parameters						Logistics' leverage			
Author, Year	RPC	PPC	CCB	DWB	Time span	System's boundaries	FU	Mid-point End-point	LCIA method	Network	Raw material extraction-production plant	Production plant - FSC's actors	FSC's actors – poolers' facilities (Only for RPCs)	EOL logistics
Singh et al., 2006	x		x		2 years	C2C	1000 [t] of product	TGG, TSW, TEn	IPCC report	USA	COS	COS	COS	NC
Levi et al., 2011	x		x		10 years	C2G	100 [kg] of product	GWP, ODP, AP, EP, PE-NR, POCP	EPD guideline	EU	NC	GPS	NC	NC
Albrecht et al., 2013	x		x	x	10 years	C2G	15 [kg] of product	ADP, PED, EP, AP, POCP	CML 2002	EU	GPS	GPS	COS	NC
Koskela et al., 2014	x		x		2 years	C2G	8 units of product	CC, TA, POCP, FE, FD, PM	ReCiPe	EU	COS	COS	NC	NC
Tua et al., 2019	x				2 years	C2G	1200 [kg] of product	CC, ODP, HTP, PM, POCP, AP, TE, FE, ME, CED, RD, WD	ILCD, CED	Italy	NC	GPS	NC	NC
Abejón et al., 2020	x		x		10 years	C2G	$[6.6 – 10]*10^6$ crate's fillings	PE, PE-R, PE-NR, GWP, ODP, AP, EP, POCP	Impact 2002+, CML 2002	Spain	COS	GPS	COS	COS
Franklin Associates, 2016	x		x		\	C2G	1000 [tons] of perishable products	PED, GWP, ODP, WD, AP, EP, POCP, TSW	TRACI 2.1	North America	COS (P only for RPC)	COS (P only for RPC)	COS (P only for RPC)	COS (P only for RPC)
This paper	x	x	x		10 years	C2G	1579.22 dm3	ADP, AP, EP, FAETP, FSE, GWP, HTP, LC, MAETP, MSETP, ODP, POCP, TETP	ReCiPe	Italy	P	P	P	P

Table 1. State of the art on RCPs' LCA (Abbreviations: C2C: Cradle to Cradle; C2G: Cradle to Grave; NC: Not Considered; GPS: General Purpose Secondary data; COS: Case Oriented Secondary data; P: Primary data; TGG: Total Greenhouse Gas; TSW: Total Solid Waste; Ten: Total Energy; ODP: Ozone Depletion Potential; AP: Acidification Potential; EP: Eutrophication Potential; PE-NR: Use of Primary Non-Renewable Energy; ADP: Abiotic Resource Depletion Potential; PED: Primary Energy Demand; POCP: Photochemical Oxidant Creation Potential (or Photochemical Ozone Formation); CC: Climate Change; TA: Terrestrial Acidification; PM: Particulate matter; FD: Fossil depletion; HT: Human toxicity potential; TE: Terrestrial Eutrophication; FE: Freshwater eutrophication; ME: Marine eutrophication; CED: Cumulative Energy Demand; RD: mineral, fossil and renewables resources depletion; WD: water resource depletion; PE: Use of Primary Energy; PE-R: Use of Primary Renewable Energy; GWP: Global Warming Potential; FAETP: Freshwater aquatic ecotoxicity; FSE: Freshwater sediment ecotoxicity; LC: Land competition (or Land Use); MAETP: Marine aquatic ecotoxicity; MSETP: Marine sediment ecotoxicity; TETP: Terrestrial ecotoxicity)

In contrast, Abejón et al. (2020), found a strong preference for RPCs compared to CCBs in the distribution of fruits and vegetables in Spain under a multi-scenario analysis, in which the percentage of virgin materials, number of rotations, and breakage index were varied. Tua et al. (2019) quantified the carbon footprint on the RPCs only, considering the role of the pooler (i.e., RPC's network manager) and overviewing the reconditioning phase. Given the literature findings, little is left to say on this topic. Nevertheless, the often misleading and incoherent results of the comparisons may be the result of various assumptions, such as crates' payload, the type of manufacturing material, the EOL treatment, and the transport distances. The last four columns of Table 1 demonstrate how logistics is considered in the LCA analysis, specifically, how logistical distances are taken into account at every phase of the container's life cycle. Distances are not always considered in the evaluation (NC), leading to a rough logistics impact assessment. However, when included, traveling is always accounted with the single average distance resulting from the network configuration (Accorsi et al., 2014). Such distance can either be gathered as general-purpose secondary (GPS) data or as case-oriented secondary (COS) data. The former adopts the same generic distance of typical transportation processes for all the packaging systems; the latter assumes a different average value for each packaging system.

LCA analysis is a widely used and well-established general-purpose method among scientists and practitioners (Torres Pineda et al., 2021), standardized by numerous regulations (ISO 14040, 2006; ISO 14044, 2006). Logistics is undoubtedly a crucial dimension of LCA application (Koskela et al., 2014), but is addressed in general terms, as shown in Table 1. In a recent survey, Vidergar et al. (2021) highlighted the added value of high-quality primary data (P) to provide LCA analysis, and the need to overcome their measurement difficulties in evaluating real-world scenarios. To model real-world network complexity with bottlenecks and unbalanced infrastructural networks, the analysis must include primary data on travel distances and flows collected throughout the logistics network. LCA experts *need to re-think and improve their methodological approaches* to recognize *high-quality primary data importance* (Vidergar et al., 2021).

Some attempts have been made to fill the gaps in logistics impact assessment in the LCA methodology through geographic information system (GIS) data integration (Gasol et al. 2011), providing primary data-driven hybrid methods (Dresen and Jandewerth, 2012). Integration of spatial analyses into LCA: calculating GHG emissions using geoinformation systems. International Journal of Life Cycle Assessment. 17. 1094-1103. 10.1007/s11367-011-0378-3. Some authors have recognized the primary data value in LCA for sustainable SC planning (Hiloidhari et al. 2017), and risk evaluation (Khoo et al. 2019). The application of LCA to food packaging solutions requires a more in-depth analysis of the logistics aspects for different reasons. First, (1) the transportation of high-perishable products compels reactive FSC operations that can satisfy tight standards in quality and delivery windows. Secondly, (2) the study of alternative packaging systems amplifies the role of logistics in handling and protecting services, and (3) the topology of different networks must be considered.

Real-world package logistic networks differ according to the container characteristics. Indeed, the packaging material greatly affects the raw material supply, production stage, and EOL treatments. However, reusable containers require reverse logistics to increase the overall network complexity. The need to collect, wash, repair, and supply RPCs compels new facilities to manage such operations and flows. Therefore, the specific spatial and temporal dimensions of network logistics are not negligible in LCA analysis.

This study provides a comparison of the environmental impacts of alternative container systems for food products in the retailer FSC using an augmented spatial LCA methodology (Hiloidhari et al. 2017). The alternatives include different logistic networks, materials, sizes, payloads, and end-of-life (EOL) strategies. To provide a holistic case-oriented comparison, this study focuses on a countrywide FSC using alternative secondary packaging systems (SPS), which are made of a crate size and a material-driven network. The life cycle environmental impacts (LCEI) of three alternative material-driven packaging networks (i.e., reusable polypropylene polymer (PP) plastic crates, corrugated cardboard (CC) boxes, and disposable and recyclable PP plastic crates networks) are performed, considering three different sizes (i.e., 3416, 6410, 6416). The functional unit (FU) is assumed to be a fully loaded pallet of 6410 RPCs distributed to growers to retailers over a horizon of 10 years (time span) throughout a country-wide retailer FSC. The novel contributions of this study lie in the following aspects, mainly concerning the type of data used (i.e., primary) and the methodological approach to face real-world models. In the analysis, we tracked (1) the crates' flow throughout the networks, considering the tasks and operations within and across the facilities of networks comprising thousands of nodes. The records gathered from the companies' Enterprise Resource Planning (ERP) are mined to feed a tailored database aiding

LCA (Baruffaldi et al., 2019). To augment the resolution of spatial information, the logistic flows of containers, food, and auxiliary materials are virtualized using an SC digital twin reading the database and incorporating GIS and routing features (Accorsi et al., 2018). This study considered primary data instead of averages (2), mainly for the transportation phase, where each shipment's actual payload, utilization rate, and route vary. The gathered data also included (3) the *packaging hierarchy* (i.e., the combination of secondary and tertiary packages) of transported food and auxiliary materials to take into account the contribution of the packaging layers to the food weight and volume in the FU. The *scale*, *accuracy*, and *logistics lens* undertaken in the spatial LCA are the novel contributions of this study, which naturally benefited from the cooperation with leading packaging companies in Italy, fruit and vegetable growers consortiums, and retailers operating countrywide. These results are intended for policymakers and practitioners. The former might introduce taxes to deter the most polluting packaging systems and sizes, or encourage the introduction of new players, improving the network's infrastructure configuration toward lower impacts. The latter might exploit tailored package configurations considering real-world network topology and facility locations. The illustrated approach, together with primary data, allows for the measurement and comparison of the impact assessment of existing network configurations. Practitioners can then ascertain improved solutions for sustainability management of food packaging.

2. Methods and materials

This study compared the LCEI of nine different SPSs for fresh food distribution from growers to retailers. Such systems differ in the materials of the crates and the associated material-driven network, size, payload, and EOL strategy. The FSC network's logistics and infrastructure (i.e., facility locations) involving growers, raw materials suppliers, package producers, and retailers, play a pivotal role in the LCEI (Ellsworth-Krebs et al., 2022). Reusable containers are sensitive to transportation (Koskela et al., 2014). This study investigates the environmental sustainability of alternative SPSs using a spatial LCA approach augmented with a transportation digital twin. The material-driven characterization of logistic networks justifies the integration of GIS into LCA to overcome the limitations of conventional GPS and COS data collection commonly used in LCA analyses (Hiloidhari et al., 2017). The benefits of GIS have already been proven by Gasol et al. (2011) while tallying the impact reduction in GWP of energy crop implementation on a local scale. Khoo et al. (2019) explored the application of a combined LCA and SC approach using GIS to increase the resolution of spatial and location datasets. Dressen and Janderwerth (2012), who stated that spatial analyses in LCA are rarely conducted, used geodata on biomass potentials and infrastructure to calculate balances of emissions within a geographic region. Although GIS successfully provides spatial information over a geographic area, such as facility locations, it has rarely been applied to gathering primary data on transportation. Indeed, the number of shipments performed throughout broad countrywide networks prevents the adoption of real-time tracking systems. Therefore, virtualization of each node-by-node shipment over time is necessary. The proposed approach for LCEI assessment was then augmented by an SC digital twin capable of virtualizing and simulating such transportation flows across alternative material-driven networks.

In this study, an augmented spatial LCA evaluates alternative SPSs and the associated material-driven networks serving a countrywide FSC from growers to retailers, counting up to 1600 nodes located in Italy over a 10-year time span. Fig. 1 illustrates the steps of the adopted method: FSC actors (i.e., growers, packagers, retailers, and distribution centers) are traced back from retailer demand to growers. SPSs actors (i.e., raw material suppliers, package makers, EOL crate collectors, and recyclers) and flows are mapped from the raw material supply to EOL. The obtained primary data are stored in a database, that is, *Primary Data Database*. For each SPS, the demand was normalized according to the FU definition. This demand triggers SPS production in a material-driven network. The *Supply Chain Digital Twin* is fed with the node location and FUs demand for each SPS. All the flows of the material-driven network were virtualized to simulate all stages of the SPS life cycle. The digital twin outputs are the primary data of *Transportation GHGs Emissions* and *Fuel Consumption* for each shipment. The resulting primary data database feeds *Inventory Analysis* allowing a precise evaluation of each SPS's impact through the LCIA.

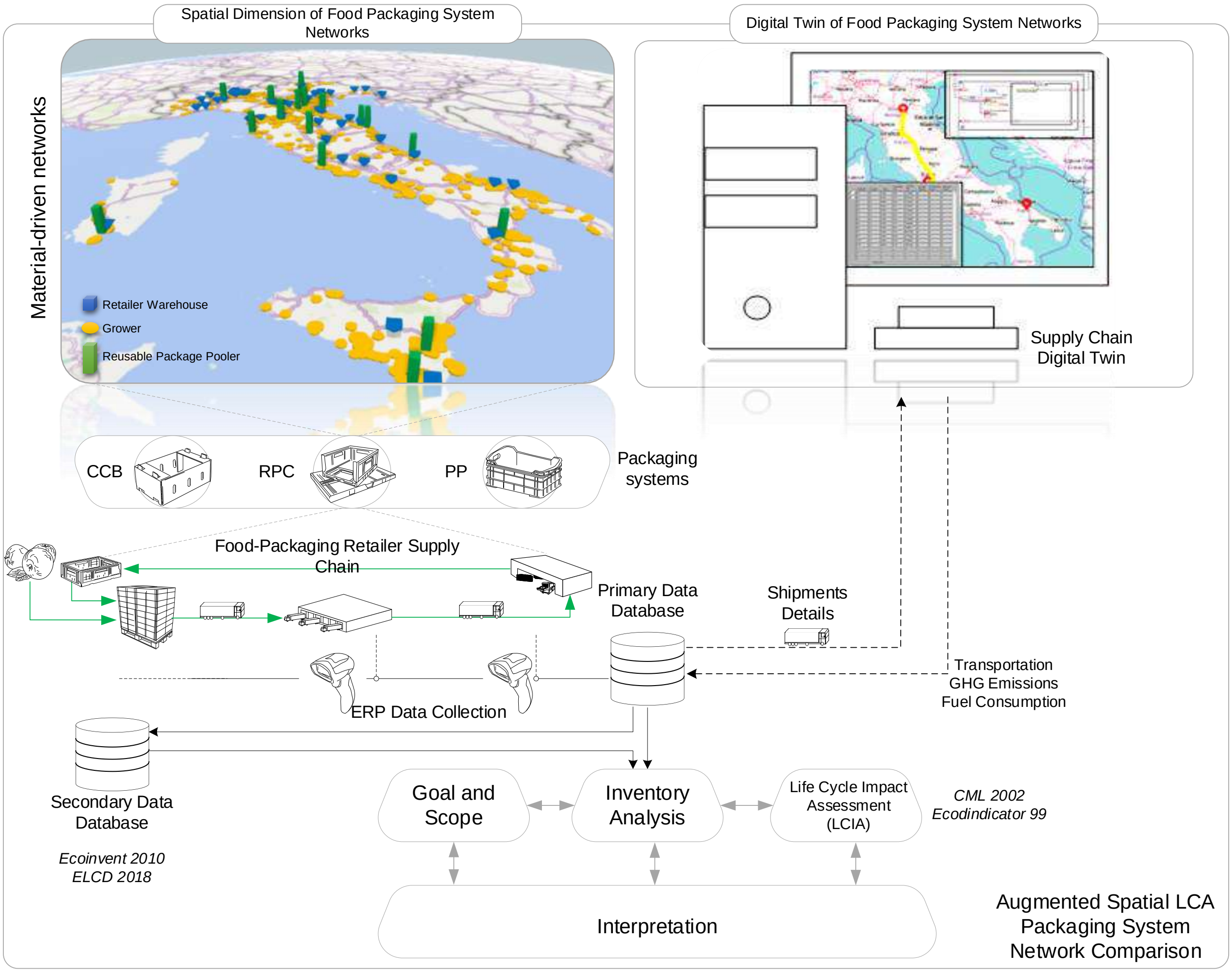

Fig. 1. Methodology: a spatial LCA augumented by virtualized shipments obtained from a SC digital twin.

2.1. Functional unit

The FU is the food distributed by a fully loaded pallet of 6410 RPCs, i.e., 1579.22 dm^3 carrying products, over a time span of 10 years throughout a country-wide grower-retailer FSC. The FU comprised a wood pallet EPAL PT8120 800 × 1200 × 144 mm (22.3 kg) capable of holding 72 opened crates 600 × 400 × 119 mm (1.4 kg). RPCs rotate (i.e., deliver food and return to the pooler) 10 times per year. This study compared nine alternative SPSs, differing in size and material, according to Table 2. The number of single-use crates necessary to satisfy the 10-year scenario demand is calculated considering to the inner volume capacity per crate (see Fig. 2). The number of circulations of the reusable crates before recycling and grinding affects the manufacturing stage and ultimately the LCIA results. When crates are shipped empty (e.g., from producer to grower), the internal volume of the crates is unexploited. For this reason, reusable crates are closable (crate's sides are foldable) and are shipped closed when empty. Single-use PP crates cannot be folded, while single-use CC crates are produced as folded layers of cardboards and, once opened, cannot be closed anymore. The chosen configuration is the most frequently used in the observed retailer supply chains (specifically, for fresh fruits and vegetables), that is, 6410, as the basic SPS. While the boundaries are the same in the comparative LCA (ILCD, 2010), the alternative SPSs differ in the raw materials, manufacturing of crates, logistics phase and networks, transportation, and EOL scenario. Despite the importance of the space utilization of containers in the transport process, the sizing of crates has not attracted much attention so far (Glock, 2017).

SPS		Weight [kg]	Outer size (Close) [mm]	Outer size (Open) [mm]	Inner size [mm]	Inner Volume [dm^3]
Size	Package/Material					
3416	PP Reusable	1.1	300x400x35	300x400x180	270x370x165	16.48
6410		1.4	600x400x35	600x400x119	570x370x104	21.93
6416		1.8	600x400x35	600x400x180	570x370x165	34.79
3416P	PP Single-use	0.400		300x400x175		17.5
6410P		0.497		600x400x120		24
6416P		0.725		600x400x175		35
3416C	CC Single-use	0.450			300x400x196	23.52
6410C		0.500			600x400x107	25.68
6416C		0.620			600x400x167	40.08

Table. 2: SPSs alternatives.

Because of the variation in the sizes of crates and pieces per pallet and in the unit loads distributed through the FSC, the SPS pallets need to be normalized. For the chosen FU, the different fully-loaded pallets are scaled according to the FU's carried food volume. Table 3 underlines the differences in stackability, volume utilization, and loading performance of the different SPS palletizations. The normalization was performed on the inner volume capacity (i.e., food volume) of the different SPSs according to Fig. 2.

SPS			Open/Close Crate Volume Gain [%]	Carrying food volume [dm^3]	Normalized volume	Open Crates per Pallet	Close Crates per Pallet	Pallet Weight (Open) [kg]	Pallet Weight (Close) [kg]
Material		Size							
Reusable	PP	3416	80	1582.41	0.997979	96	480	105.6	528
		6410	70	1579.22	1	72	240	100.8	336
		6416	80	1670.33	0.945454	48	400	86.4	432
Single-use	PP	3416P	0	1680	0.9400114	96	96	38.4	38.4
		6410P	0	1728	0.9139	72	72	35.78	35.78
		6416P	0	1680	0.9400114	48	48	34.8	34.8
Single-use	CC	3416C	91	2069.76	0.7629962	88	1000	39.6	450
		6410C	89	2054.4	0.7687009	80	740	40	370
		6416C	93	1923.84	0.8208683	48	700	29.76	434

Table 3. SPSs' pallets features.

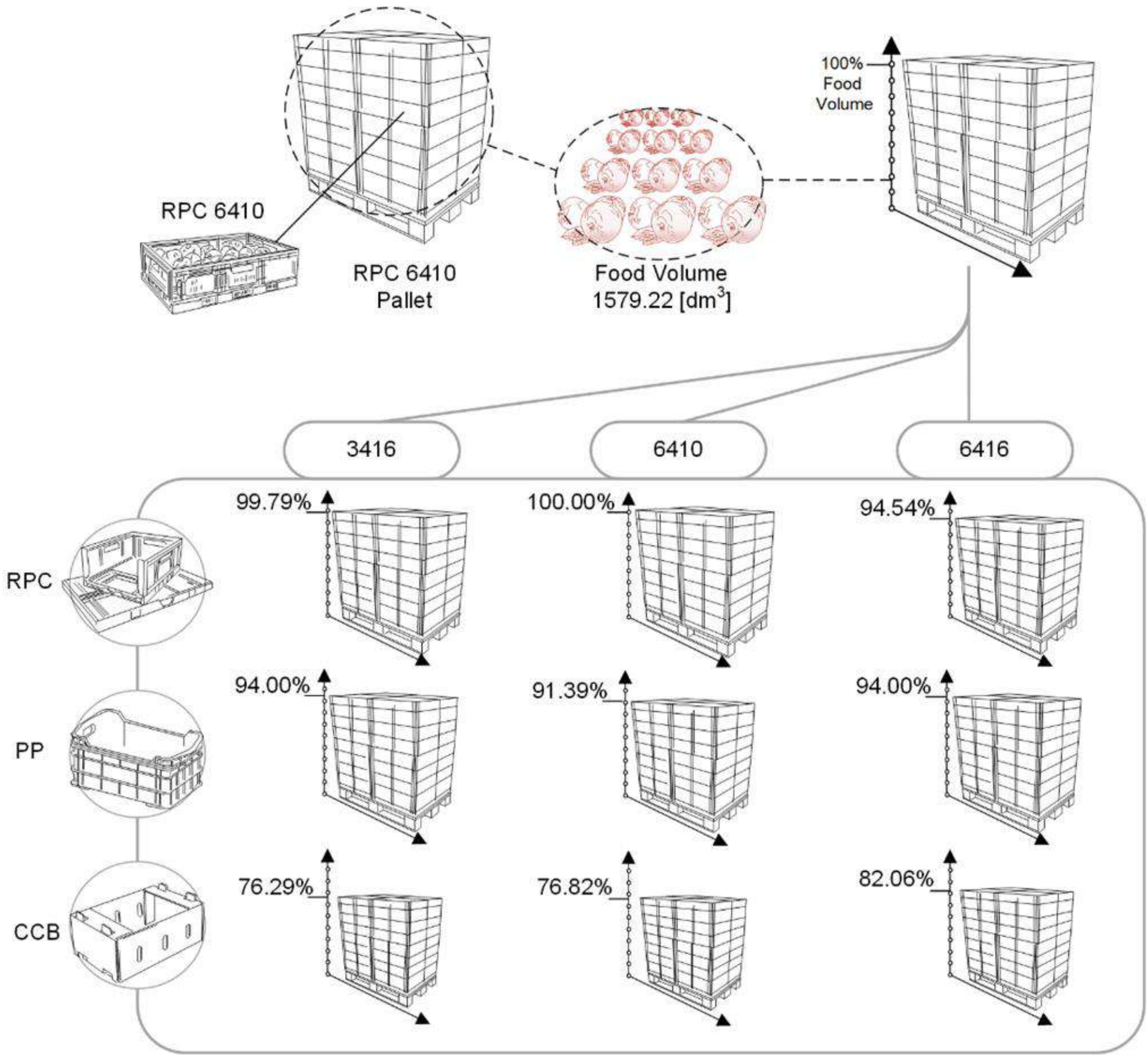

Fig 2. SPSs' composition and conversion factors.

2.2. Systems boundaries

The system boundaries include the life cycle of a fully loaded pallet of nine SPSs serving countrywide retailers over ten years. The reference flow includes the materials, processes, and resources needed to produce, supply, handle, and dispose of alternative SPSs.

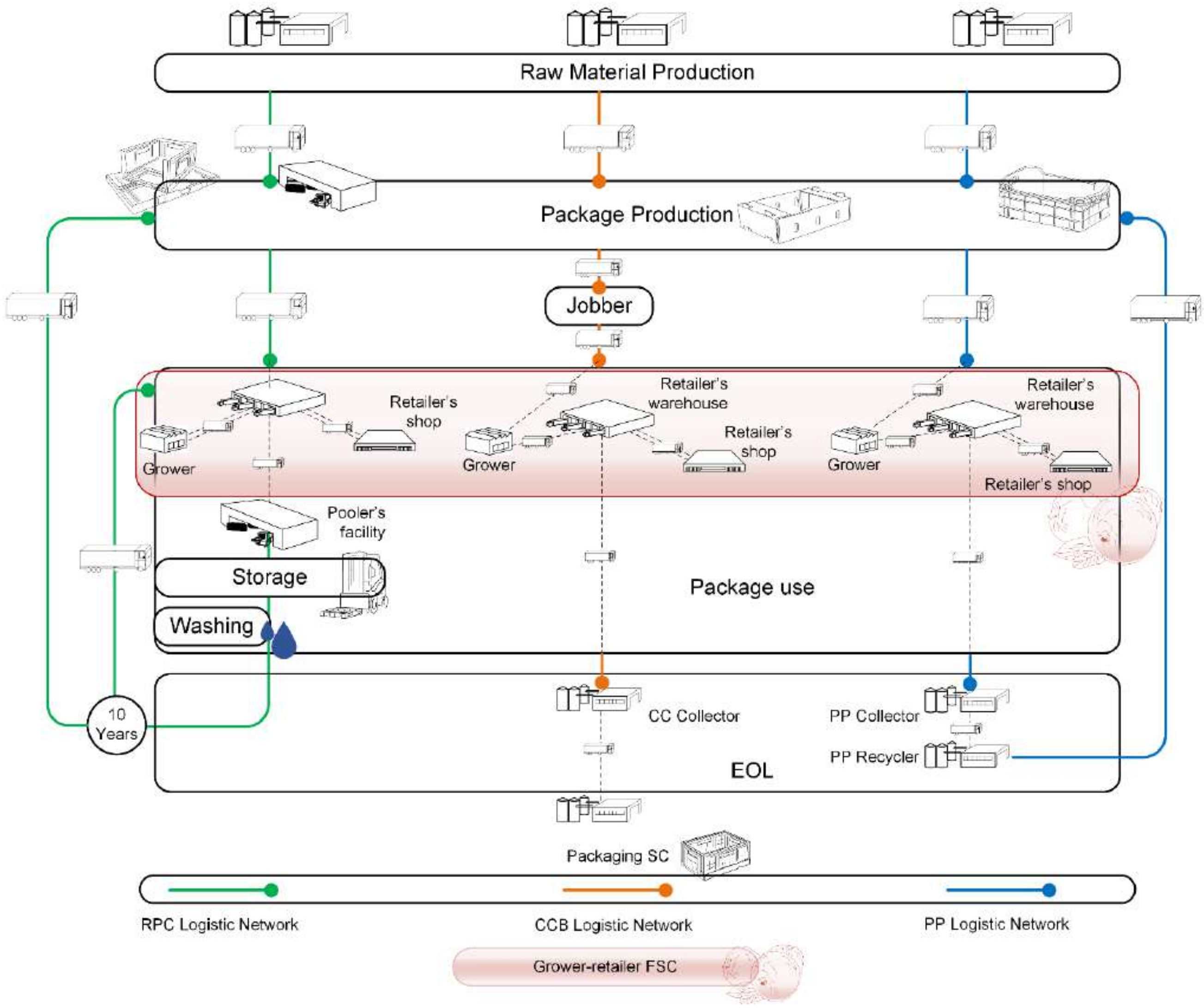

Fig. 3. Alternative SPSs material-driven networks.

Fig. 3 illustrates the differences among the SPSs for the three-alternative material-driven logistic networks. The different colors represent the three material-driven networks characterized by four framed stages. In the *Row Material Production* stage, the virgin materials are supplied according to the recipe. The crates are manufactured at the *Package Production* stage, merging virgin, secondary, and auxiliary materials. The CC crate production step does not use secondary material and related reverse flows. In the *Package Use* stage, the crates enter the FSC, are shipped to the growers, food processors, or packers, filled with products, and sent to the retailer's distribution center for deliveries to the retailer's shops. Before reaching the growers, the CC crates need to be shaped into ready-to-fill boxes by a dedicated actor (i.e., the *Jobber*). In addition to the facilities' locations, the RPCs network differs in the presence of a new actor: the pooler. This player is responsible for collecting and washing empty RPCs. On average, 50% of collected crates are washed, so each container is cleaned after two rotations. In the observed network, a reusable box performs ten rotations per year and is washed five times per year and has a lifespan of 10 years before being disposed and recycled. In the *EOL* stage, the three packaging systems experience different treatments. The pooler collects and sends the closed RPCs to the grinding and printing facilities (i.e., *Package Production* stage). Likewise, single-use containers experience reverse flows during the EOL treatments. However, the lack of a pooler narrows down the pivotal role of the retailer's distribution centers. Although CC crates are collected and treated by collectors facilities, the *Package Production* stage does not involve secondary material due to Italian legislation (D.M. 21.03.1973 and update D.M. 220 26.04.1993). The on-field observation of such networks brought out highly complex scenarios where the environmental convenience is far to be clear-cut.

2.3. Life Cycle Inventory

The life cycle inventory (LCI) organizes the data associated with the observed system and networks. The data include material and resource (e.g., energy and water) flow, inputs, and outputs of all life cycle processes. The variety of processes involved and the broad geography of networks compel structured data collection through data warehouse support (Baruffaldi et al., 2019). The data were divided into primary and secondary data. The first is collected on-field via direct observation of the container maker and pooler's facilities. Such data are used to set the inventory for production, storage, washing (for reusables), grinding, and recycling. The pooler's ERP system also provides primary transportation data for any shipment organized by the pool. Origins and destinations enable the retrieval of routing distances from the GIS incorporated into the digital twin. Transportation, emissions, and fuel consumption were tallied for each shipment according to the Finnish Lipasto database (VTT, 2009). The primary data of the single-use SPSs networks are collected through on-field questionnaires. Primary data on fuel consumption and GHGs emissions were obtained through the SC digital twin for every SPS flow. The remaining secondary data were gathered from renowned LCI databases, such as Ecoinvent v2.2 and v3.01 (Ecoinvent, 2010), and the European Life Cycle database (ELCD, 2018).

Processes can be classified into two categories: *internodes* and *in-node*. The former, like transportation, follows the containers' flows across the network and the nodes' location by mapping geographical coordinates and addresses. The *in-node* processes the trace operations within each facility. Business process management (BPMN) is a notation used in the literature to aid knowledge management in mapping industrial and information processes (Salvadorinho and Teixeira, 2021; Haseeb and Ahmad, 2020). Here, the BPMN is used to trace the physical flow of crates within the facilities and to link the records tracked by the companies' ERPs. Each information record, labeled with a timestamp, recognizes a task corresponding to a control point (CP) in the layout of the facility. Because all single-use CC crate and PP crate processes are included among the RPCs, the processes shown in Fig. 4 are those experienced by the RPCs' containers. A detailed description of the main processes in the BPMN of the RPC is outlined in the following paragraphs.

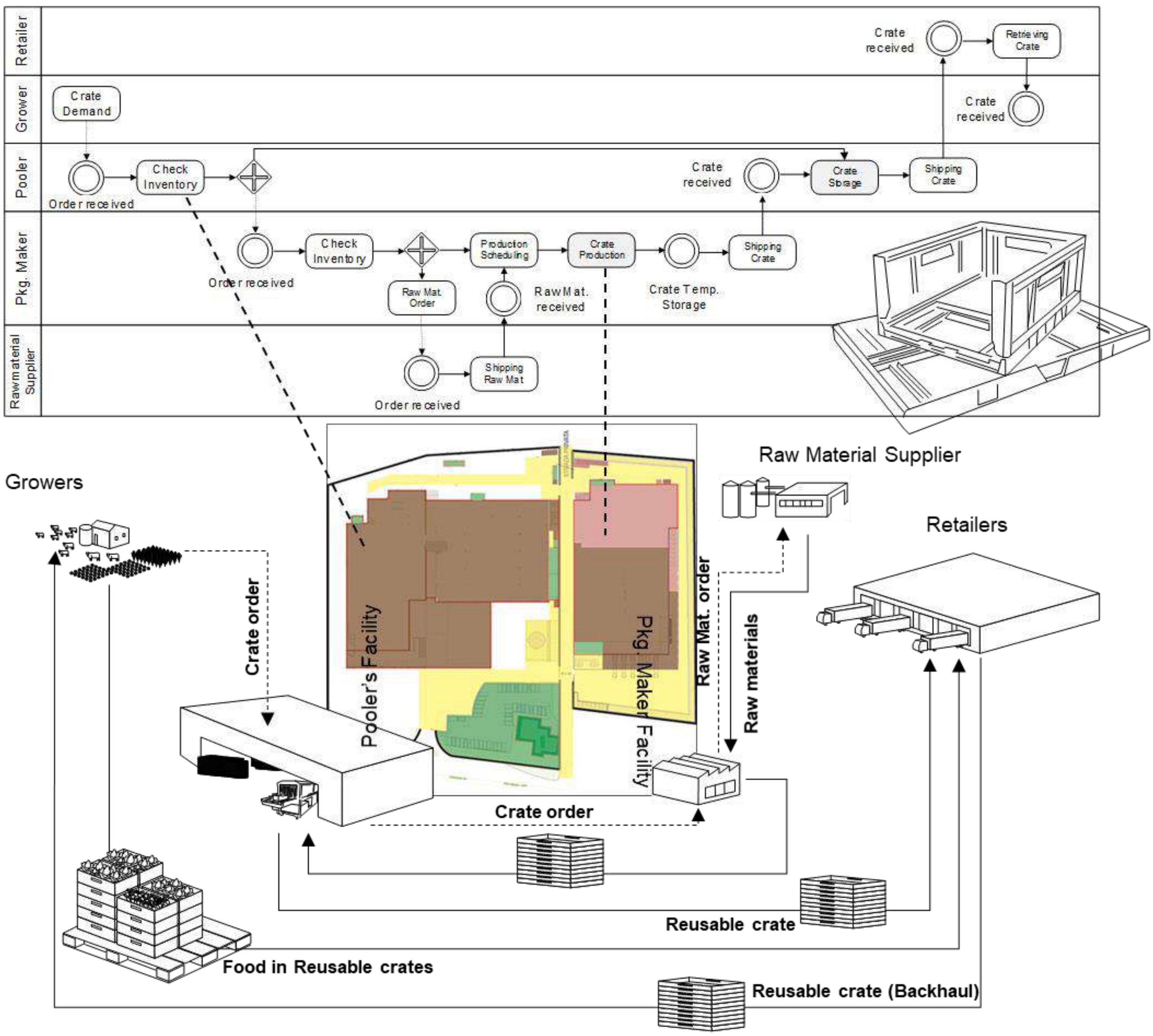

Fig. 4. BPMN for *in-node* and *internodes* processes assessment.

2.3.1. Production

On-field monitoring of an Italian RPC's network is used to gather primary data on the production phase of single-use PP and RPC SPSs, while renowned LCI databases are the source of COS data for CC container production. The RPC network is a group of facilities distributed countrywide to serve growers and retailers with reusable packages. Table 4 illustrates the production phases of the nine SPSs, which differ in the material-driven network. Raw materials are sourced according to the given recipe, for example, 59% of the virgin, 39% of the secondary, and 2% of the coloring masterbatch (PE) for RPC. In the section *Supplier* (Table 4), the facility locations of the raw materials suppliers and distances from the *primary* and *back-up facilities* locations. The former is the leader package maker in the network, whereas the latter is a back-up facility. Their locations can be found in the *Package maker* section. The complete inventory for each SPS is reported in Section *Inputs*: *Material and Energy* in Table 4.

SPSs			Package Makers		Recipe			Suppliers		Inputs: Materials and energy [kg]							
Package	Type	Material	Primary Facility Location	Back-up Facility Location	First material [Location; %Flow]	Second material [Location; %Flow]	Coloring masterbatch [Flow%]	Distance [material supplier→ Primary facility]	Norm. FU weight [kg]	First material [kg]	Second Material [kg]	Oil [kg]	Color [kg]	Gas [kg]	LDPE [kg]	Used Oil [kg]	E_{FU}^{Prod} grid/IT [kWh]
Reusable	3416	PP	Gallo (FE)	Polesine Parmense (PR) - 162 km from primary facility	Secondary PP [Malalbergo (BO); 59%]	Virgin PP [Antwerp - Belgium; 39%]	2%	2.7 km [Gallo → Malalbergo]; 1186 km [Gallo → Antwerp]	104.5	61.655	40.755	0.027	0.06	0.176	2.09	0.027	116.449
	6410								100.8	59.472	39.312	0.041	0.09	0.266	2.016	0.021	88.485
	6416								85.5	50.445	33.345	0.014	0.03	0.003	1.71	0.014	58.376
Single-use	3416	PP	Forli-Cesena (FC) Salerno (SA)	/	Secondary PP [CONIP network; 99%]	/	1%	158 km [Forli-Cesena → Modena*]; 232 km [Salerno → Modugno*]	39.09	38.304	0	0.027	0.06	0.176	0.782	0.027	116.449
	6410								35.41	34.703	0	0.041	0.09	0.266	0.708	0.021	88.485
	6416								35.42	34.713	0	0.014	0.03	0.003	0.708	0.014	58.376
Single-use	3416	CC	Suppliers αβ	/	Kraft Paper [San Felice Sul Panaro / Bellusco; 60%]	Semichemical papers [San Felice Sul Panaro / Bellusco; 40%]	/	See table 5	39.26	23.556	15.7						0.0438
	6410								39.92	23.95	15.97						0.0623
	6416								31.73	19.04	12.69						0.0374

Table 4. (Legend: * nearest CONIP Collectors: Rende (CS), Modena (MO), Modugno (BA), Lentini (SR), Legnano (MI); Suppliers αβ: San Felice sul Panaro, Bellusco, Buglio in Monte, Catania, Pomezia; Oil: *Lubrificant Oil; Color: Printing Colour; Gas: Liquefied Natural Gas; LDPE: Low-Density Polyethylene; Used Oil: Disposal, Used mineral Oil)*

The RPC container production stage (i.e., the inputs, the processes, and the outputs) is illustrated in Fig. 5. After temporary storage, the two raw materials are sent to the hoppers by forklifts. A vacuum aspiration system merges the polymers and conveys them toward the injection pressing, where the parts are shaped. Finished container stacks (i.e., 30 pieces) are placed on pallets, filmed, and labeled before being stored in the container's warehouse. The production stage of the single-use PP container is equivalent to the RPC's one, aside from the recipe. As for the CC boxes, according to Italian legislation, recycled paper pulp and fibers are allowed in packaging for food items not subjected to pathogens migration. These include dry food, bakery products, fresh, frozen, or dry fruits and vegetables, spices, and plants. Notwithstanding the regulation, most food packers and retailers only accept virgin materials for boxes. Here, it is assumed that the disposed CC containers are not used as secondary material, not contributing to a new box. Levi et al. (2011) provide the Eq. (1) to aid in calculating the energy consumption for CC boxes production as in Table 4:

$$E_{FU_{CC}} = \frac{FU_{food}}{wcap_{CC}} \cdot w_{CC} \cdot 0.025 \qquad \text{[kWh/FU]} \qquad (1)$$

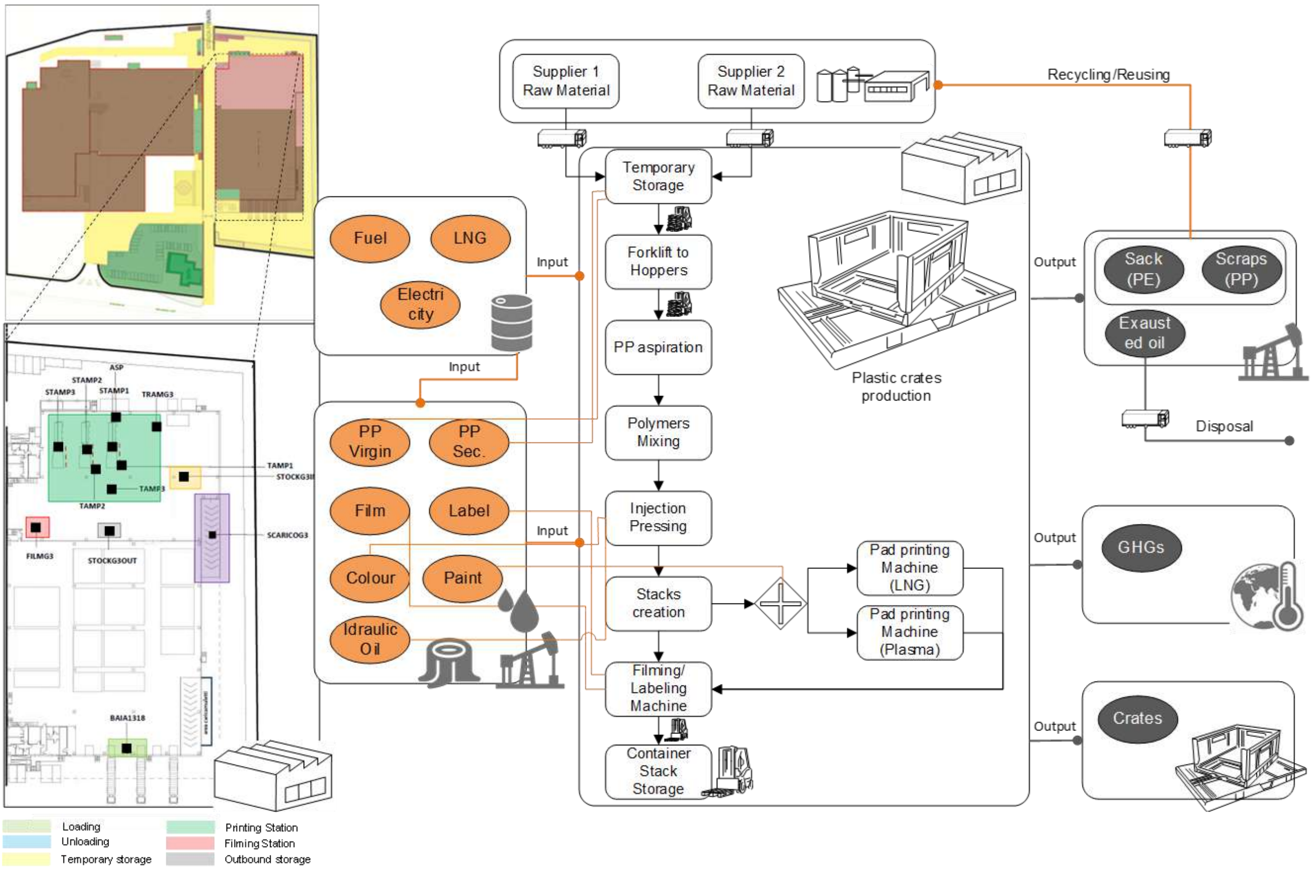

Fig. 5. Reusable containers production phase.

2.3.2. *Use phase*

After production, single-use plastic containers are sent directly to growers and packers. These fill containers and ship packed food to retailers' distribution centers. An equivalent process is for the CC boxes, which also requires a shaping stage (performed by the Jobber) that makes the carton sheets ready for packaging. The lack of a pool avoids the need for storage and associated operations, as occurs in a reusable packaging network. The shared processes among the three systems are container transportation and collection. The remaining use processes, that is, storage, balancing inventory, washing, and refurbishing, are only observed for reusable systems. These processes are discussed in the following subsections.

2.3.2.1. *Transportation*

Compared to previous studies (Levi et al., 2011; Koskela et al., 2014), transportation was not treated as a simplified phase with average distances. Fig. 6 shows all shipments performed across all network nodes associated with a process and route (i.e., given traveling distance). Carried loads, weight, volume utilization, and resulting impacts were simulated with the SC Digital Twin and evaluated according to the definition of FUs. As the FU consists of the distribution service provided by a fully loaded pallet of 6410 RPCs to a countrywide food distribution network over a horizon of 10 years, the infrastructure of nodes and transportation modes is crucial to allow a better understanding of the complexity of this study. Table 5 outlines the main features of the transportation modes considered in the SC Digital Twin analysis.

	Vehicle	Dimension	Features	Emission Profile and Fuel Consumption	Network to serve
Roadways Transportation	Semitrailer truck	13600x2480x3000 [mm]	mass: 40 [tons]; pay load capacity: 25 [tons]	EU1-EU6 average value (2016) by Lipasto database (VTT, 2009)	994 food vendors and 58 retailer's warehouses (Italy)
Intermodal Transportation	Short-range containership	1000 [TEUs]	mass: 14000 [tons]; pay load capacity: 10000 [tons]	EU1-EU6 average value (2016) by Lipasto database (VTT, 2009)	clients within the two main Italian isles
	Cargo electric train		mass: 1016 [tons/train km]; pay load capacity: 525 [tons/train km]		international food vendors (we consider one from Belgium)

Table 5. Transportation modes.

The observed transport processes involve opened and closed crates. The former are the ones involved in the FSC grower- retailer's warehouse- retailer's shop; the latter are illustrated in Fig. 3 and range from raw material supply to EOL. Manufacturing, maintenance, transport means' disposal, and road infrastructure construction are not included in the system boundaries.

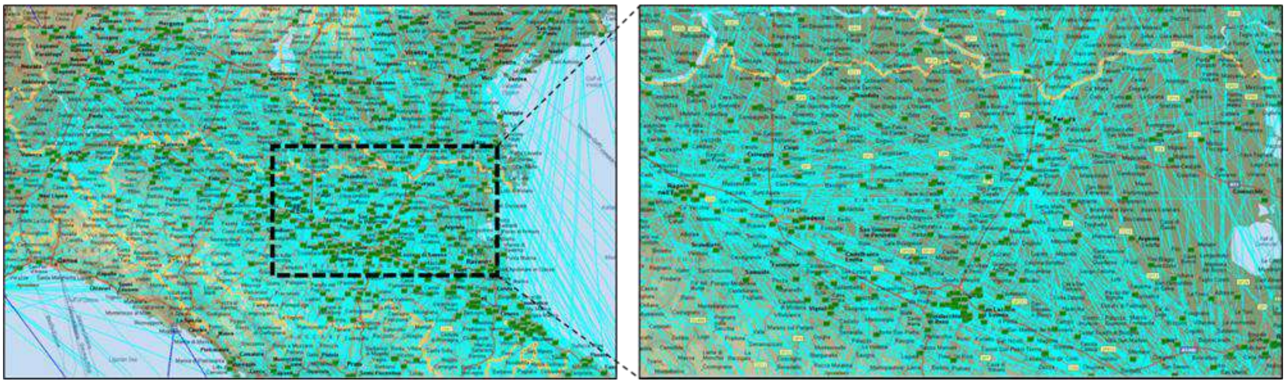

Fig. 6. Connections traveled by the containers throughout the networks.

The connections shown in Fig. 6 represent the containers shipment throughout the network. Due to the network complexity, this section overviews the SC flows generated by two specific vendors over one year to exemplify the overall system's behavior. Two renowned fruits producers with 12 and 6 packing facilities are selected. The former, namely *Vendor α*, is distributed in the Center and South of the country, while the latter i.e., *Vendor β*, is concentrated in Trento (TN). Three alternative networks can supply the two vendors' facilities. Concerning the CC boxes, *Vendor α* receives the paper sheets from a few suppliers, three serving the North and center, while the remaining for the Southern facilities. Since the CC material-driven network includes the Jobber, Table 6 exemplifies the network's features for Vendor α.

Food Vendor α Nodes	Node Code	CC Sheets Supply Node [km $_{Supplier \rightarrow Vendor\ \alpha}$; Flow %]					CC Boxes Opening Node	
		San Felice sul Panaro	Bellusco	Buglio in Monte	Catania	Pomezia	Jobber Code	[km $_{Vendor\ \alpha \rightarrow Jobber}$; Flow %]
Altedo	002AL	48; 35	257; 35	352; 30			JOBCE	5; 70
Aprilia	002AP	472; 35	18.5; 35	746; 30			JOBCE	11.8; 100

Cesena	002C	413; 35	313; 35	410; 30			JOBLA	39.4; 50
Donnalucata	002DO			1595; 30	135; 35	950; 35	JOBAP	23.6; 50
Faenza	002FA	108; 35	286; 35	383; 30			JOBCE	23; 30
Forlì	002FO	126; 35	304; 35	401; 30			JOBCE	20.8; 30
Lavezzola	002LA	84.5; 35	292; 35	389; 30			JOBSC	7.3; 100
Romagnano	002RO	168; 35	346; 35	443; 30			JOBDO	33.3; 100
Scanzano Jonico	002SC			1113; 30	429; 35	503; 35	JOBVI	3.1; 100
San Pietro in Vincoli	002SP	131; 35	309; 35	406; 30			JOBLA	2.6; 30
Vignola	002VI	50.5; 35	210; 35	307; 30			JOBCE	40.1; 70
Longiano	002LO	149; 35	371; 35	424; 30			JOBCE	302; 50

Table 6. CC sheets and boxes supplies to *Vendor α*.

Vendorβ's facilities share a smaller set of CC makers whose supplies are distributed as follows: 15% from San Felice sul Panaro, 15% from Bellusco, 40% from Buglio in Monte, and the rest from Parma. No external companies are involved in shaping the boxes.

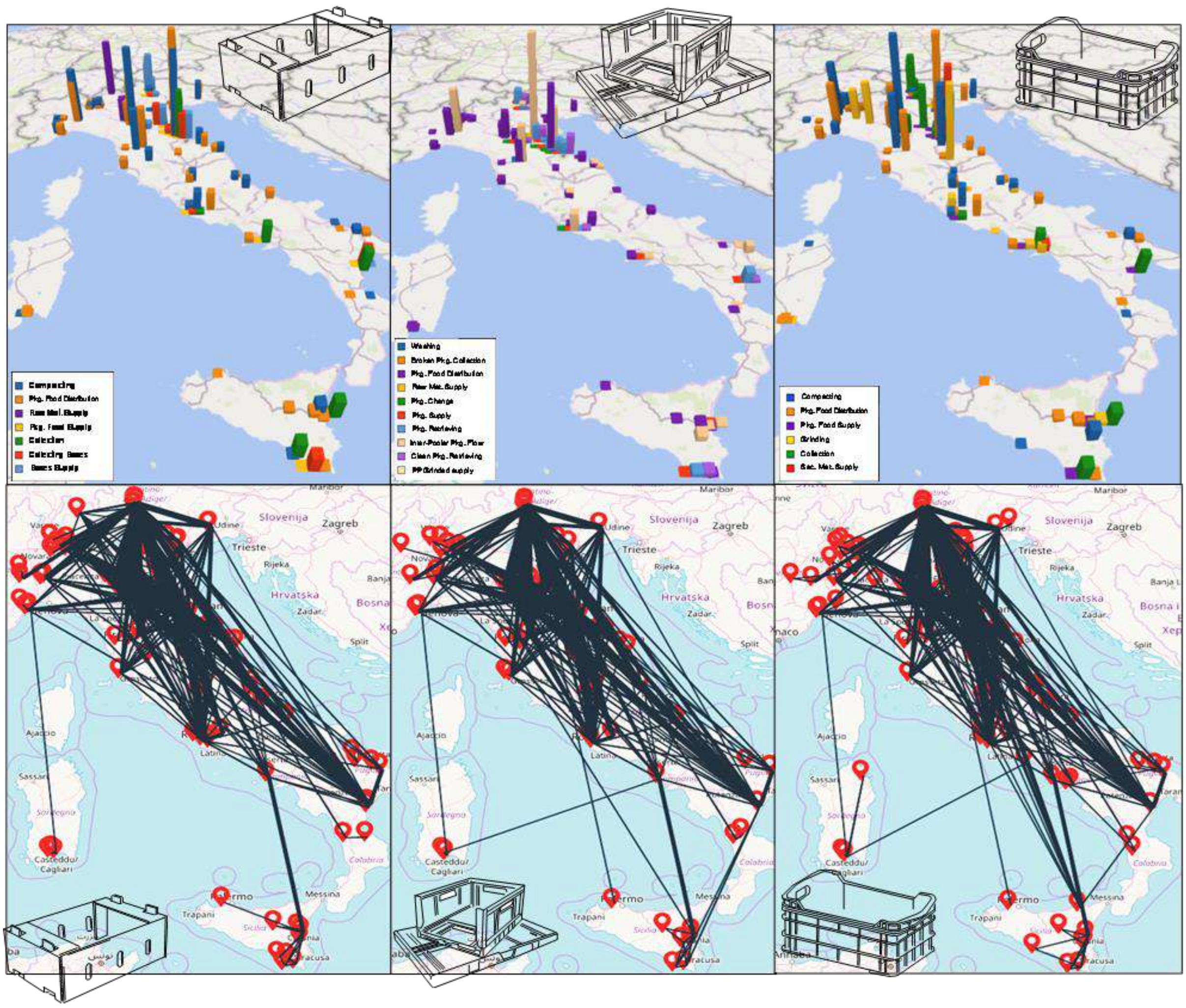

Fig. 7. Transport phase for the three packaging networks: focus on Vendors *α*, *β*.

Conversely, the single-use PP containers are supplied by one package maker. This is located in Forlì-Cesena for *Vendor α* and in Castel San Giorgio (Salerno) for *Vendor β.* Once the crates are pressed by injection, they are distributed empty to food packers throughout the country. The RPCs are transported throughout the pooler's network, which has 19 facilities.

In Fig. 7, the three material-driven networks and distribution flows considering vendors α and β serving all the 58 retailers' warehouses are compared. The RPCs network infrastructure depends on the strategic decision of the pool, which merges the demand and flow opening facilities where needed (Accorsi et al., 2020). However, the reusable network requires substantially more complex transport processes than the single-use ones: collecting broken crates, shipping to washing, and balancing the inventory among the pool nodes.

In Fig. 8, each dot denotes a shipment carried out during one year of observation regarding traveling distance and carried weight. Considering the flow of raw, secondary and auxiliary materials, crates, pallets and food supplies, 131,842 shipping records are counted (i.e., a route, a date and a given shipped item) in the RPC network, 129,643 for CC boxes, and 128,560 for PP crates during a year. The PP boxes are lighter, thus saturating the trucks in volume before weight. The CC boxes are transported in stacks of carton sheets (between 700 to 1000 per pallet) and shaped near the food packing facility. The reusable crates shipments present higher truck capacity utilization because these are closed when empty, resulting in consolidated package supplies and backhauls. The single-use PP containers are lighter than RPCs but bear poor truckload utilization. Concerning the EOL stages (i.e., collecting, processing, recycling), per each shipment s is assumed the closest possible destination n^d for both single-use networks when otherwise details were missing.

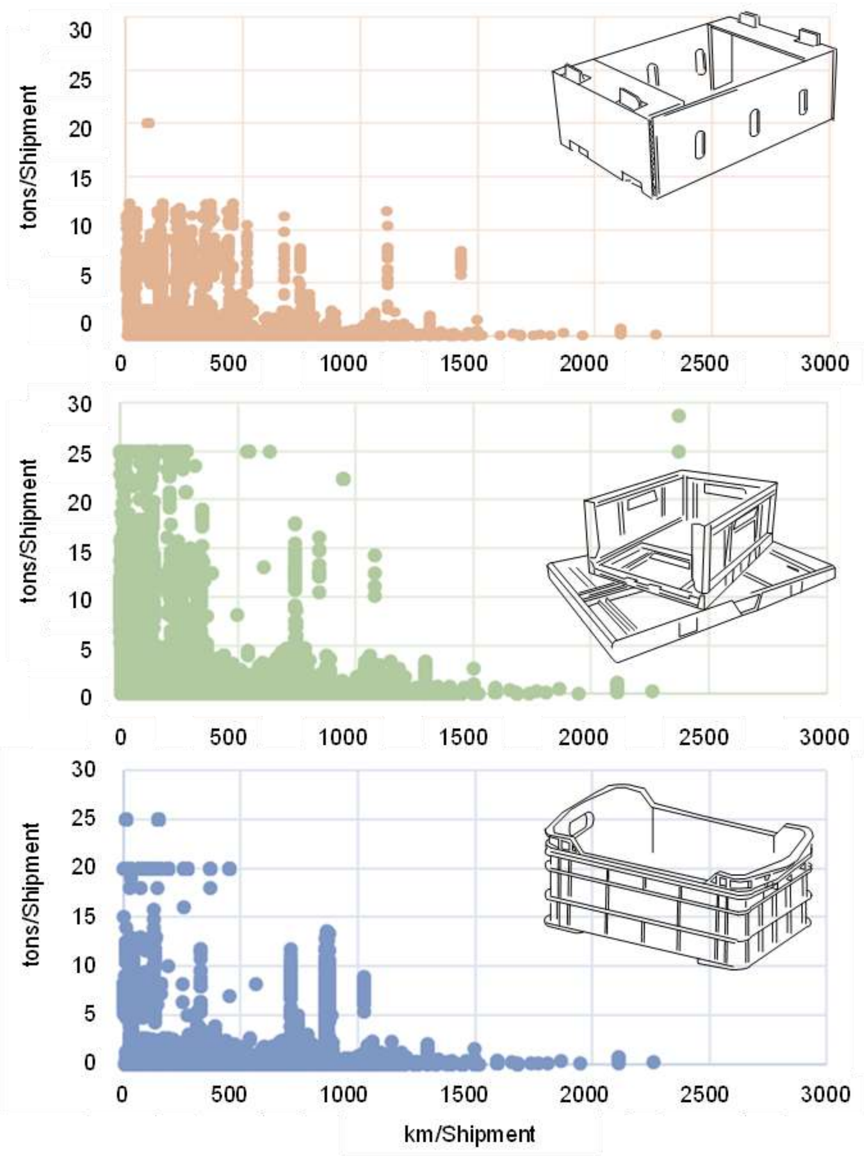

Fig. 8. Travelled distance and load utilization (per shipment) for the three packaging networks: focus on Vendors α, β.

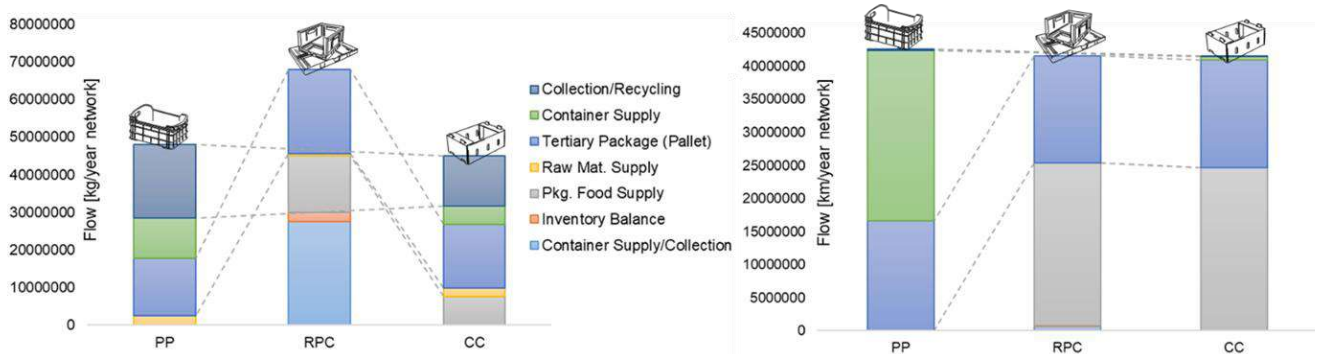

Fig. 9. Contribution of the transportation processes to the distributed flow [kg] (left) and traveled km (right)

Fig. 9 allocates a traveling time of one year to the alternative material-driven networks to the crate's manufacturing, crate use, and crate collection and disposal processes. While the service is the same among the SPSs, because of the differences between the networks, processes are not necessarily comparable. For instance, the PP container supply process includes the packed food supply, which is tallied in the case of RPC and CC boxes separately. Raw materials (i.e., yellow bar) are negligible compared to the crate's flows and are much higher for recyclable containers than reusables. The contribution given by the containers' supplies and backhauls are merged for the RPC (*Container Supply/Collection*), while split for PP and CC boxes as *Container Supply*, and *Collection/Recycling*, respectively. PP containers supply and collection intensifies the transportation flows compared to carton boxes due to the empty crate's pallet configuration. For RPCs the *Inventory Balance* flow consists of transporting reusable containers throughout the pooler's facilities to prevent shortages and shorten the routes to the food packers. Table 7 summarizes the transportation flows per SPS extended to a horizon of 10 years (exemplified for container type 6410).

Package	Type	Material	Transportation Loads [kg $\cdot 10^6/_{1\text{Years}}$]			
			Network (Overall)			
			Auxiliary Materials (Without Pallet)	Pallets	Crates	Total
Reusable	3416	PP	0.526	22.448	5.798	67.909
	6410				22.405	
	6416				16.731	
Single-use	3416P	PP	21.969	15.288	1.330	48.012
	6410P				5.614	
	6416P				3.811	
Single-use	3416C	CC	15.693	16.953	2.187	45.043
	6410C				6.530	
	6416C				3.679	

Table 7. Transport loads and flows across the networks.

The transportation modes data and flow data (e.g., volumes, weights, trucks saturation) are fed to the SC Digital Twin. Virtualizing the shipment quantifies punctual GHGs and Fuel Consumption data for each shipment throughout the SPS's network. Table 8 lists the SC Digital Twin output for the crate size 6410. First, the contribution of open, closed, auxiliaries and pallets to the transport emission is reported. Then, emissions are scaled to the time-span, the number of rotation and the FU. Emission^{x,y,z} represents the GHGs emissions and the fuel consumption of x rotations per years of crates y per z years. Emission *10,1FU (Normalized),10* indicates the emission generated by a normalized FU of the SPS in its specific material-driven network for *10 years* with *10 rotation* per year providing inputs to the LCI phase.

SPS		Flow [kg$\cdot 10^6$]	Transport *Output* (GHG emissions) and *Input* (Fuel) [kg]									
			$Co_2Eq \cdot 10^4$	CO	HC	NO_x	PM	CH_4	N_2O	SO_2	$CO_2 \cdot 10^4$	Fuel $\cdot 10^4$
6410	Close crate											

RPC	Semitrailer truck	14.203	17.296	24.515	2.920	49.353	0.896	0.151	11.284	0.574	16.954	5.972
	Containership (1000 TEUs)	0.169	0.281	6.512	2.138	54.425	0.972	0.262	0.069	1.652	0.272	0.088
	Open crate											
	Semitrailer truck	7.978	362.610	574.286	52.421	1039.09	19.042	3.450	275.16	12.121	354.022	124.743
	Containership (1000 TEUs)	0.054	0.064	1.479	0.486	12.366	0.221	0.060	0.016	0.375	0.0618	0.020
	Auxiliares Material	0.263	0.403	2.83	0.82	20.68	0.37	0.10	0.24	0.61	0.393	0.135
	Pallet	3.684	64.514	102.95	9.74	194.30	3.56	0.66	48.74	2.45	62.992	22.194
			Co_2Eq	$CO \cdot 10^{-2}$	$HC \cdot 10^{-2}$	$NO_x \cdot 10^{-2}$	$PM \cdot 10^{-3}$	$CH_4 \cdot 10^{-3}$	$N_2O \cdot 10^{-3}$	$SO_2 \cdot 10^{-3}$	CO_2	Fuel
	GHGs Emissions^{1,1,1}		0.915	0.0146	0.0014	0.0281	0.005	0.001	0.069	0.004	0.893	0.315
	GHGs Emissions^{1,FU,1}		65.847	1.0540	0.1014	2.0268	0.371	0.069	4.963	0.263	64.298	22.654
	GHGs Emissions^{10,FU,10}		6584.747	105.40	10.1	202.7	37	7	496	26	6429.810	2265.397
			$Co_2Eq \cdot 10^4$	CO	HC	NO_x	PM	CH_4	N_2O	SO_2	$CO_2 \cdot 10^4$	$Fuel \cdot 10^4$
6410 PP	Open crate											
	Semitrailer truck	5.457	265.596	419.975	38.493	761.045	13.944	2.524	201.118	8.877	259.321	91.374
	Containership (1000 TEUs)	0.157	0.175	4.063	1.334	33.959	0.606	0.164	0.043	1.031	0.169	0.055
	Auxiliares Material	11.468	5.395	9.38	1.60	32.33	0.58	0.13	3.35	0.70	5.292	1.861
	Pallet	3.498	143.950	229.86	21.64	432.34	7.91	1.46	108.94	5.42	140.548	49.521
			Co_2Eq	$CO \cdot 10^{-2}$	$HC \cdot 10^{-2}$	$NO_x \cdot 10^{-2}$	$PM \cdot 10^{-3}$	$CH_4 \cdot 10^{-3}$	$N_2O \cdot 10^{-3}$	$SO_2 \cdot 10^{-3}$	CO_2	Fuel
	GHGs Emissions^{1,1,1}		0.8538	0.0136	0.0013	0.0259	0.005	0.001	0.064	0.003	0.833	0.2937
	GHGs Emissions^{1,1FLP,1}		61.4741	0.9822	0.0934	1.8654	0.341	0.063	4.642	0.237	60.025	21.1488
	GHGs Emissions^{10,1FLP,10}		6147.407	98.2	9.3	186.5	34	6	464	24	6002.48	2114.88
	GHGs Emissions$^{10,1FU}_{(Normalized),10}$		5618.115	89.77	8.54	170.48	31.2	5.8	424.2	21.7	5485.67	1932.79
			$Co_2Eq \cdot 10^4$	CO	HC	NO_x	PM	CH_4	N_2O	SO_2	$CO_2 \cdot 10^4$	$Fuel \cdot 10^4$
6410 CC	Open crate											
	Semitrailer truck	6.337	254.130	402.7211	36.70	728.26	13.35	2.42	193.00	8.50	248.106	87.423
	Containership (1000 TEUs)	0.193	0.216	4.9897	1.64	41.71	0.74	0.20	0.05	1.27	0.208	0.067
	Auxiliares Material	8.267	1.565	2.2057	0.27	4.47	0.08	0.01	1.01	0.05	1.534	0.540
	Pallet	4.553	164.580	263.3769	24.75	496.01	9.08	1.68	124.80	6.25	160.681	56.614
			Co_2Eq	$CO \cdot 10^{-2}$	$HC \cdot 10^{-2}$	$NO_x \cdot 10^{-2}$	$PM \cdot 10^{-3}$	$CH_4 \cdot 10^{-3}$	$N_2O \cdot 10^{-3}$	$SO_2 \cdot 10^{-3}$	CO_2	Fuel
	GHGs Emissions^{1,1,1}		0.8649	0.0138	0.0013	0.0261	0.005	0.001	0.066	0.003	0.8444	0.2975
	GHGs Emissions^{1,1FLP,1}		69.1886	1.1079	0.1043	2.0904	0.383	0.071	5.247	0.264	67.550	23.800
	GHGs Emissions^{10,1FLP,10}		6918.863	110.8	10.4	209	38	7	525	26	6754.96	2380.03
	GHGs Emissions$^{10,1FU}_{(Normalized),10}$		5318.536	85.2	8.0	160.7	29	5	403	20	5192.54	1829.54

Table 8. Transportation emissions comparison among 6410 SPSs. Emissions^{x,y,z} corresponds to the emissions associated to *x* rotations per year of *y* crates during *z* years (without fuel/Diesel production).

2.3.2.2. Storage, handling, and washing

Every pool's facility stores closed, used, or new containers. Inbound and outbound processes are traced on-field, and the BPMN is used to point out insights, as shown in Fig. 4. The pooler receives a centralized order from the grower or the retailer and triggers retrieval from the closest facility to supply the demander with the available inventory. The CP analysis outlined in Fig. 10 enables tracking the internal routes of forklifts and assessing the average working hours per year scaled on the FU.

The uncleaned containers were manually checked, residues and leftovers were removed, and the crates were stored. Open containers allow quality checking and refurbishment when necessary. The broken case is sent to the grinding node when the recovery is not feasible. The washing lines were then placed on rotating filters to capture the dirty residues, while water was collected in storage tanks. The station was made of four modules consisting of a cold pre-washing, two hot-washes (at 50 °C) with sodium hydroxide (NaOH), and a flushing system using sodium hypochlorite (NaClO). The washing line worked 142 h per week with a throughput of 4200 crates/h. Only four pool facilities (out of 19) had washing plants behaving, as shown in Fig. 11: Gallo (FE), Casei Gerola (PV), Aprilia (LT), and Lastra a Signa (FI). Table 9 presents the washing process inventory.

Palletization of the containers, filming, strapping, and labelling conclude this phase and let the crates ready for delivery. While handling and washing only pertain to RPCs, warehousing processes are replicated for CC and PP containers and differ in the material.

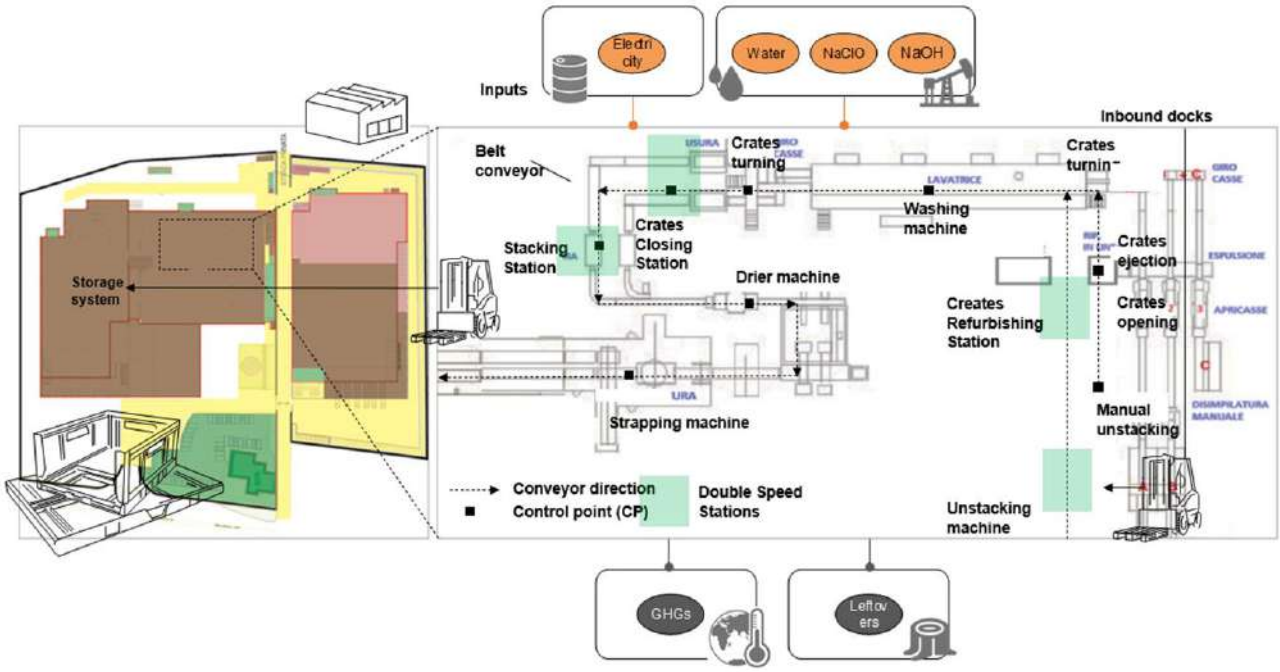

Fig. 10. Washing process for reusable containers.

Inputs (Washing Process 5,1FU (Normalized),10)		Reusable SP		
		3416	6410	6416
Water, process, unspecified natural origin/kg		3719.01	2818.62	1859.51
Sodium hydroxide, 50% in H2O, production mix, at plant/RER S		7.66	5.80	3.83
Sodium hypochlorite, 15% in H2O, at plant/RER S		1.33	1.01	0.66
Sulphuric acid, liquid, at plant/RER S		3.04	2.31	1.52
Aluminium sulphate, powder, at plant/RER S	[kg]	2.61	1.98	1.30
Acrylic acid, at plant/RER S		0.03	0.02	0.01
Acrylonitrile, at plant/RNA		0.03	0.02	0.01
Polypropylene fibres (PP), crude oil based, production mix, at plant, PP granulate without additives EU-27 S		4.55	6.89	4.55
Natural gas, high pressure, at consumer/IT S	kWh	1298.54	984.15	649.27
Electricity mix, AC, consumption mix, at consumer, < 1kV IT S		172.35	139.61	92.11
Outputs (Washing Process 5,1FU (Normalized),10)				
Waste incineration of municipal solid waste (MSW), EU-27 S	[kg]	15.15	11.48	7.58
Composting organic waste/RER S		4.35	3.30	2.17

Table 9. Washing inventory for reusable *SPs (SP_{RPC}).* Legend: *Washing Process* *n. of cleanings per year,n. of normalized FU, n. of years.*

2.3.3. End-of-life

The reusable crates are disposed after ten years and sent for grinding at MeYuMa Plast, located in Malalbergo (BO). The shipping unit is an average weighted 0.35 t pallet. The PE film used to hold the crates was disposed of in bins sent for recycling. Paper residues (i.e., glued labels) were manually removed and sent for incineration. A gross pregrinder prepares the crates for treatment in the *mill*, grinding the material, and sending it to a silo by aspiration. The extruding machine heats, extrudes, and cuts the granules until a uniform paste is obtained. The outflowing granulate is stored in a silo and sent to production lines when ordered, as shown in Fig. 6.

When backhauled from the retailer's shops, empty single-use PP containers are temporarily stored outside the distribution center. Plastic grinding consortiums collect empty crates at the retailer's warehouse and fulfil the nearest grinding facility. For single-use PP containers, the CO.N.I.P. is a consortium operating nationwide that puts up to 2000 facilities among producers of plastic polymer-based products, users (i.e., growers and retailers), collectors (responsible for transportation of used packaging), and recyclers (processing the waste into secondary material) (Conip, 2017). The collectors used a compactor truck with a loading capacity of 3.5 tons and a container weight of 4.7 tons to retrieve disposed crates at the retailers' warehouse. Given the weight of the PP crate and the backhauled packaging flow, the number of compactor trucks traveling daily from each distribution center of the network was quantified. Each retailer's warehouse is served by a collection facility, five to more than 100 km away. The waste is separated by density at the collector's facility and pressed into 1-ton bales (sized 2300 × 1200 × 1200 mm) and sent to the closest recycling facility within the CO.N.I.P. network. At this stage, 99% of the material was used as a secondary PP, and the remainder was incinerated. A standard semi-trailer truck carries 20 bales per fully loaded shipment.

The disposal of CC boxes is equivalent to that of PP containers. A compactor truck with a loading capacity of 3.5 tons gathers empty boxes at the retailer's warehouse and delivers the packaging waste to a collecting facility. The Italian consortium devoted to carton packaging end-of-life treatments is CONAI, which has a broad distribution of plants nationwide (Conai, 2017). When details in the questionnaire shared with the retailer logistics officers were missing, each warehouse's closest collecting facility was assumed to be the destination of the crates. For the collection of CC packages, the traveling distances ranged from less than 1 kilometer to 85.6 kilometers. Once collected, ground, and pressed, the material was sent to paper mills. Although 96% of the disposed material can be recycled and the remaining material is sent for incineration, retailers commonly impose only virgin material crates for fresh food. Therefore, the outputs from EOL treatments (i.e., recycling) of CC boxes are not included in the boundaries.

2.4. Life Cycle Impacts Assessment

LCIA was conducted using the software Simapro 8.2, adopting the environmental impact categories and the energy indicators as CML2002 mid-point (i.e., normalization factor: Western Europe 1995) developed by the Center for Environmental Science in Leiden (CML) (Guinée et al., 2002; Huijbregts et al., 2003). Furthermore, Ecoindicator 99 endpoint impacts (normalized Europe EI 99 H/A) associated with the three packaging networks were calculated and scaled to the SPSs. Concerning transportation, the GHGs emissions and fuel consumption per kilogram of transported food were quantified via the digital twin. Emissions $e_{tn^o n^d m_{sp}^{o \to d}}$ from each shipment *s* from node n^o to n^d considering the actual weight $m_{sp}^{o \to d}$ to deliver, volume utilization $\frac{v_{sp}^{o \to d}}{vcap_t}$ of vehicle t, and unit load configurations with SPS *p* are given by Eqs. 2 and 3:

$$n_{ts}^{full} = max\left\{\left\lfloor \frac{m_{sp}^{o \to d}}{wcap_t} \right\rfloor ; \left\lfloor \frac{v_{sp}^{o \to d}}{vcap_t} \right\rfloor\right\} \qquad \text{[trucks]} \qquad (2)$$

$$e_{tn^o n^d m_{sp}^{o \to d}} = \begin{cases} \left[e_t^{empty} + \left(\frac{e_t^{full} - e_t^{empty}}{wcap_t}\right) \cdot m_{sp}^{o \to d}\right] \cdot d_{n^o n^d}, & if\ \left(m_{sp}^{o \to d} \le wcap_t\right) \wedge \left(v_{sp}^{o \to d} \le vcap_t\right) \\ \left\{e_t^{full} \cdot n_{ts}^{full} + \left[e_t^{empty} + \left(\frac{e_t^{full} - e_t^{empty}}{wcap_t}\right) \cdot \left(m_{sp}^{o \to d} - wcap_t \cdot n_{ts}^{full}\right)\right]\right\} \cdot d_{n^o n^d}, & Otherwise \end{cases} \qquad \text{[g/shipment]} \qquad (3)$$

The symbol $e_{tn^o n^d m_{sp}^{o \to d}}$ in Eqs. Three represents the emissions (g/shipment) released by vehicle *t* considering the actual loads instead of using user-defined (or average) payloads. The terms $wcap_t$ and $vcap_t$ are the carrying capacities as the weight and volume of the vehicle t. $d_{n^o n^d}$ is the traveling distance from origin n^o to destination n^d. The primary data database collects the routes from each origin and destination stage by stage across all nodes of the three material-driven networks. e_t^{full} and e_t^{empty} are the vehicle-kilometer emissions (g/v km) of t when fully loaded and empty, respectively. Emissions metrics were obtained from the Lipasto database (VTT 2009). The inventory included CO, HC, NO_x, PM, CH_4, N_2O, NH_3, SO_2, CO_2, and the fuel consumption of several vehicles. Thus, emissions were quantified for all shipments across the stages of material-driven networks that occurred over one year. The resulting values over a period of 10 years were scaled for each SPS to the reference FU. Fig. 11 shows the SimaPro calculation conducted through the lifecycle process assembly for the 6410 RPC SPS. The contributions to the FU are split into four subprocesses in agreement with the schemes shown in Fig. 3: *Production*, *Transportation*, *Use* (washing and storage for RPCs), and *EOL*. Primary data concern the transportation phase cumulating emissions and fuel from each shipment virtualized by the SC digital twin for raw material supply, empty crate supply, filled crate distribution, and crate collection and disposal over a time span of 10 years. The cumulative values of GHGs emissions and fuel are divided by the overall mass of food distributed over 10 years and scaled to the FU per SPS according to the conversion factors shown in Fig. 2.

Secondary data (i.e., ELCD 2018, Ecoinvent 2009) were used to quantify the outputs from the production of raw materials supplied to the container manufacturer and from the treatment processes of the EOL, whenever not explicitly described in the above inventory. The results of LCIA are illustrated and discussed in Section 3.

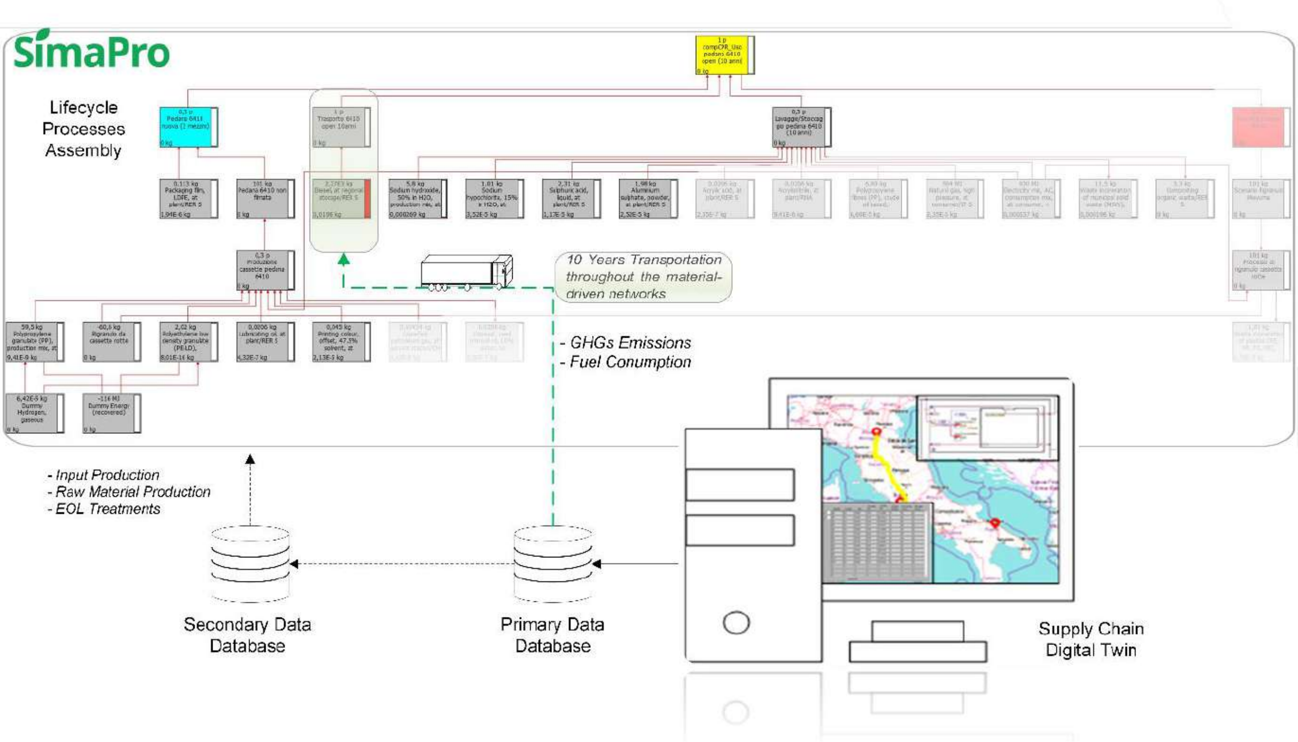

Fig. 11. SimaPro 8.2 lifecycle processes' assembly fed by the digital twin and secondary databases: the 6410 *RPC SPS.*

3. Results and discussion

The collected LCI allows the comparison of the environmental impacts of the distribution of one fully loaded pallet of fresh food over a time span of 10 years throughout a countrywide retailer SC with alternative SPSs different in size and material. Previous studies (Levi et al., 2011; Koskela et al., 2014; Abejón et al., 2020), stated that the footprint and impact of SPSs are extremely sensitive to transportation. The key drivers were confirmed to be the distances between the SC facilities, demand turnover (i.e., container rotation), and transportation modes. While agreeing on the importance of transportation, state of the art assumed an oversimplified logistic phase involving few nodes and routes and average truckload utilization. Such assumptions are uncommon in real-world food packaging networks. To fill this gap, this study mines the companies' ERPs to gather detailed shipment details and adopts an SC digital twin to virtualize the logistics throughout a country-wide distribution network made of retailers (i.e., warehouses and shops), package manufacturers, food growers (i.e., packing facilities), and disposal and recycling consortiums. The Network Analyzer software (2.0), as illustrated in Accorsi et al. (2018), implemented the SC digital twin. The transportation outputs in terms of GHGs emissions and fuel consumption resulting from the digital twin for alternative SPSs were assembled into other lifecycle processes using SimaPro 8.2 software (Fig. 11). The LCIA conducted using CML2002 is shown in Table 10. To test the sensitivity of the results, the LCIA analysis is also conducted using the ReCiPe2008 method considering the commonly used Hierarchist perspective (H).

SPS		Impact Category (CML 2002)												
Size	Material/ Network	ADP [kg Sb eq.] 10^2	AP [kg SO_2 eq.] 10^2	EP [kg PO_4 eq.]	FAETP-20 [kg 1.4-DB eq.] 10^2	FSETP-20 [kg 1,4-DB eq.] 10^2	GWP-20 [kg CO_2 eq.] 10^2	HTP-20 [kg 1,4-DB eq.] 10^2	LC [m2a]	MAE-20 [kg 1,4-DB eq.] 10^2	MSE-20 [kg 1,4-DB eq.] 10^2	ODP-20 [kg CFC-11 eq.] 10^{-2}	POCP [kg C_2H_4 eq.]	TE-20 [kg 1,4-DB eq.]
3416	RPC (1 Normalized FU, 10 Years)	1.25008	0.349903	5.18452	3.82424	8.47941	180.132	9.06140	40.9551	6.83616	11.5726	0.207695	1.907914	0.287396
6410		0.581333	0.165011	2.40417	1.74059	3.85694	82.7658	4.18038	18.5407	3.09194	5.23253	0.094043	0.895716	0.133161
6416		0.43922	0.124468	1.82984	1.31135	2.90639	62.5191	3.14090	14.0001	2.33602	3.95369	0.071014	0.674227	0.099769
3416P	PP (1 Normalized FU, 10 Years)	1.57125	0.820918	6.4412	3.16274	6.96689	247.434	17.9946	42.0217	6.41591	10.7037	0.188566	3.896741	0.612842
6410P		0.922742	0.542576	3.76849	1.58946	3.48739	147.898	11.5637	24.1262	3.36824	5.58392	0.097295	2.524406	0.396282
6416P		0.767344	0.41704	3.13726	1.46772	3.22686	121.040	9.00414	22.3081	2.97332	4.94931	0.086173	1.963161	0.303083
6410C	CC (1 Normalized FU, 10 Years)	0.642157	0.286982	11.133	11.0403	23.6736	96.8599	14.7370	19431.1	9.33540	15.5173	0.099219	1.689271	1.938393
3416C		1.10244	0.411049	12.8951	12.3137	26.5142	163.898	17.9015	19109.8	11.8209	19.7318	0.177815	2.368933	2.012458
6416C		0.540776	0.236504	8.97556	8.86601	19.0185	81.4193	11.9308	15438.8	7.58893	12.6197	0.084062	1.388180	1.547029

Table 10. Results: CML 2002 Impact categories (Results include fuel/Diesel production). For each SPS is reported the impact categories of 1 Normalized FU circulating in the system for 10 years (*Legend: Abiotic depletion: ADP; Acidification: AP; Eutrophication: EP; Freshwater aquatic ecotox. 20 years: FAETP-20; Freshwater sediment ecotox. 20 years: FSETP-20; Global warming potential 20 years; GWP-20; Human toxicity 20 years: HTP-20; Land competition: LC; Marine aquatic ecotox. 20 years : MAE-20; Marine sediment ecotox. 20 years: MSE-20; Ozone layer depletion 20 years : ODP-20; Photochemical oxidation formation: POCP; Terrestrial ecotoxicity 20 years: TE-20)*

After a time-span of 10 years, Table 10 confirms that the environmental impacts of the single-use PP and CC SPSs are both higher than the RPC SPSs in all the impact categories considered. Iterated for the PP and CC containers at each reusable package rotation, the manufacturing phase weights on the carbon footprint balance (Global warming 20 y, GWP_{20}) among the three alternative material-driven networks. Considering container 6410, the impacts found are 8277 (RPC), 14790 (PP), and 9686 (CC) kg CO_2 eq/Normalized Pallet · 10 year.

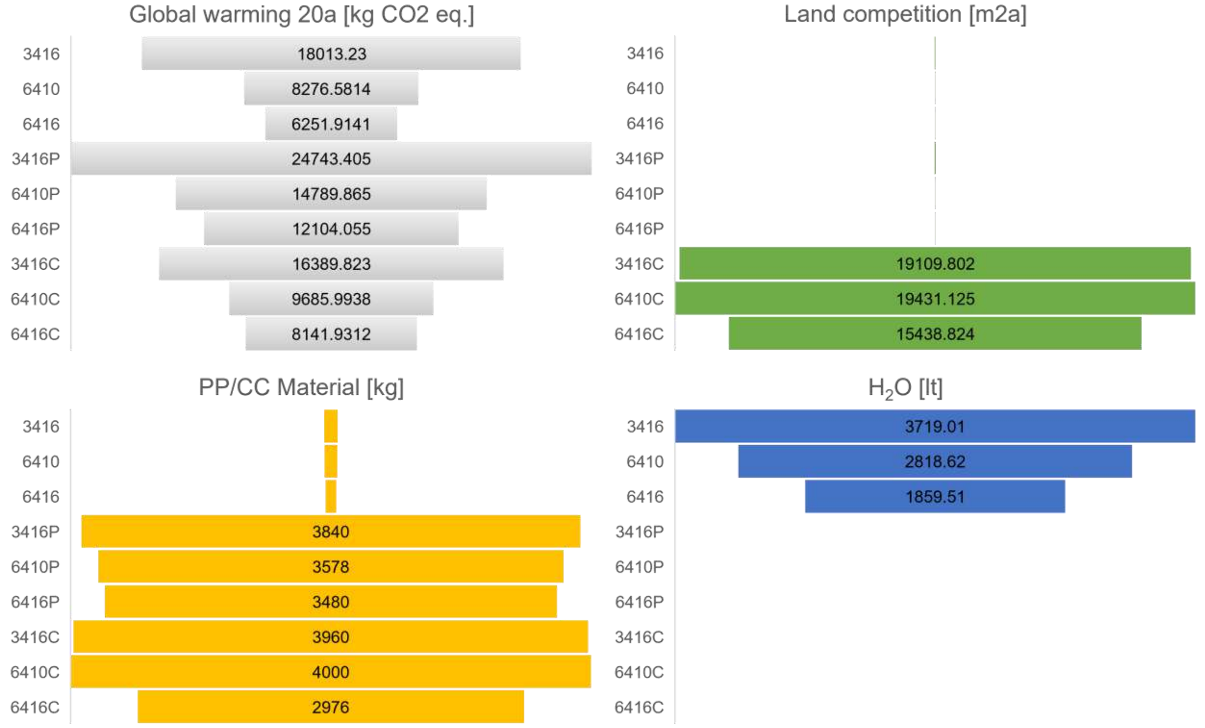

Fig. 12. Carbon footprint and natural resources exploitation (land use, water, raw materials): SPSs comparison.

Whilst depicting the exploitation of natural resources from the SPSs systems, Fig. 12 demonstrates that Global warming 20 (GWP_{20}) is sensitive to the packaging hierarchy (i.e., combination of secondary package and pallet) and the container size, affecting truckload utilization and shipping weight. It is not surprising that smaller containers with lower payload (i.e., 3416) emit more than the others. Water usage is intensive in the reusable network requiring up to 3719 liter over the time-span of 10 year. Land use is solely accounted for CCBs, because of the paper pulp's extraction from plantings. The solid waste produced in the SPSs network is accounted for in the Global Warming Potential. While single-use crates are disposed of after every use, reusable PP crates are disposed of only when broken. In RPCs' network, data collected on raw material supply and crates disposal include the flows needed to replace the broken crates and fulfill the demanded circulations in the network. The actual number of broken crates is deduced from the RPCs company's IT system (i.e. ERP). For reference, the weight of broken reusable containers occurred over one year is 17,264 kg corresponding to 12,331 6410 RPCs. The number of broken crates is calculated per each SPS considering the ratio of the total weight crates shipped to grinding divided to the container's weight. The flows and processes needed to compensate the RPCs breakdown are yet included in the primary data. Therefore, this study did not consider any assumption on crates' breaking rate.

When the mid-point CML2002 indicators were normalized (Fig. 13), the impact of smaller crates became increasingly evident. Type 3416 presents a lower GWP_{20} for CCB than for reusables, but global warming underestimates the environmental impacts compared with abiotic depletion (AD) or aquatic ecosystems (AEs).

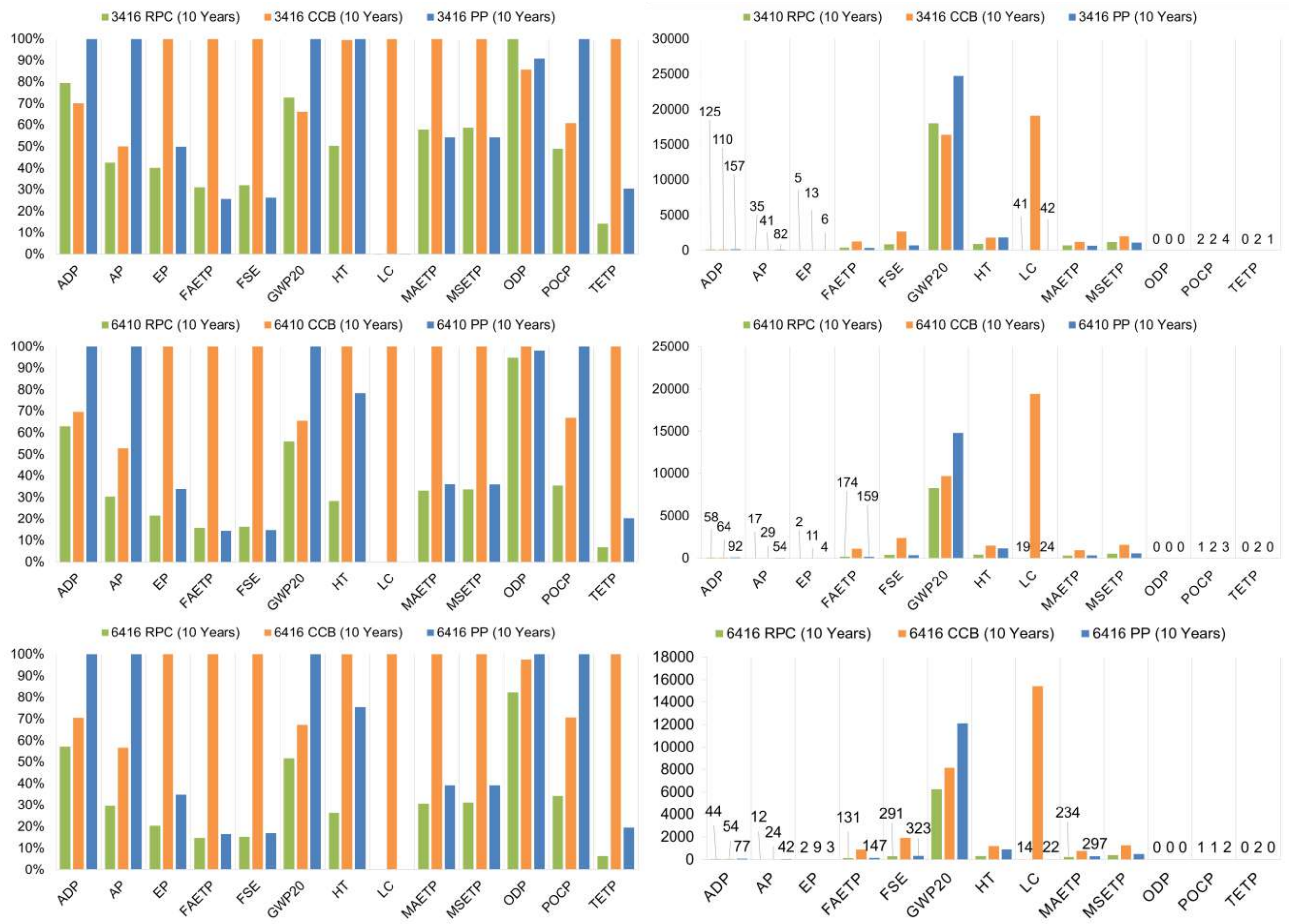

Fig. 13. Mid-point indicators (CML2002) (NF: West Europe, 1995). Left: Normalized SPSs comparison. Right: Characteristic SPSs comparison. (*Legend: ADP: Abiotic Resource Depletion Potential [kg Sb eq]; AP: Acidification Potential [kg SO_2 eq]; EP: Eutrophication Potential [kg PO_4 eq]; FAETP: Freshwater aquatic ecotoxicity 20y [kg 1.4-DB eq]; FSE: Freshwater sediment ecotoxicity 20y [kg 1.4-DB eq]; GWP20: Global Warming Potential 20y [kg CO_2 eq]; HT: Human toxicity potential 20y [kg 1.4-DB eq]; LC: Land competition [m^2y]; MAETP: Marine aquatic ecotoxicity 20y [kg 1.4-DB eq]; MSETP: Marine sediment ecotoxicity 20y [kg 1.4-DB eq]; ODP: Ozone Depletion Potential 20y [kg CFC-11 eq]; POCP: Photochemical Oxidant Creation Potential [kg C_2H_4 eq]; TETP: Terrestrial ecotoxicity 20y [kg 1.4-DB eq]*).

A summary is provided in Fig. 15 through the representation of the *end-point EcoIndicator '99*. RPC appears to be the most environmentally friendly SPS for the distribution of fresh food in a country-wide retailer SC made of thousands of facilities over a time-span of 10 years. The time-span affects the number of rotations for reusables which tips the scale of the conclusion, particularly when comparing RPCs' to single-use CCs' SPSs. By tracing the actual circulations of RPCs, this paper extends the analysis proposed by Koskela et al. (2014). Each RPC's rotation corresponds to manufacturing a CC box using virgin instead of recycled fibers by assumption. Although the Italian regulation (D.M. 21.03.1973 and update D.M. 220 26.04.1993) allows adopting recycled paper kraft as SP for some food varieties, retailers seldom differentiate carton waste, and the required level of purity and quality of fibers is no longer guaranteed. It results in higher impacts from the manufacturing process for CC boxes, increasing proportionally to each RPC rotation. While the assumption of a 10-years lifespan with 10 circulations per year was statistically reasonable (after direct observation), CC boxes might be environmentally convenient with early disposal of the reusables (as in Koskela et al., 2014).

EcoIndicator '99 (Eco-indicator 99 (H) v2.08/ Europe EI 99 H/A) quantifies the endpoint indicators (i.e., in terms of DALY, PDF·m^2yr, and MJ surplus). In Fig 14. provides a single-score indicator (Pt). for all impact categories. The packaging hierarchy affects truckload utilization in a way that only accurately tracing the shipments' payload permits reliable considerations about the outputs of GHGs emissions and fossil fuel. While confirming the importance of transportation in the LCA results (Abejon et al., 2020; Koskela et al., 2014), this study uses a GIS-based SC digital twin to augment the resolution of transportation data and provide a logistic-driven punctual LCA comparison of alternative SPS in a country-wide real distribution network mode of thousands of facilities. The importance of considering different material-driven networks results from the fact that different actors manage different SPSs and the logistics infrastructure (i.e., the spatial configuration of the facilities' network) cannot be assumed to be equal. In this analysis, the pooler provides, collects, and replenishes the RPCs, some manufacturers supply single-use containers, and two independent country-wide consortiums are responsible for single-use EOL processes. Because the material-driven networks are different, the LCEI is extremely sensitive to the network topology and the operational capacity and throughput of the facilities. This conclusion paves the way for merging environmental sciences and assessment with proactive operations and logistic network planning and optimization modelling (Bortolini et al., 2018; Accorsi et al., 2020) to support environmentally friendly holistic packaging systems.

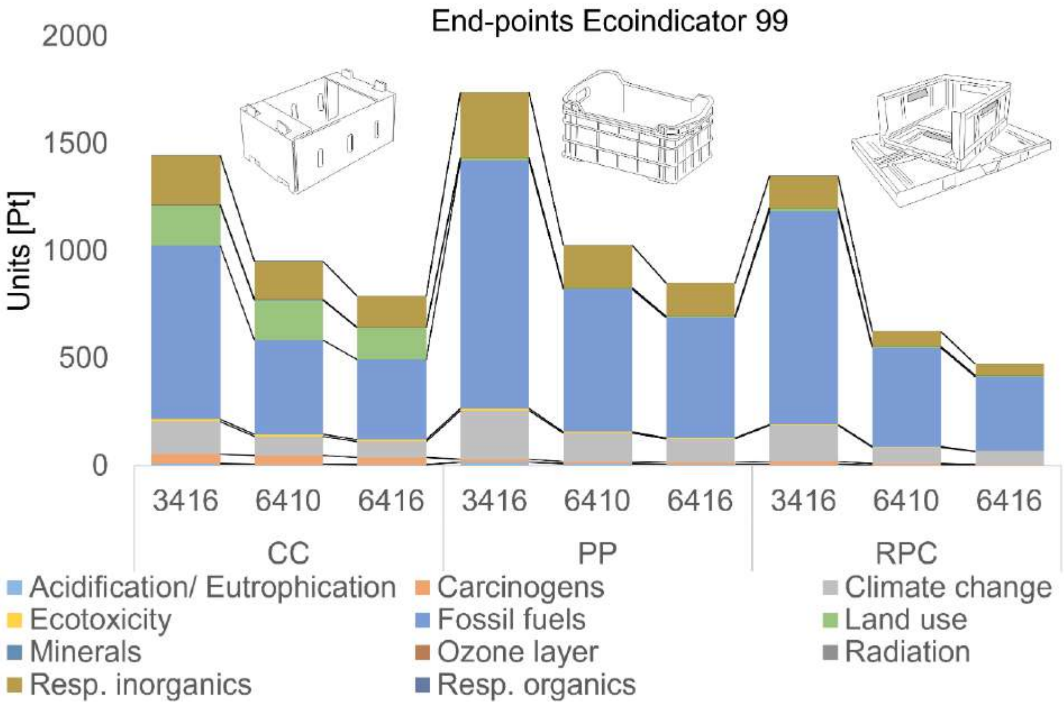

Fig. 14. End-point indicators (Eco-indicator 99 (H) V2.08 / Europe EI 99 H/A); No skip categories: SPSs comparison.

This augmented spatial LCA is based on primary data resulting from tracking real-world processes and virtualizing the containers' transportation flows throughout the material-driven networks. To confirm the findings, a sensitivity analysis is carried out upon the rotations of RPCs. This focus is justified by the relevance of the different material-driven networks and the logistic complexities that such a network entails. Fig. 15 compares the impact GWP_{20} considering the SPS 6410-sized container of the two most environmentally friendly packages: single-use CC boxes and RPCs. The Mid-points and End-points indicators resulting from the ReCiPe method are in Appendix A. As expected, the results are not perfectly overlapping, but the environmental impact of the RPCs still stands.

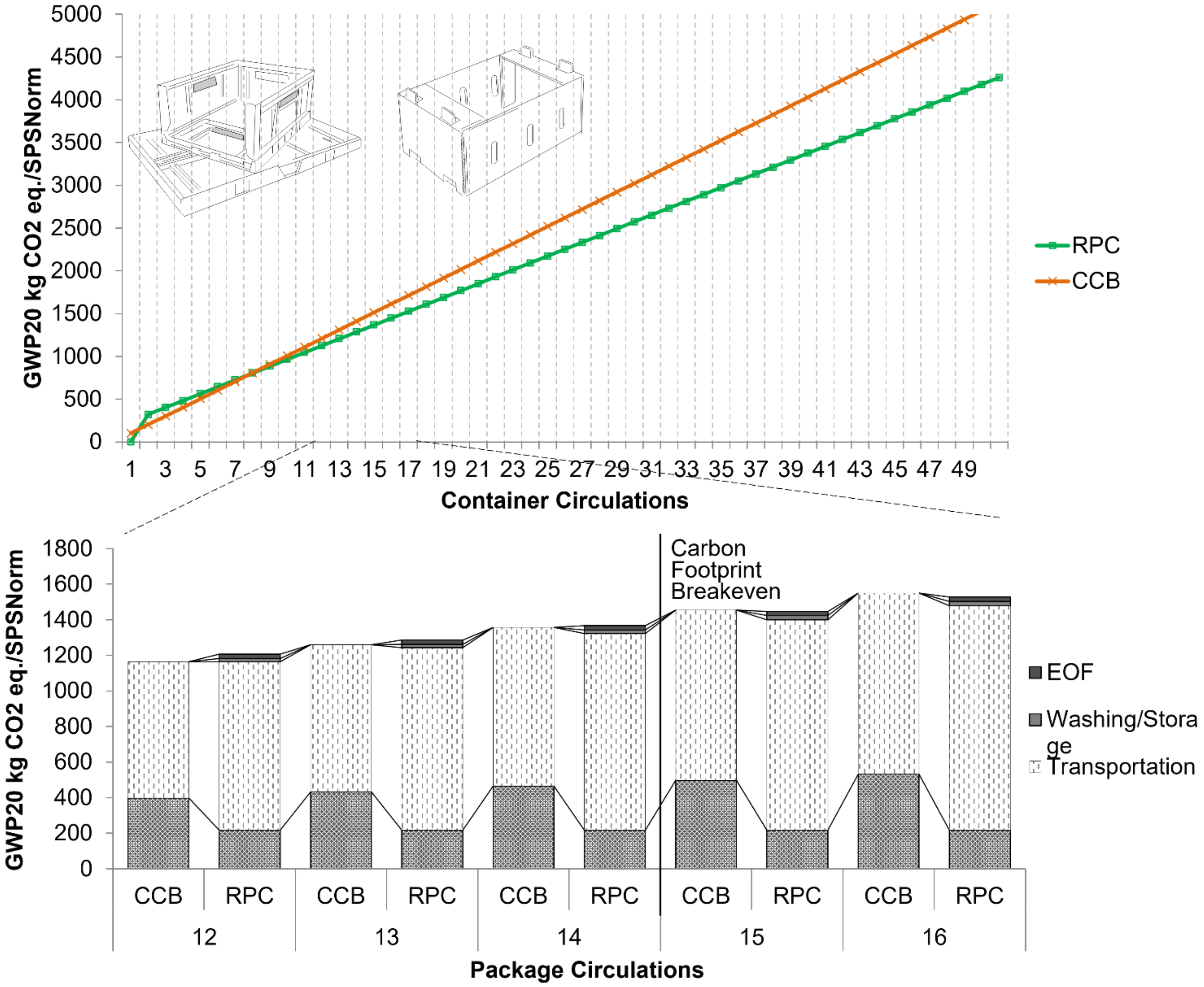

Fig. 15. Sensitivity analysis on the number of reusable containers circulations before recycling: 6410 SPSs comparison.

The results demonstrate that containers' manufacturing provides a substantial impact on GWP_{20}. Given the percentage of virgin PP assumed for the RPC (60%) and the weight of each crate (1.4 kg), the results in Fig. 15 leave room for further reducing RPCs impact compared to CC made of virgin fibers. Transportation is intensified with RPCs but not negligible for CCBs, because the shipments from the *jobbers* to the growers occur with a low truckload. Furthermore, although the recycling consortium is distributed broadly country-wide, the carton waste collection is not optimized as with the RPCs pooler. The latter is indeed a centralized player, operating as a logistic provider, able to handle inter-facilities flows of containers without empty backhauls and with standardized operations. Washing and warehousing processes have limited effects as they put off the environmental breakeven, achieved at the 15th circulations, of only two rotations. Because CCBs are made of virgin fibers solely, the impacts of the recycling process are excluded from the LCIA. Because 80–100 rotations are empirically feasible before disposal with the considered RPC recipe (i.e., 60% virgin PP, 40% secondary PP), the environmental payback from using RPCs compared to CC boxes is within one year and a half. Given the country-wide spatial boundaries of the observed networks and the related complexity, other levers of sensitivity are out-of-scope for this article and left to future research.

4. Conclusions

FSCs are hotspots for climate change control and mitigation. The packaging industry plays a pivotal role in the overall impact of FSC owing to waste, resource utilization, and transportation issues. The trade-off between RPCs and single-use packaging systems remains unclear. The reuse of RPCs during the use phase shares the impacts of crate production and EOL treatments over the entire crate lifespan. Moreover, the role of the pool centralizing container collection and supplies aids in planning logistics operations and transportation of open and closed RPCs accurately. However, the collection, washing, repairing, warehousing, and replenishing operations of RPCs trigger new flows, increasing the logistic complexity of such a network. Therefore, the comparison of different SPSs impacts cannot overlook the material-driven network configuration (i.e., topology). In this context, high-quality primary data represent the keystone in SPSs impact assessments (Vidergar et al., 2021).

Previous studies tackled the reusable single-use dilemma using LCA. Despite the critical role of logistics, the complexity of the network configuration is hardly considered, and aspects such as truckload utilization or traveling routes are neglected when using averages (Genovesi et al., 2022). In this study, augmented spatial LCA analysis was conducted. The novel contributions lie in the *scale*, *accuracy*, and *logistics lens* undertaken in the spatial dimension of this study. The augmented resolution of the spatial information was provided by an SC Digital Twin. This tool virtualizes the logistic flows of containers, food, and auxiliary materials and evaluates GHGs emissions and fuel consumption outputs for each shipment. An input/output database supports the digital twin, providing high-quality primary data on transportation modes and flows to the LCEI assessment.

The LCIA shows that the RPCs network is generally preferable to other single-use SPSs for Italian retailers' fruits and vegetables. Considering the impact category GWP_{20}, RPCs were preferable after only 15 rotations. The different performances of the normalized SPSs indicate that the environmental impacts are sensitive to the size of the crate and the packaging hierarchy. In terms of GWP_{20}, the transport phases of RPC were +23.80% and +17.20% compared to CCB and PP, respectively. Such results are extremely case-dependent and leave room for material-network optimization. Considering crates as transport items, the configuration of the closed-loop network and the minimization of the traveled distances during the supply and collection of crates are critical success factors for facilitating RPCs, at least in the retailers' supply chain (Gustavo et al., 2018; Gardas et al., 2019).

FSC stakeholders can benefit from applying the proposed augmented spatial LCA. The LCA methodology and the environmental impact indicators applied in this study reveal logistics hotspots and criticalities, such as bottlenecks, facility locations, and truck capacity underutilization. The identification of such criticalities and the quantification of the resulting environmental impacts can help practitioners in strategic network redesign. Network optimization and LCEI monitoring can also be encouraged by policymakers through incentives supporting specific sizes and materials, or packaging networks quantified as more environmentally friendly. Furthermore, the lack of high-quality primary data in FSC LCA analysis is overcome by an SC digital twin, providing a proof-of-concept for future academic research on the topic. Moreover, Digital Twin flexibility allows the virtualization and comparison of alternative network configurations in terms of number, locations, and operational processes.

The sensitivity of the results to the input parameters requires precise tracking of packaging flows. Despite the materials, different networks or logistics infrastructures have different environmental impacts. Adopting internet-of-things architectures, which aid data collection and/or digital twins, to virtualize the supply chain operations, ensure accuracy of the measurement, and pave the way for quantitative decision-support tools integrating operations optimization, LCA methodology, and impact mitigation strategies toward packaging ecosystem carbon neutrality. These are left for future research.

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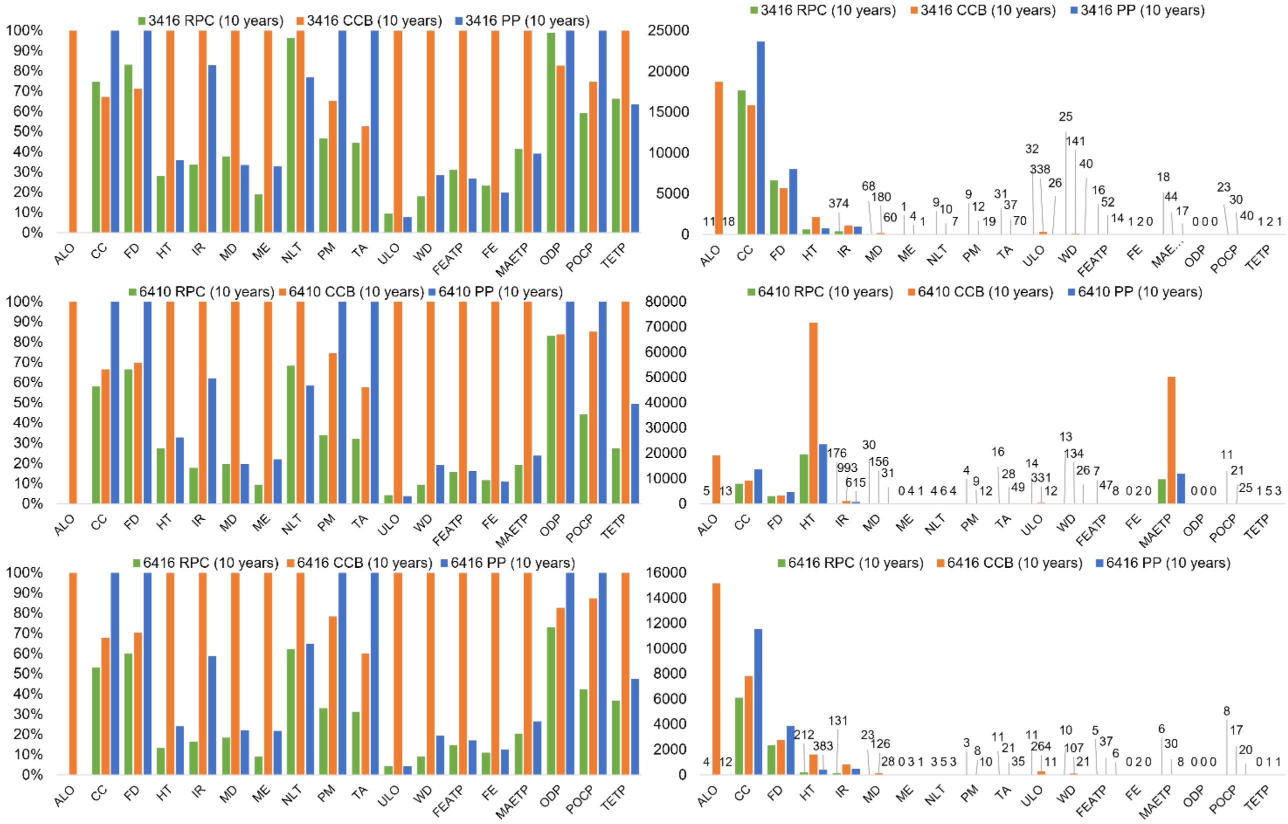
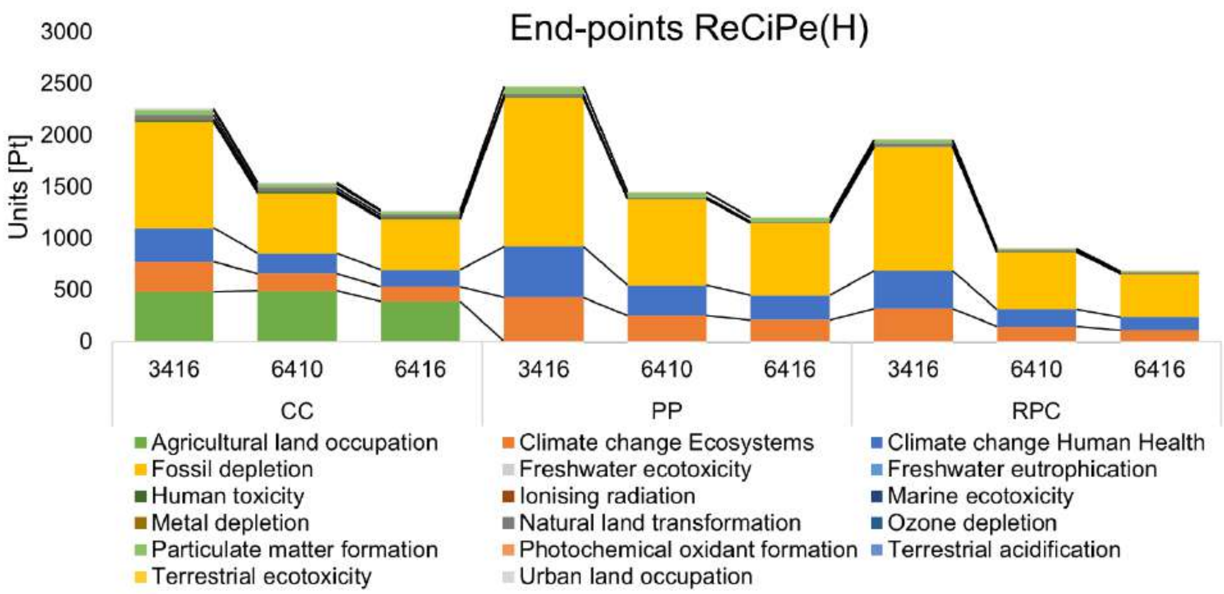
Appendix A – Mid-points and End-points ReCiPe results



Mid-point indicators (ReCiPe2008): Left: Normalized SPSs comparison. Right: Characteristic SPSs comparison. (Legend: ALO: Agricultural land occupation [m^2a]; CC: Climate change [kg CO_2 eq]; FD: Fossil depletion [kg oil eq]; HT: Human toxicity [kg 1,4-DB eq]; IR: Ionising radiation [kg U_{235} eq]; MD: Metal depletion [kg Fe eq]; ME: Marine eutrophication [kg N eq]; NLT: Natural land transformation [m^2]; PM: Particulate matter formation [kg PM10 eq]; TA: Terrestrial acidification [kg SO_2 eq]; ULO: Urban land occupation [m^2a]; WD: Water depletion [m^3]; FEATP: Freshwater ecotoxicity [kg 1,4-DB eq]; FE: Freshwater eutrophication [kg P eq]; MAETP: Marine ecotoxicity [kg 1,4-DB eq]; ODP: Ozone depletion [kg CFC-11 eq]; POCP: Photochemical oxidant formation [kg NMVOC]; TETP: Terrestrial ecotoxicity [kg 1,4-DB eq])



1 *End-point indicators (ReCiPe2008 (H)); No skip categories: SPSs comparison.*

	Containers type				Scenarios parameters						Logistics' leverage			
Author, Year	RPC	PPC	CCB	DWB	Time span	System's boundaries	FU	Mid-point End-point	LCIA method	Network	Raw material extraction-production plant	Production plant - FSC's actors	FSC's actors – poolers' facilities (Only for RPCs)	EOL logistics
Singh et al., 2006	x		x		2 years	C2C	1000 [t] of product	TGG, TSW, TEn	IPCC report	USA	COS	COS	COS	NC
Levi et al., 2011	x		x		10 years	C2G	100 [kg] of product	GWP, ODP, AP, EP, PE-NR, POCP	EPD guideline	EU	NC	GPS	NC	NC
Albrecht et al., 2013	x		x	x	10 years	C2G	15 [kg] of product	ADP, PED, EP, AP, POCP	CML 2002	EU	GPS	GPS	COS	NC
Koskela et al., 2014	x		x		2 years	C2G	8 units of product	CC, TA, POCP, FE, FD, PM	ReCiPe	EU	COS	COS	NC	NC
Tua et al., 2019	x				2 years	C2G	1200 [kg] of product	CC, ODP, HTP, PM, POCP, AP, TE, FE, ME, CED, RD, WD	ILCD, CED	Italy	NC	GPS	NC	NC
Abejón et al., 2020	x		x		10 years	C2G	$[6.6 – 10]*10^6$ crate's fillings	PE, PE-R, PE-NR, GWP, ODP, AP, EP, POCP	Impact 2002+, CML 2002	Spain	COS	GPS	COS	COS
Franklin Associates, 2016	x		x		\	C2G	1000 [tons] of perishable products	PED, GWP, ODP, WD, AP, EP, POCP, TSW	TRACI 2.1	North America	COS (P only for RPC)	COS (P only for RPC)	COS (P only for RPC)	COS (P only for RPC)
This paper	x	x	x		10 years	C2G	1579.22 dm3	ADP, AP, EP, FAETP, FSE, GWP, HTP, LC, MAETP, MSETP, ODP, POCP, TETP	CML 2002, EcoIndicator 99	Italy	P	P	P	P

Table 1. State of the art on RCPs' LCA (Abbreviations: C2C: Cradle to Cradle; C2G: Cradle to Grave; NC: Not Considered; GPS: General Purpose Secondary data; COS: Case Oriented Secondary data; P: Primary data; TGG: Total Greenhouse Gas; TSW: Total Solid Waste; Ten: Total Energy; ODP: Ozone Depletion Potential; AP: Acidification Potential; EP: Eutrophication Potential; PE-NR: Use of Primary Non-Renewable Energy; ADP: Abiotic Resource Depletion Potential; PED: Primary Energy Demand; POCP: Photochemical Oxidant Creation Potential (or Photochemical Ozone Formation); CC: Climate Change; TA: Terrestrial Acidification; PM: Particulate matter; FD: Fossil depletion; HT: Human toxicity potential; TE: Terrestrial Eutrophication; FE: Freshwater eutrophication; ME: Marine eutrophication; CED: Cumulative Energy Demand; RD: mineral, fossil and renewables resources depletion; WD: water resource depletion; PE: Use of Primary Energy; PE-R: Use of Primary Renewable Energy; GWP: Global Warming Potential; FAETP: Freshwater aquatic ecotoxicity; FSE: Freshwater sediment ecotoxicity; LC: Land competition (or Land Use); MAETP: Marine aquatic ecotoxicity; MSETP: Marine sediment ecotoxicity; TETP: Terrestrial ecotoxicity)

SPS		Weight [kg]	Outer size (Close) [mm]	Outer size (Open) [mm]	Inner size [mm]	Inner Volume [dm^3]
Size	Package/Material					
3416	PP Reusable	1.1	300x400x35	300x400x180	270x370x165	16.48
6410		1.4	600x400x35	600x400x119	570x370x104	21.93
6416		1.8	600x400x35	600x400x180	570x370x165	34.79
3416P	PP Single-use	0.400		300x400x175		17.5
6410P		0.497		600x400x120		24
6416P		0.725		600x400x175		35
3416C	CC Single-use	0.450			300x400x196	23.52
6410C		0.500			600x400x107	25.68
6416C		0.620			600x400x167	40.08

Table. 2: SPSs alternatives.

SPS			Open/Close Crate Volume Gain [%]	Carrying food volume [dm^3]	Normalized volume	Open Crates per Pallet	Close Crates per Pallet	Pallet Weight (Open) [kg]	Pallet Weight (Close) [kg]
Material		Size							
Reusable	PP	3416	80	1582.41	0.997979	96	480	105.6	528
		6410	70	1579.22	1	72	240	100.8	336
		6416	80	1670.33	0.945454	48	400	86.4	432
Single-use	PP	3416P	0	1680	0.9400114	96	96	38.4	38.4
		6410P	0	1728	0.9139	72	72	35.78	35.78
		6416P	0	1680	0.9400114	48	48	34.8	34.8
Single-use	CC	3416C	91	2069.76	0.7629962	88	1000	39.6	450
		6410C	89	2054.4	0.7687009	80	740	40	370
		6416C	93	1923.84	0.8208683	48	700	29.76	434

Table 3. SPSs' pallets features.

SPSs			Package Makers		Recipe			Suppliers		Inputs: Materials and energy [kg]							
Package	Type	Material	Primary Facility Location	Back-up Facility Location	First material [Location; %Flow]	Second material [Location; %Flow]	Coloring masterbatch [Flow%]	Distance [material supplier→ Primary facility]	Norm. FU weight [kg]	First material [kg]	Second Material [kg]	Oil [kg]	Color [kg]	Gas [kg]	LDPE [kg]	Used Oil [kg]	E_{FU}^{Prod} grid/IT [kWh]
Reusable	3416	PP	Gallo (FE)	Polesine Parmense (PR) - 162 km from primary facility	Secondary PP [Malalbergo (BO); 59%]	Virgin PP [Antwerp - Belgium; 39%]	2%	2.7 km [Gallo → Malalbergo]; 1186 km [Gallo → Antwerp]	104.5	61.655	40.755	0.027	0.06	0.176	2.09	0.027	116.449
	6410								100.8	59.472	39.312	0.041	0.09	0.266	2.016	0.021	88.485
	6416								85.5	50.445	33.345	0.014	0.03	0.003	1.71	0.014	58.376
Single-use	3416	PP	Forlì-Cesena (FC) Salerno (SA)	/	Secondary PP [CONIP network; 99%]	/	1%	158 km [Forlì-Cesena → Modena*]; 232 km [Salerno → Modugno*]	39.09	38.304	0	0.027	0.06	0.176	0.782	0.027	116.449
	6410								35.41	34.703	0	0.041	0.09	0.266	0.708	0.021	88.485
	6416								35.42	34.713	0	0.014	0.03	0.003	0.708	0.014	58.376
Single-use	3416	CC	Suppliers αβ	/	Kraft Paper [San Felice Sul Panaro / Bellusco; 60%]	Semichemical papers [San Felice Sul Panaro / Bellusco; 40%]	/	See table 5	39.26	23.556	15.7						0.0438
	6410								39.92	23.95	15.97						0.0623
	6416								31.73	19.04	12.69						0.0374

Table 4. (Legend: * nearest CONIP Collectors: Rende (CS), Modena (MO), Modugno (BA), Lentini (SR), Legnano (MI); Suppliers αβ: San Felice sul Panaro, Bellusco, Buglio in Monte, Catania, Pomezia; Oil: *Lubrificant Oil; Color: Printing Colour; Gas: Liquefied Natural Gas; LDPE: Low-Density Polyethylene; Used Oil: Disposal, Used mineral Oil)*

	Vehicle	Dimension	Features	Emission Profile and Fuel Consumption	Network to serve
Roadways Transportation	Semitrailer truck	13600x2480x3000 [mm]	mass: 40 [tons]; pay load capacity: 25 [tons]	EU1-EU6 average value (2016) by Lipasto database (VTT, 2009)	994 food vendors and 58 retailer's warehouses (Italy)
Intermodal Transportation	Short-range containership	1000 [TEUs]	mass: 14000 [tons]; pay load capacity: 10000 [tons]	EU1-EU6 average value (2016) by Lipasto database (VTT, 2009)	clients within the two main Italian isles
	Cargo electric train		mass: 1016 [tons/train km]; pay load capacity: 525 [tons/train km]		international food vendors (we consider one from Belgium)

Table 5. Transportation modes.

Food Vendor α Nodes	Node Code	CC Sheets Supply Node [km $_{Supplier \rightarrow Vendor\ \alpha}$; Flow %]					CC Boxes Opening Node	
		San Felice sul Panaro	Bellusco	Buglio in Monte	Catania	Pomezia	Jobber Code	[km $_{Vendor\ \alpha \rightarrow Jobber}$; Flow %]
Altedo	002AL	48; 35	257; 35	352; 30			JOBCE	5; 70
Aprilia	002AP	472; 35	18.5; 35	746; 30			JOBCE	11.8; 100
Cesena	002C	413; 35	313; 35	410; 30			JOBLA	39.4; 50
Donnalucata	002DO			1595; 30	135; 35	950; 35	JOBAP	23.6; 50
Faenza	002FA	108; 35	286; 35	383; 30			JOBCE	23; 30
Forlì	002FO	126; 35	304; 35	401; 30			JOBCE	20.8; 30
Lavezzola	002LA	84.5; 35	292; 35	389; 30			JOBSC	7.3; 100
Romagnano	002RO	168; 35	346; 35	443; 30			JOBDO	33.3; 100
Scanzano Jonico	002SC			1113; 30	429; 35	503; 35	JOBVI	3.1; 100
San Pietro in Vincoli	002SP	131; 35	309; 35	406; 30			JOBLA	2.6; 30
Vignola	002VI	50.5; 35	210; 35	307; 30			JOBCE	40.1; 70
Longiano	002LO	149; 35	371; 35	424; 30			JOBCE	302; 50

Table 6. CC sheets and boxes supplies to *Vendor α*.

Package	Type	Material	Transportation Loads [kg ·10^6/$_{1Years}$]			
			Network (Overall)			
			Auxiliary Materials (Without Pallet)	Pallets	Crates	Total
Reusable	3416	PP	0.526	22.448	5.798	67.909
	6410				22.405	
	6416				16.731	
Single-use	3416P	PP	21.969	15.288	1.330	48.012
	6410P				5.614	
	6416P				3.811	
Single-use	3416C	CC	15.693	16.953	2.187	45.043
	6410C				6.530	
	6416C				3.679	

Table 7. Transport loads and flows across the networks.

SPS		Flow [kg·10^6]	Transport *Output* (GHG emissions) and *Input* (Fuel) [kg]									
			$Co_2Eq \cdot 10^4$	CO	HC	NO_x	PM	CH_4	N_2O	SO_2	$CO_2 \cdot 10^4$	Fuel $\cdot 10^4$
6410 RPC	Close crate											
	Semitrailer truck	14.203	17.296	24.515	2.920	49.353	0.896	0.151	11.284	0.574	16.954	5.972
	Containership (1000 TEUs)	0.169	0.281	6.512	2.138	54.425	0.972	0.262	0.069	1.652	0.272	0.088
	Open crate											
	Semitrailer truck	7.978	362.610	574.286	52.421	1039.09	19.042	3.450	275.16	12.121	354.022	124.743
	Containership (1000 TEUs)	0.054	0.064	1.479	0.486	12.366	0.221	0.060	0.016	0.375	0.0618	0.020
	Auxiliares Material	0.263	0.403	2.83	0.82	20.68	0.37	0.10	0.24	0.61	0.393	0.135
	Pallet	3.684	64.514	102.95	9.74	194.30	3.56	0.66	48.74	2.45	62.992	22.194
			Co_2Eq	CO·10^{-2}	HC·10^{-2}	$NO_x \cdot 10^{-2}$	PM·10^{-3}	$CH_4 \cdot 10^{-3}$	$N_2O \cdot 10^{-3}$	$SO_2 \cdot 10^{-3}$	CO_2	Fuel
	GHGs Emissions^{1,1,1}		0.915	0.0146	0.0014	0.0281	0.005	0.001	0.069	0.004	0.893	0.315
	GHGs Emissions^{1,FU,1}		65.847	1.0540	0.1014	2.0268	0.371	0.069	4.963	0.263	64.298	22.654
	GHGs Emissions^{10,FU,10}		6584.747	105.40	10.1	202.7	37	7	496	26	6429.810	2265.397
			$Co_2Eq \cdot 10^4$	CO	HC	NO_x	PM	CH_4	N_2O	SO_2	$CO_2 \cdot 10^4$	Fuel·10^4
6410 PP	Open crate											
	Semitrailer truck	5.457	265.596	419.975	38.493	761.045	13.944	2.524	201.118	8.877	259.321	91.374
	Containership (1000 TEUs)	0.157	0.175	4.063	1.334	33.959	0.606	0.164	0.043	1.031	0.169	0.055
	Auxiliares Material	11.468	5.395	9.38	1.60	32.33	0.58	0.13	3.35	0.70	5.292	1.861
	Pallet	3.498	143.950	229.86	21.64	432.34	7.91	1.46	108.94	5.42	140.548	49.521
			Co_2Eq	CO·10^{-2}	HC·10^{-2}	$NO_x \cdot 10^{-2}$	PM·10^{-3}	$CH_4 \cdot 10^{-3}$	$N_2O \cdot 10^{-3}$	$SO_2 \cdot 10^{-3}$	CO_2	Fuel
	GHGs Emissions^{1,1,1}		0.8538	0.0136	0.0013	0.0259	0.005	0.001	0.064	0.003	0.833	0.2937
	GHGs Emissions^{1,1FLP,1}		61.4741	0.9822	0.0934	1.8654	0.341	0.063	4.642	0.237	60.025	21.1488
	GHGs Emissions^{10,1FLP,10}		6147.407	98.2	9.3	186.5	34	6	464	24	6002.48	2114.88
	GHGs Emissions$^{10,1FU}_{(Normalized),10}$		5618.115	89.77	8.54	170.48	31.2	5.8	424.2	21.7	5485.67	1932.79
			$Co_2Eq \cdot 10^4$	CO	HC	NO_x	PM	CH_4	N_2O	SO_2	$CO_2 \cdot 10^4$	Fuel·10^4
6410 CC	Open crate											
	Semitrailer truck	6.337	254.130	402.7211	36.70	728.26	13.35	2.42	193.00	8.50	248.106	87.423
	Containership (1000 TEUs)	0.193	0.216	4.9897	1.64	41.71	0.74	0.20	0.05	1.27	0.208	0.067
	Auxiliares Material	8.267	1.565	2.2057	0.27	4.47	0.08	0.01	1.01	0.05	1.534	0.540
	Pallet	4.553	164.580	263.3769	24.75	496.01	9.08	1.68	124.80	6.25	160.681	56.614
			Co_2Eq	CO·10^{-2}	HC·10^{-2}	$NO_x \cdot 10^{-2}$	PM·10^{-3}	$CH_4 \cdot 10^{-3}$	$N_2O \cdot 10^{-3}$	$SO_2 \cdot 10^{-3}$	CO_2	Fuel
	GHGs Emissions^{1,1,1}		0.8649	0.0138	0.0013	0.0261	0.005	0.001	0.066	0.003	0.8444	0.2975
	GHGs Emissions^{1,1FLP,1}		69.1886	1.1079	0.1043	2.0904	0.383	0.071	5.247	0.264	67.550	23.800
	GHGs Emissions^{10,1FLP,10}		6918.863	110.8	10.4	209	38	7	525	26	6754.96	2380.03
	GHGs Emissions$^{10,1FU}_{(Normalized),10}$		5318.536	85.2	8.0	160.7	29	5	403	20	5192.54	1829.54

Table 8. Transportation emissions comparison among 6410 SPSs. Emissions^{x,y,z} corresponds to the emissions associated to x rotations per year of y crates during z years (without fuel/Diesel production).

Inputs (Washing Process $_{5,1FU (Normalized),10}$)		Reusable SP		
		3416	6410	6416
Water, process, unspecified natural origin/kg		3719.01	2818.62	1859.51
Sodium hydroxide, 50% in H2O, production mix, at plant/RER S		7.66	5.80	3.83
Sodium hypochlorite, 15% in H2O, at plant/RER S		1.33	1.01	0.66
Sulphuric acid, liquid, at plant/RER S		3.04	2.31	1.52
Aluminium sulphate, powder, at plant/RER S	[kg]	2.61	1.98	1.30
Acrylic acid, at plant/RER S		0.03	0.02	0.01
Acrylonitrile, at plant/RNA		0.03	0.02	0.01
Polypropylene fibres (PP), crude oil based, production mix, at plant, PP granulate without additives EU-27 S		4.55	6.89	4.55
Natural gas, high pressure, at consumer/IT S		1298.54	984.15	649.27
Electricity mix, AC, consumption mix, at consumer, < 1kV IT S	kWh	172.35	139.61	92.11
Outputs (Washing Process $_{5,1FU (Normalized),10}$)				
Waste incineration of municipal solid waste (MSW), EU-27 S	[kg]	15.15	11.48	7.58
Composting organic waste/RER S		4.35	3.30	2.17

Table 9. Washing inventory for reusable *SPs* (*SP_{RPC}*). Legend: *Washing Process $_{n. of cleanings per year, n. of normalized FU, n. of years}$*.

SPS		Impact Category (CML 2002)												
Size	Material/ Network	ADP [kg Sb eq.] 10^2	AP [kg SO_2 eq.] 10^2	EP [kg PO_4 eq.]	FAETP-20 [kg 1.4-DB eq.] 10^2	FSETP-20 [kg 1,4-DB eq.] 10^2	GWP-20 [kg CO_2 eq.] 10^2	HTP-20 [kg 1,4-DB eq.] 10^2	LC [m2a]	MAE-20 [kg 1,4-DB eq.] 10^2	MSE-20 [kg 1,4-DB eq.] 10^2	ODP-20 [kg CFC-11 eq.] 10^{-2}	POCP [kg C_2H_4 eq.]	TE-20 [kg 1,4-DB eq.]
3416	RPC (1 Normalized FU, 10 Years)	1.25008	0.349903	5.18452	3.82424	8.47941	180.132	9.06140	40.9551	6.83616	11.5726	0.207695	1.907914	0.287396
6410		0.581333	0.165011	2.40417	1.74059	3.85694	82.7658	4.18038	18.5407	3.09194	5.23253	0.094043	0.895716	0.133161
6416		0.43922	0.124468	1.82984	1.31135	2.90639	62.5191	3.14090	14.0001	2.33602	3.95369	0.071014	0.674227	0.099769
3416P	PP (1 Normalized FU, 10 Years)	1.57125	0.820918	6.4412	3.16274	6.96689	247.434	17.9946	42.0217	6.41591	10.7037	0.188566	3.896741	0.612842
6410P		0.922742	0.542576	3.76849	1.58946	3.48739	147.898	11.5637	24.1262	3.36824	5.58392	0.097295	2.524406	0.396282
6416P		0.767344	0.41704	3.13726	1.46772	3.22686	121.040	9.00414	22.3081	2.97332	4.94931	0.086173	1.963161	0.303083
6410C	CC (1 Normalized FU, 10 Years)	0.642157	0.286982	11.133	11.0403	23.6736	96.8599	14.7370	19431.1	9.33540	15.5173	0.099219	1.689271	1.938393
3416C		1.10244	0.411049	12.8951	12.3137	26.5142	163.898	17.9015	19109.8	11.8209	19.7318	0.177815	2.368933	2.012458
6416C		0.540776	0.236504	8.97556	8.86601	19.0185	81.4193	11.9308	15438.8	7.58893	12.6197	0.084062	1.388180	1.547029

Table 10. Results: CML 2002 Impact categories (Results include fuel/Diesel production). For each SPS is reported the impact categories of 1 Normalized FU circulating in the system for 10 years (*Legend: Abiotic depletion: ADP; Acidification: AP; Eutrophication: EP; Freshwater aquatic ecotox. 20 years: FAETP-20; Freshwater sediment ecotox. 20 years: FSETP-20; Global warming potential 20 years; GWP-20; Human toxicity 20 years: HTP-20; Land competition: LC; Marine aquatic ecotox. 20 years : MAE-20; Marine sediment ecotox. 20 years: MSE-20; Ozone layer depletion 20 years : ODP-20; Photochemical oxidation formation: POCP; Terrestrial ecotoxicity 20 years: TE-20)*

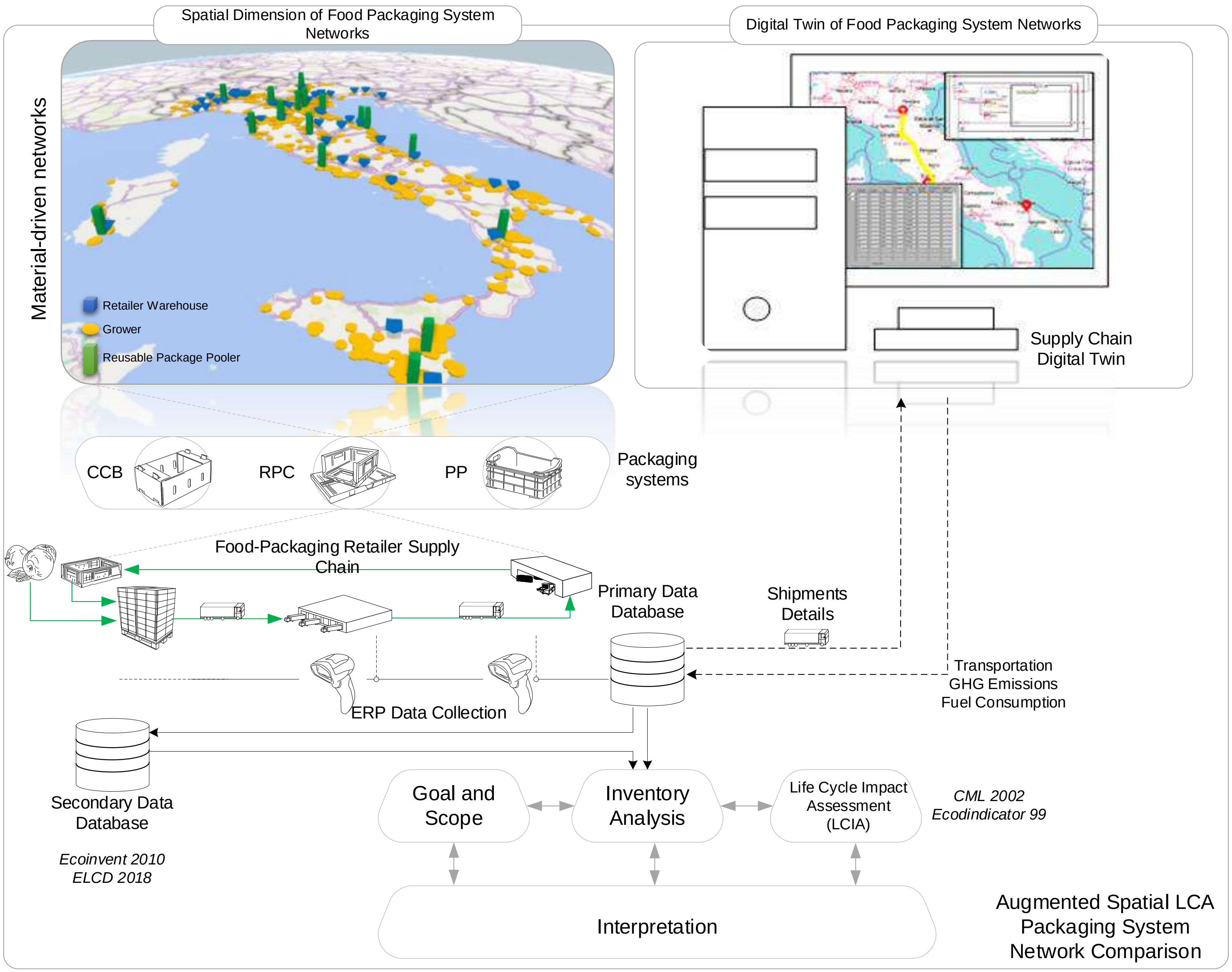


Fig. 1. Methodology: a spatial LCA augumented by virtualized shipments obtained from a SC digital twin.

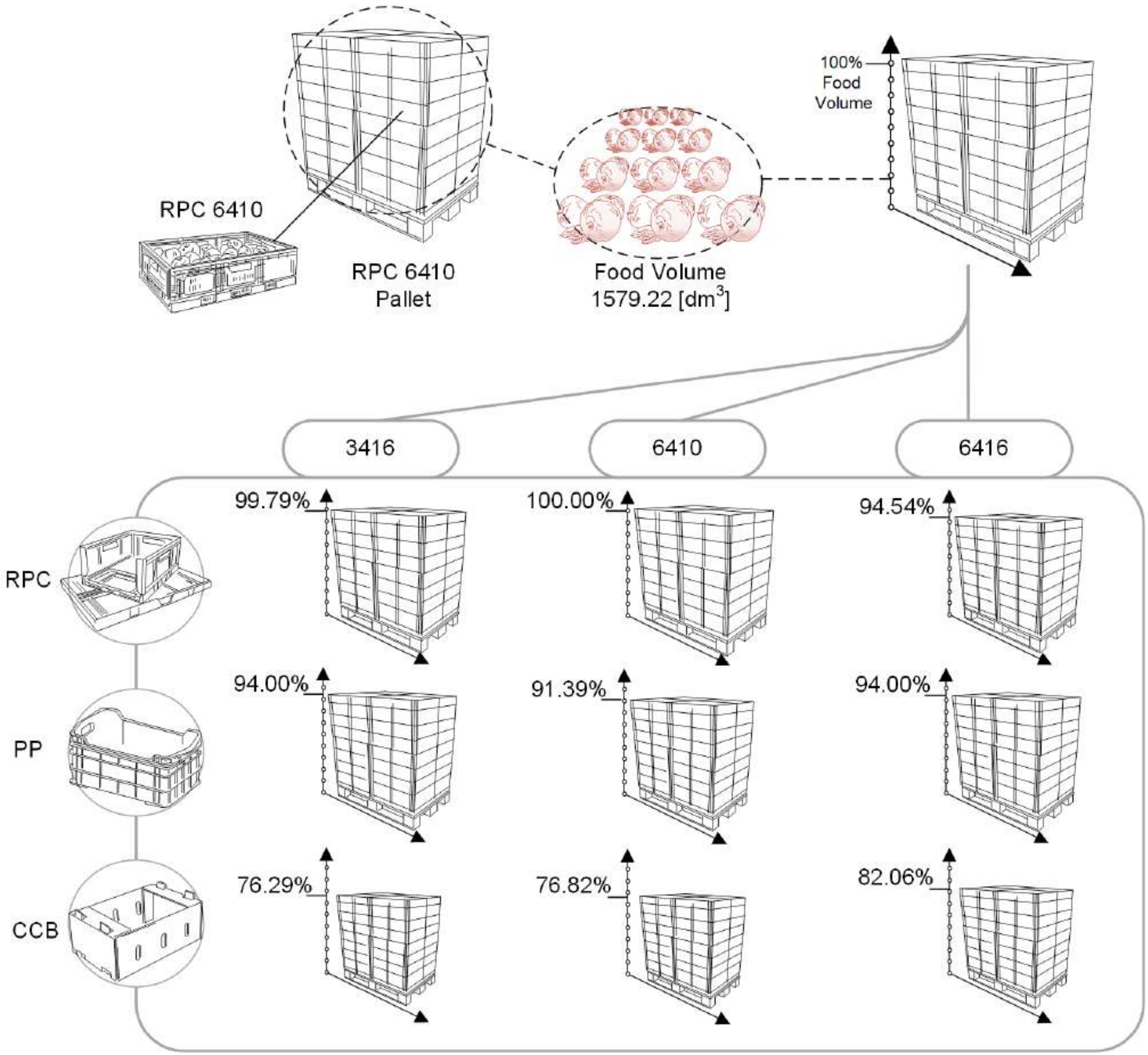


Fig 2. SPSs' composition and conversion factors.

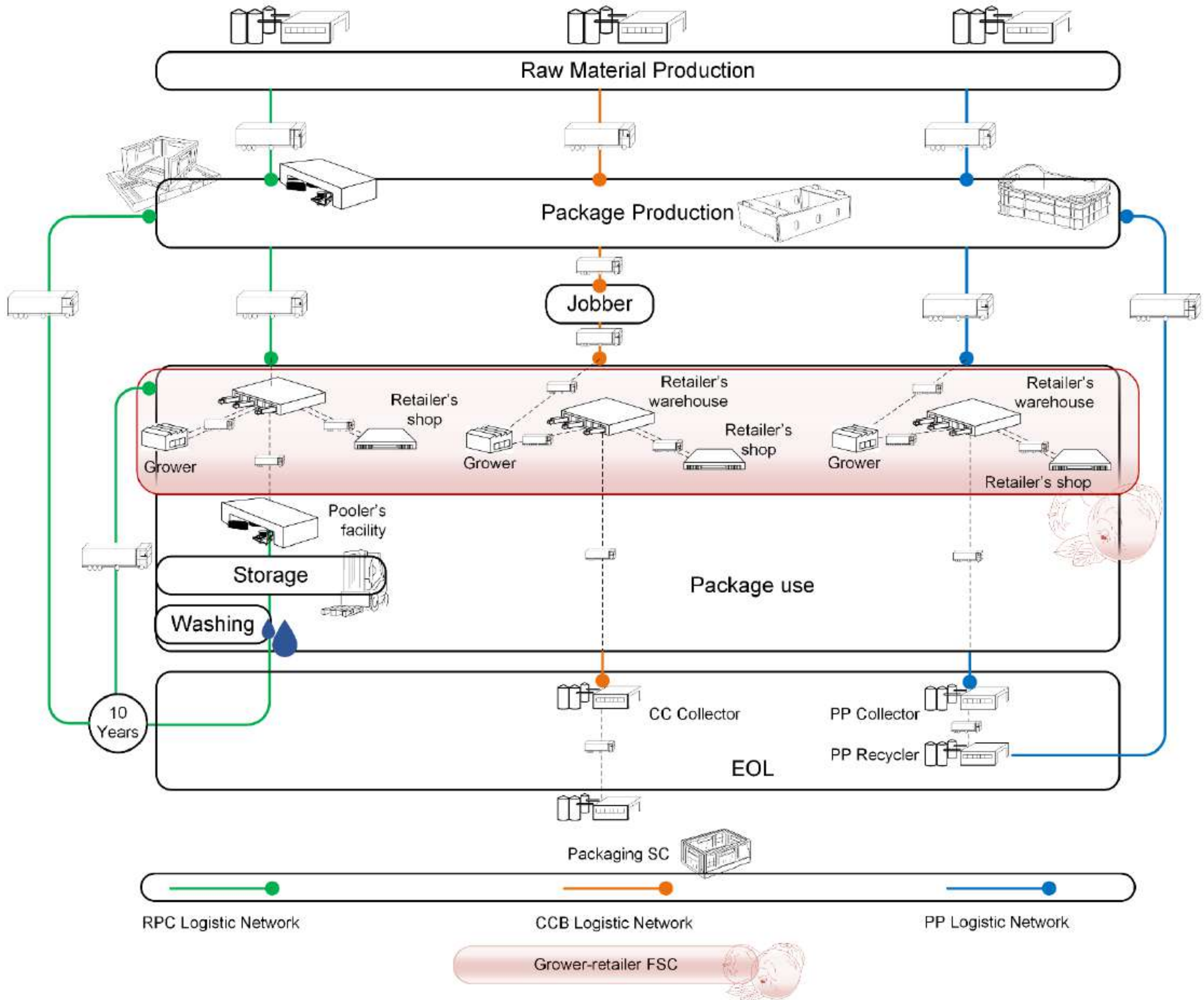


Fig. 3. Alternative SPSs material-driven networks.

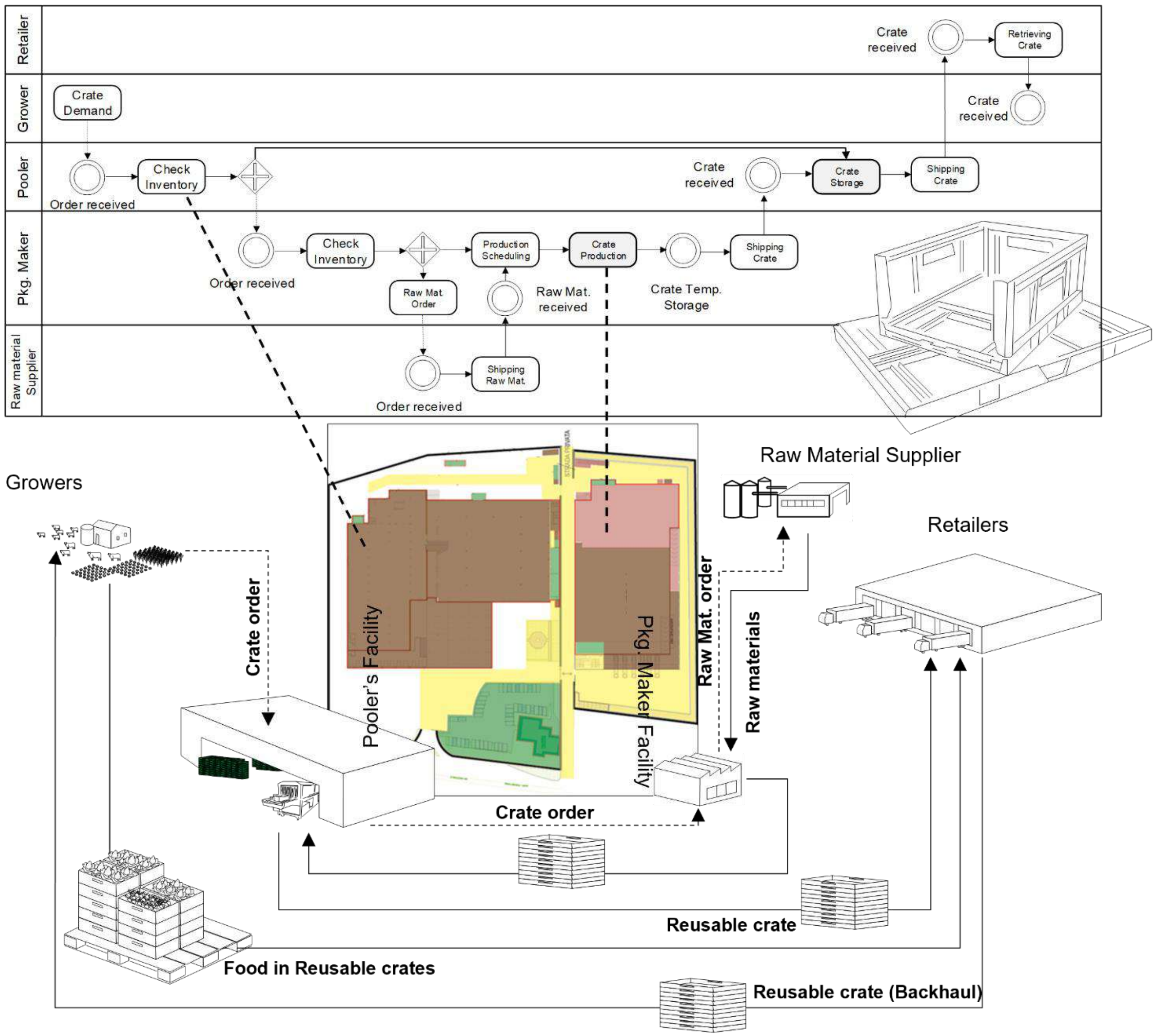


Fig. 4. BPMN for *in-node* and *internodes* processes assessment.

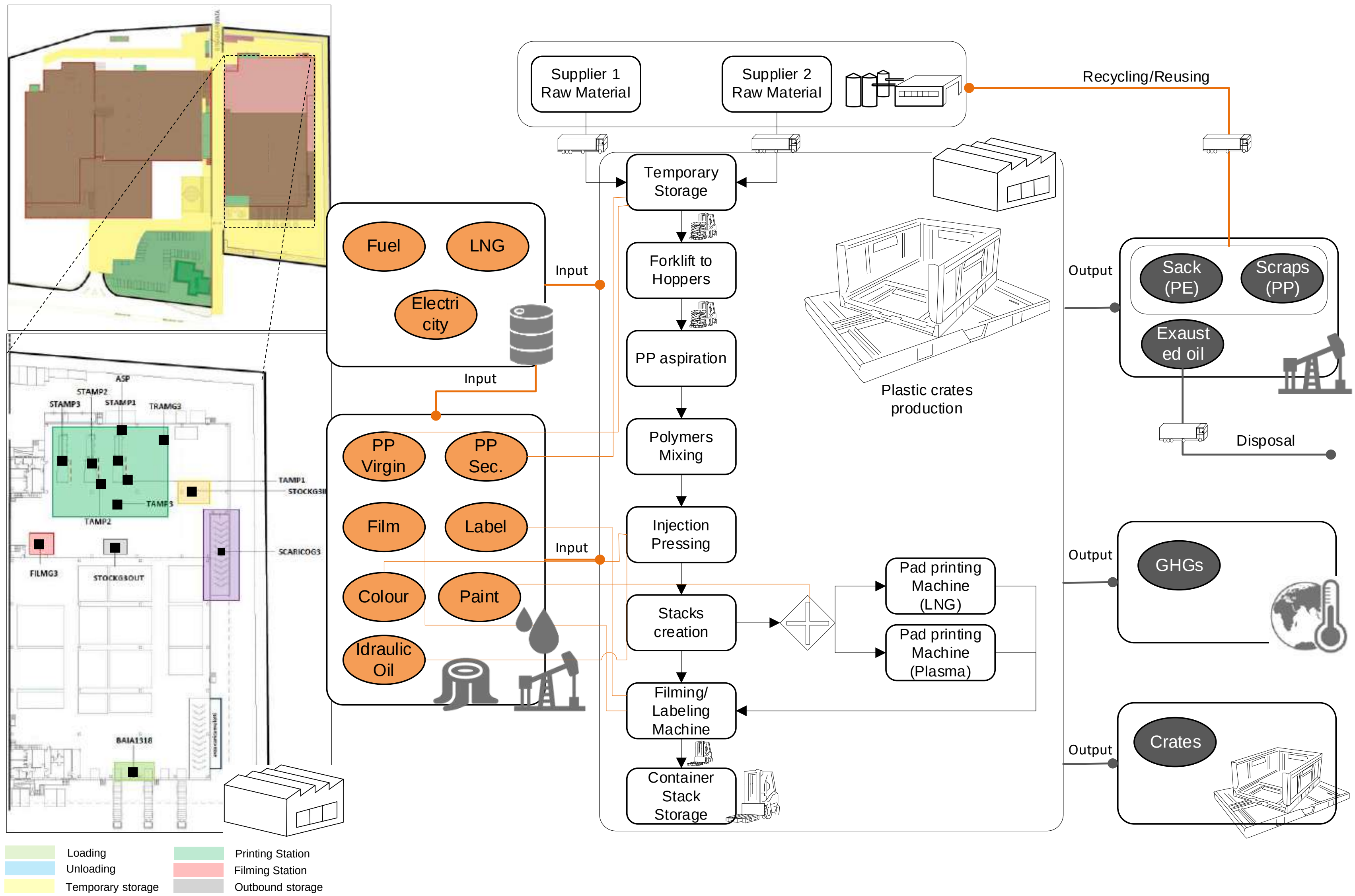


Fig. 5. Reusable containers production phase.

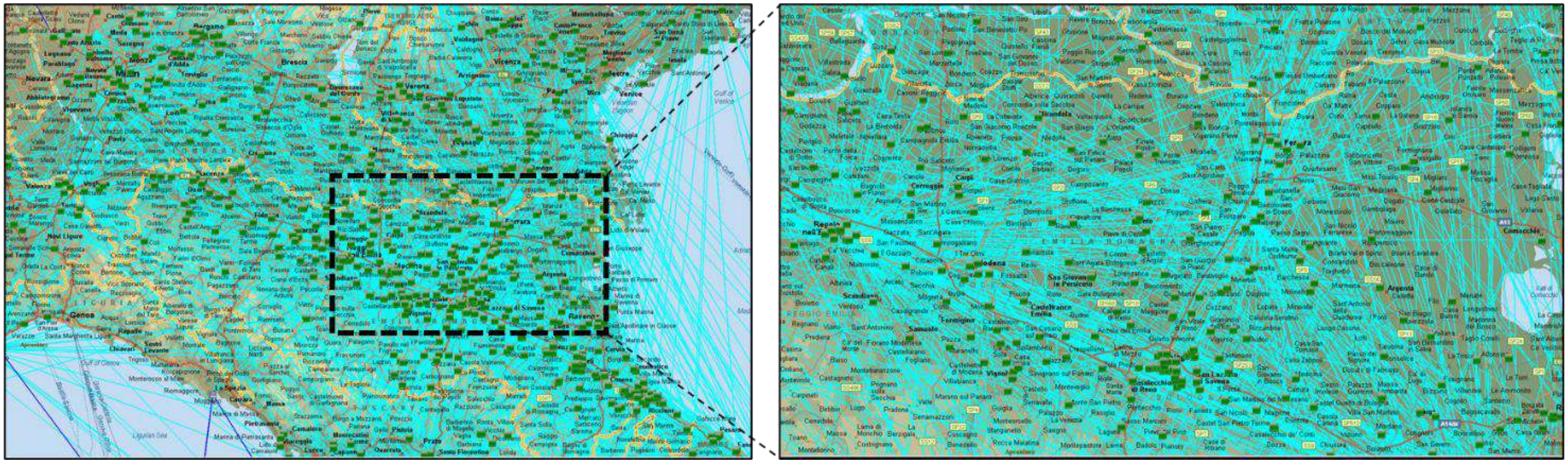


Fig. 6. Connections traveled by the containers throughout the networks.

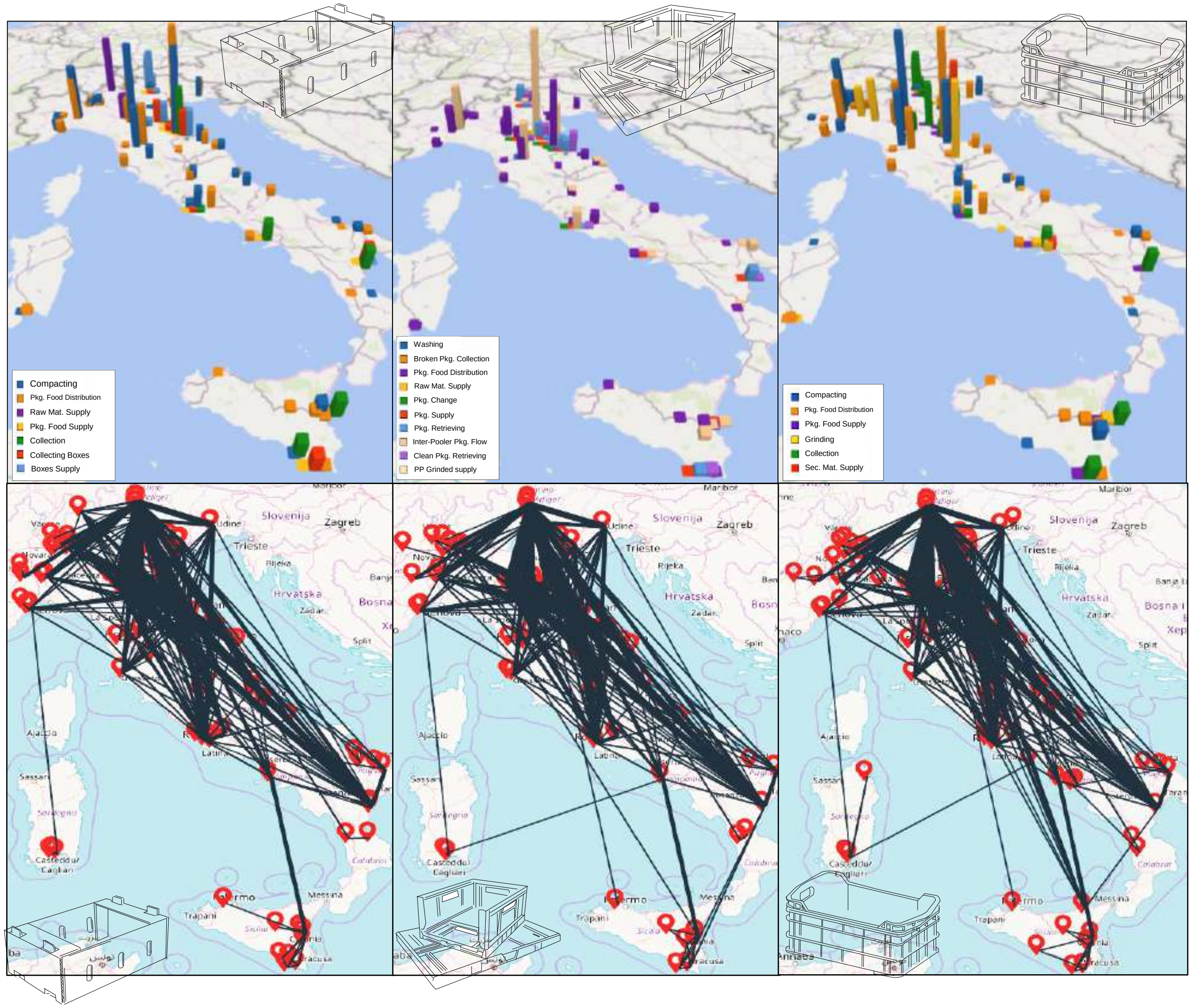


Fig. 7. Transport phase for the three packaging networks: focus on Vendors α, β.

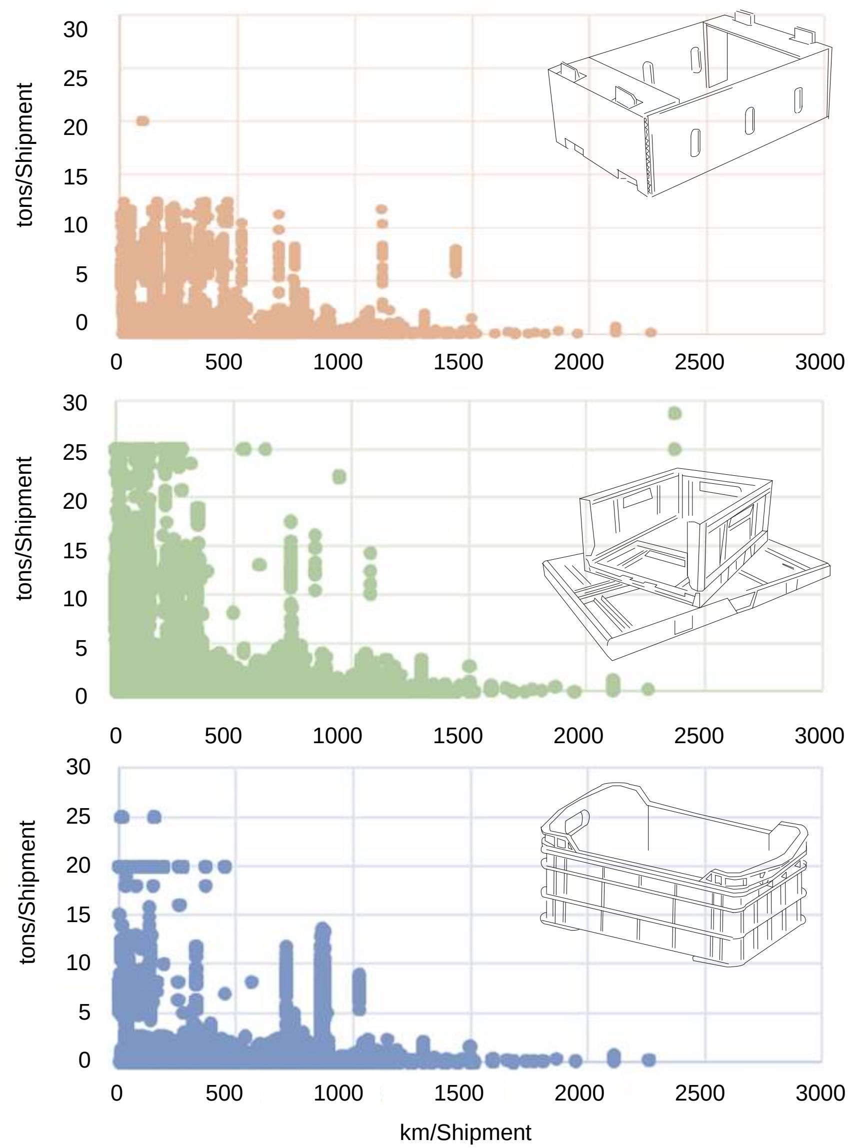


Fig. 8. Travelled distance and load utilization (per shipment) for the three packaging networks: focus on Vendors α, β.

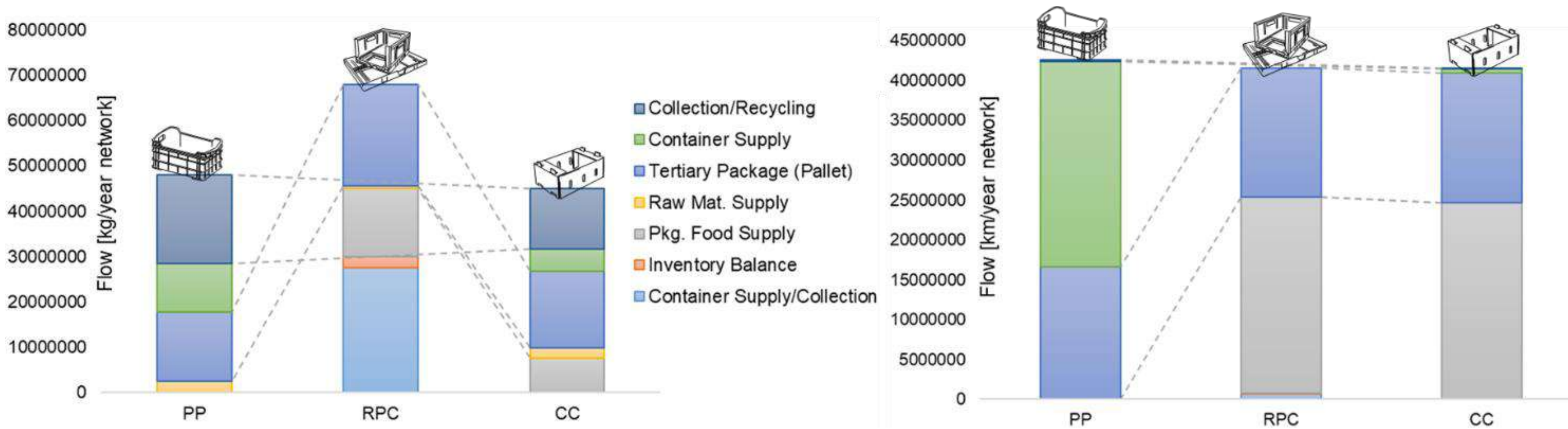


Fig. 9. Contribution of the transportation processes to the distributed flow [kg] (left) and traveled km (right).

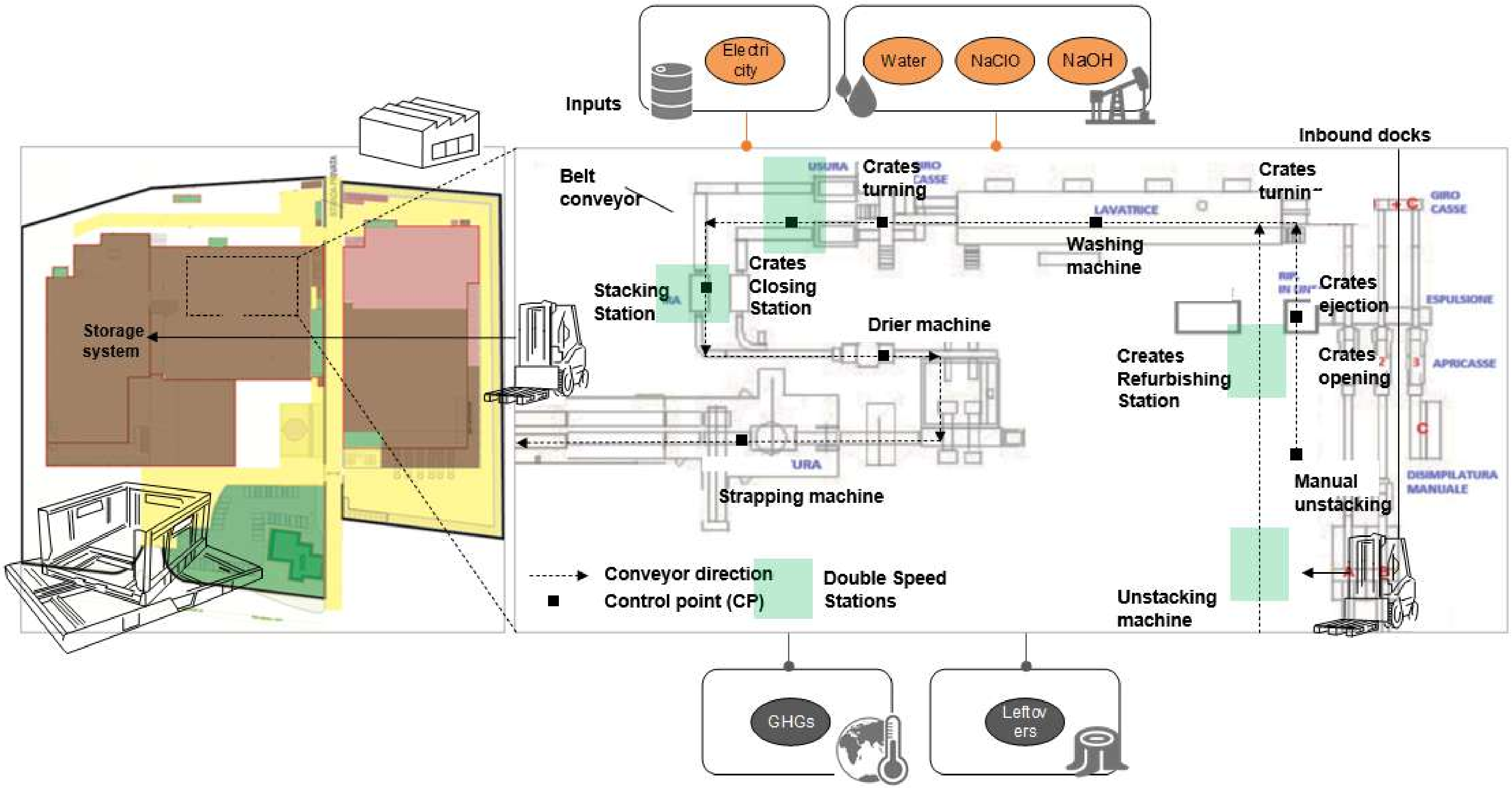


Fig. 10. Washing process for reusable containers.

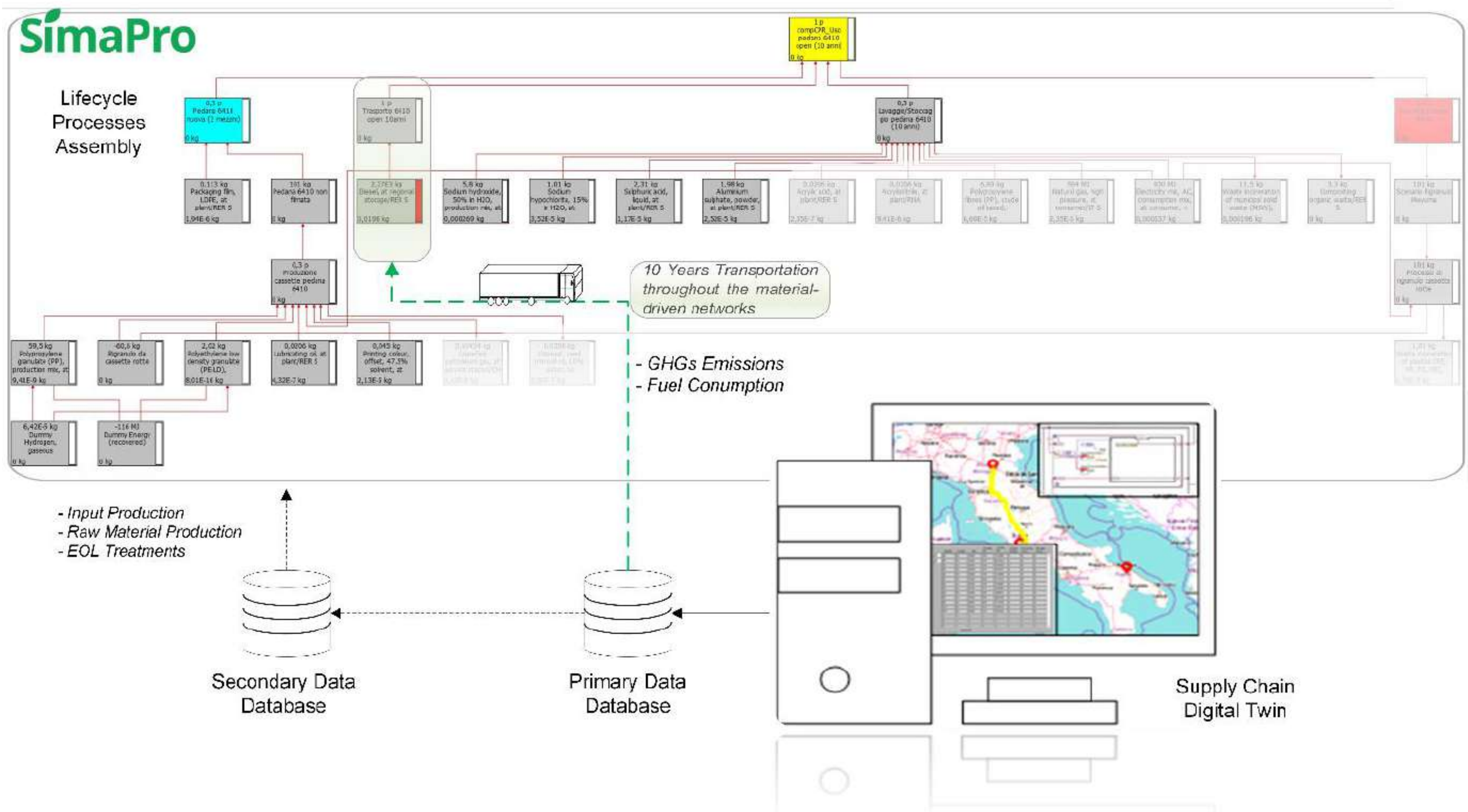


Fig. 11. SimaPro 8.2 lifecycle processes' assembly fed by the digital twin and secondary databases: the 6410 *RPC SPS*..

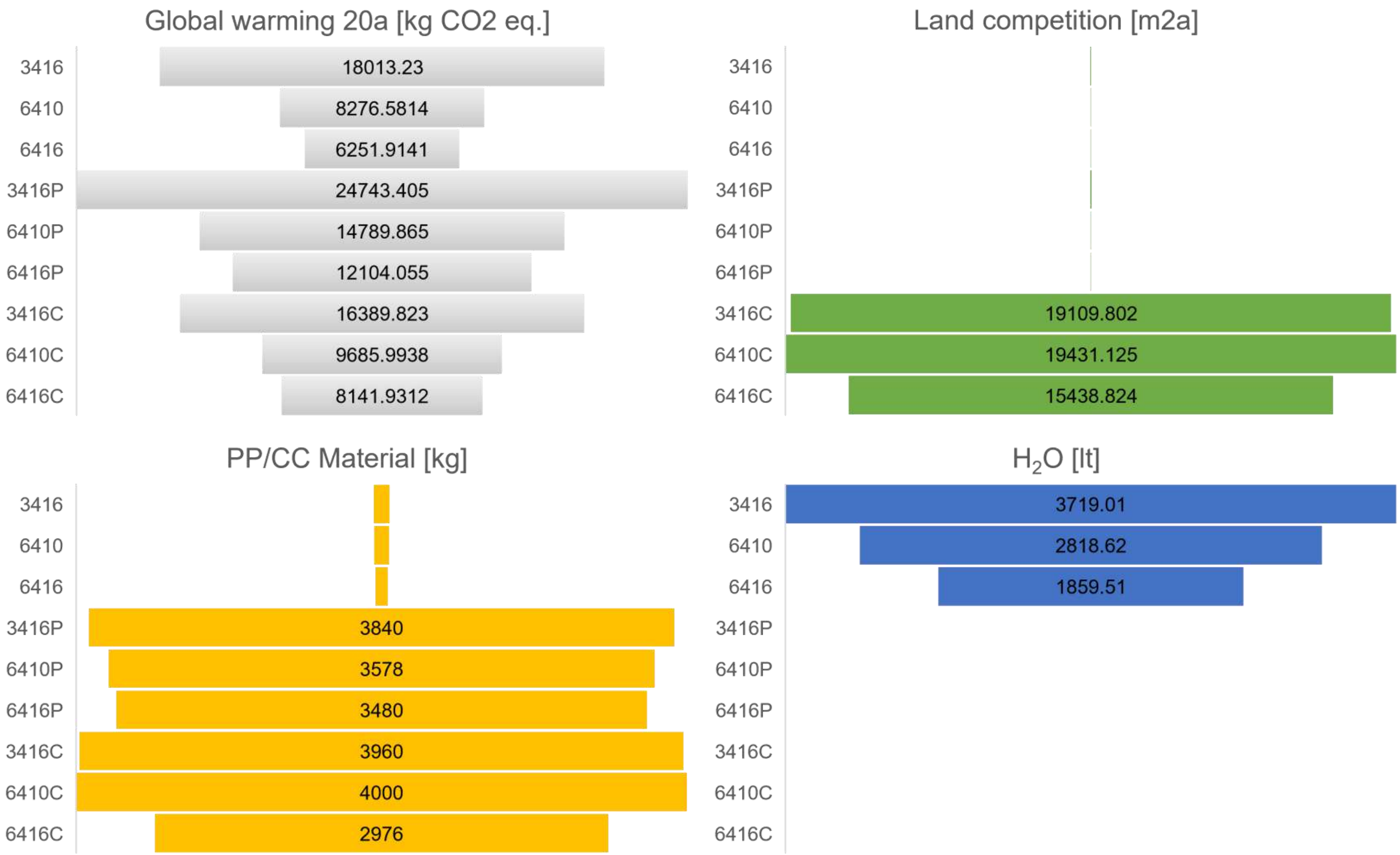


Fig. 12. Carbon footprint and natural resources exploitation (land use, water, raw materials): SPSs comparison.

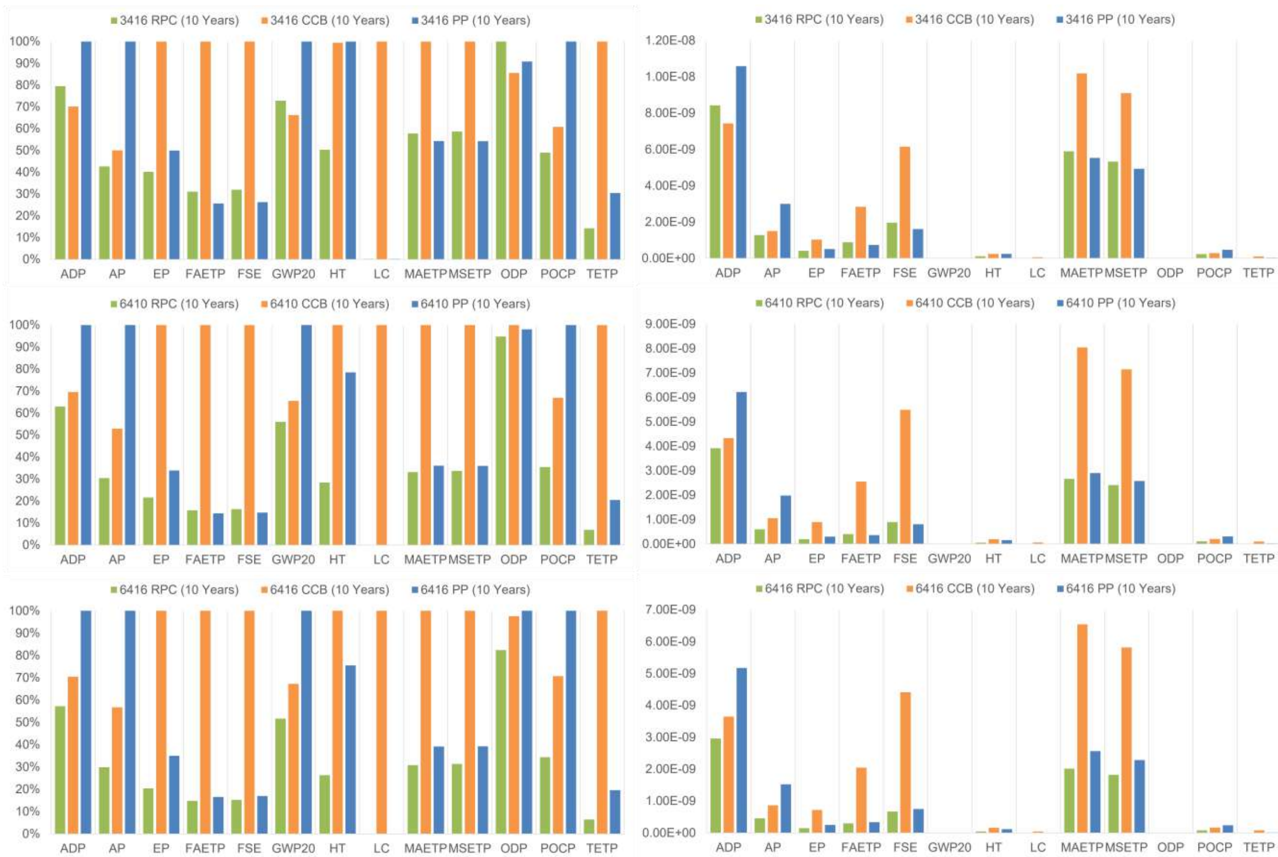


Fig. 13. Mid-point indicators (CML2002) (NF: West Europe, 1995): Normalized SPSs comparison. (*Legend: ADP: Abiotic Resource Depletion Potential [kg Sb eq]; AP: Acidification Potential [kg SO_2 eq]; EP: Eutrophication Potential [kg PO_4 eq]; FAETP: Freshwater aquatic ecotoxicity 20y [kg 1.4-DB eq]; FSE: Freshwater sediment ecotoxicity 20y [kg 1.4-DB eq]; GWP20: Global Warming Potential 20y [kg CO_2 eq]; HT: Human toxicity potential 20y [kg 1.4-DB eq]; LC: Land competition [m^2y]; MAETP: Marine aquatic ecotoxicity 20y [kg 1.4-DB eq]; MSETP: Marine sediment ecotoxicity 20y [kg 1.4-DB eq]; ODP: Ozone Depletion Potential 20y [kg CFC-11 eq]; POCP: Photochemical Oxidant Creation Potential [kg C_2H_4 eq]; TETP: Terrestrial ecotoxicity 20y [kg 1.4-DB eq]*).

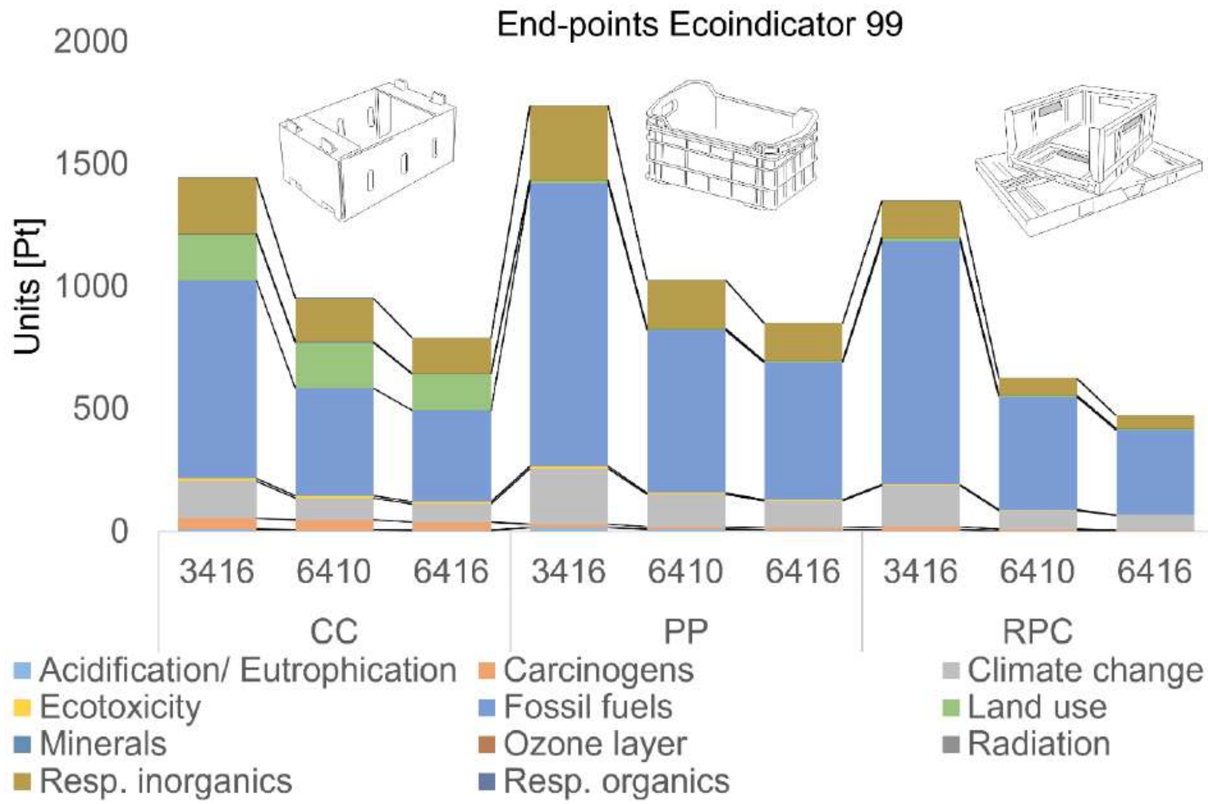


Fig. 14. End-point indicators (Eco-indicator 99 (H) V2.08 / Europe EI 99 H/A); No skip categories: SPSs comparison.

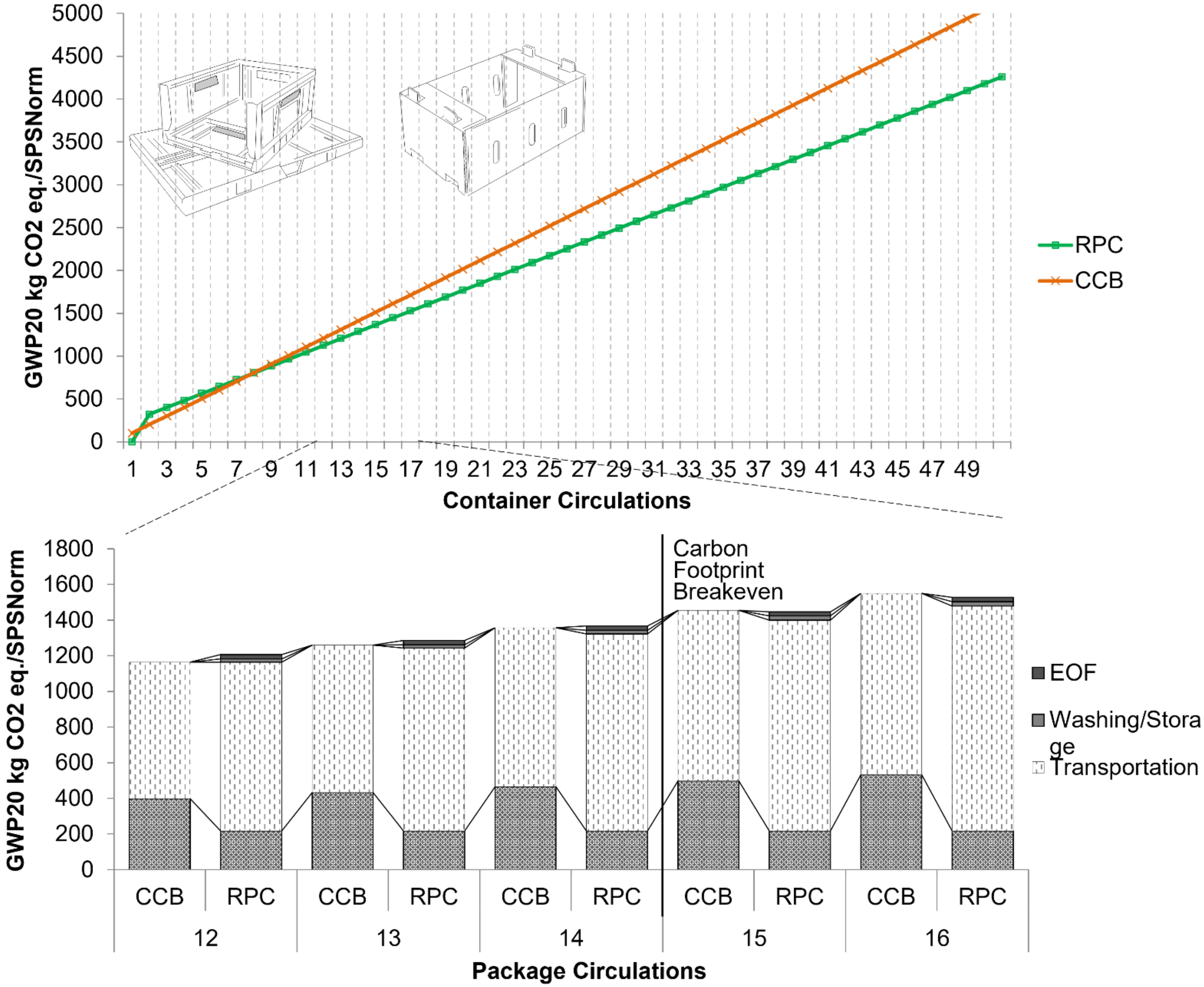
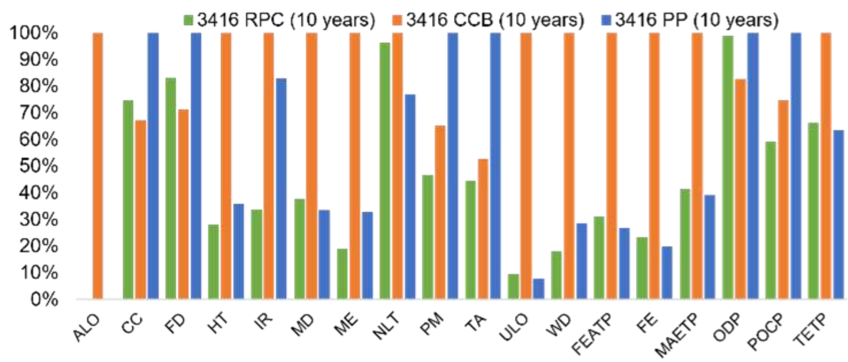


Fig. 15. Sensitivity analysis on the number of reusable containers circulations before recycling: 6410 SPSs comparison.

Appendix A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3416 CCB (10 years)
3416 PP (10 years)
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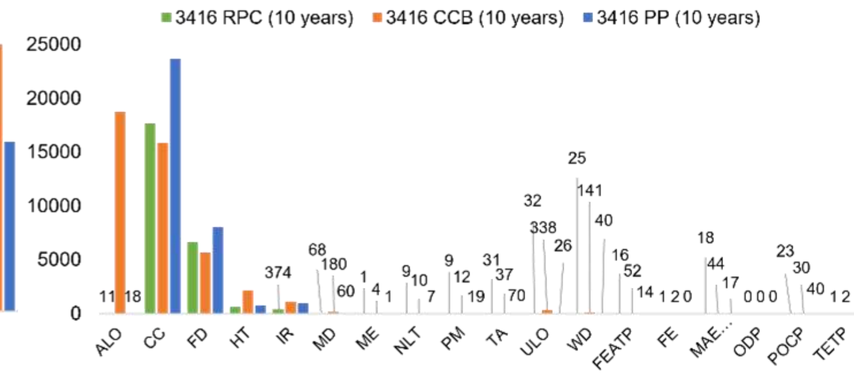
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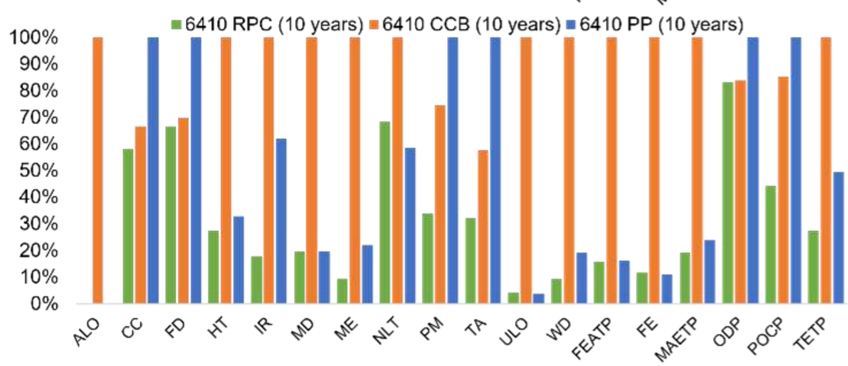
3416 CCB (10 years)
3416 PP (10 years)
25000 20000 15000 10000 5000 0
ALO CC FD HT IR MD ME NLT PM TA ULO WD FEATP FE MAE... ODP POCP TETP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6410 CCB (10 years)
6410 PP (10 years)
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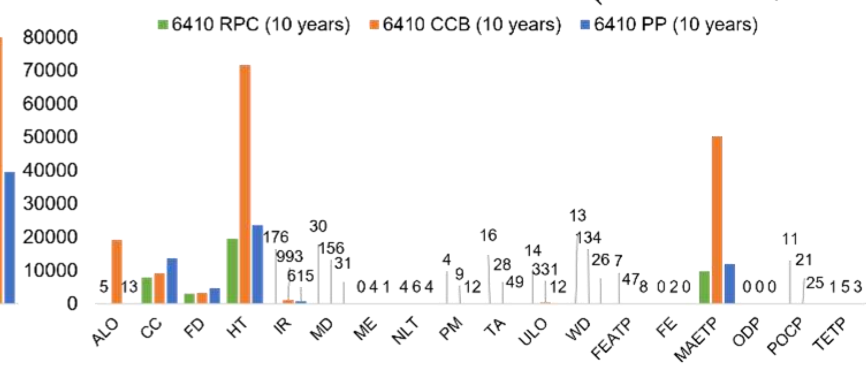
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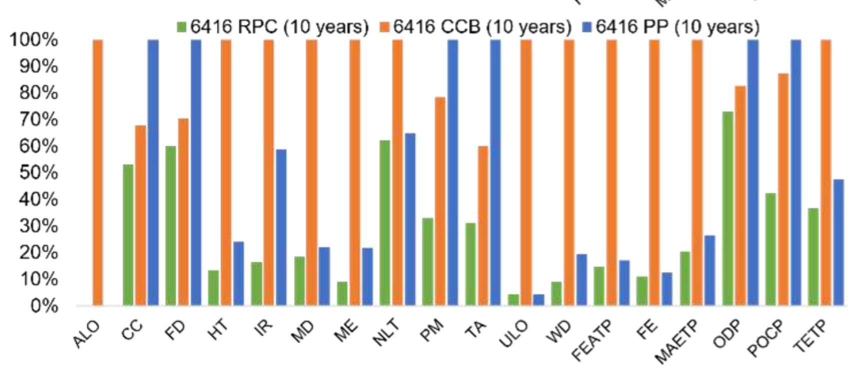
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6416 CCB (10 years)
6416 PP (10 years)
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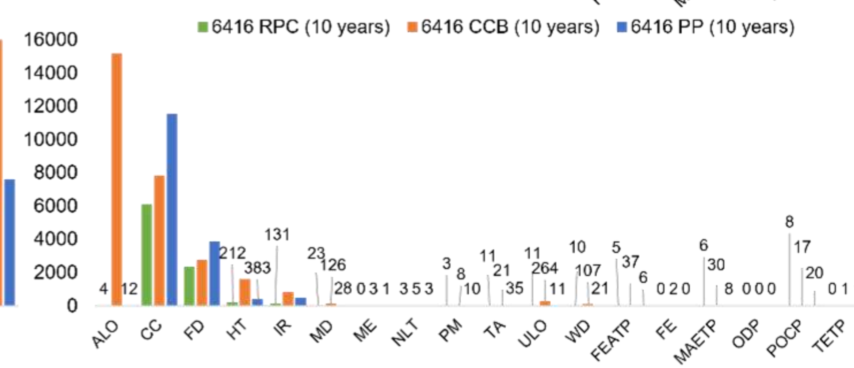
ALO CC FD HT IR MD ME NLT PM TA ULO WD FEATP FE MAETP ODP POCP TETP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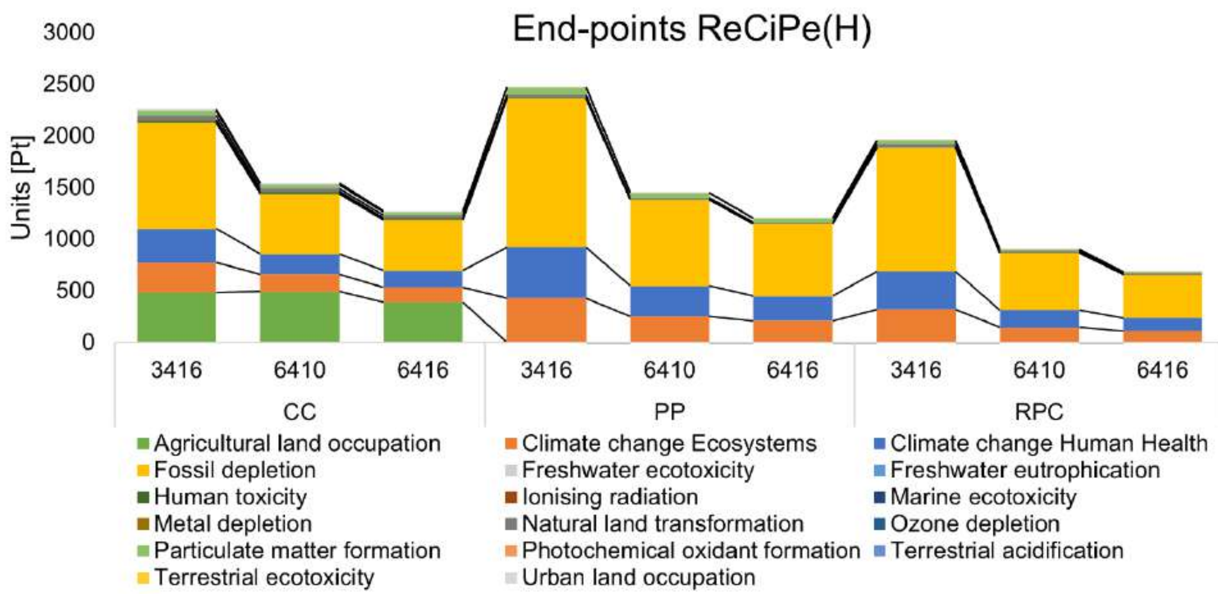
6416 CCB (10 years)
6416 PP (10 years)
16000 14000 12000 10000 8000 6000 4000 2000 0
ALO CC FD HT IR MD ME NLT PM TA ULO WD FEATP FE MAETP ODP POCP TETP

Mid-point indicators (ReCiPe2008): Left: Normalized SPSs comparison. Right: Characteristic SPSs comparison. (Legend: ALO: Agricultural land occupation [m^2a]; CC: Climate change [kg CO_2 eq]; FD: Fossil depletion [kg oil eq]; HT: Human toxicity [kg 1,4-DB eq]; IR: Ionising radiation [kg U_{235} eq]; MD: Metal depletion [kg Fe eq]; ME: Marine eutrophication [kg N eq]; NLT: Natural land transformation [m^2]; PM: Particulate matter formation [kg PM10 eq]; TA: Terrestrial acidification [kg SO_2 eq]; ULO: Urban land occupation [m^2a]; WD: Water depletion [m^3]; FEATP: Freshwater ecotoxicity [kg 1,4-DB eq]; FE: Freshwater eutrophication [kg P eq]; MAETP: Marine ecotoxicity [kg 1,4-DB eq]; ODP: Ozone depletion [kg CFC-11 eq]; POCP: Photochemical oxidant formation [kg NMVOC]; TETP: Terrestrial ecotoxicity [kg 1,4-DB eq])



End-point indicators (ReCiPe2008 (H)); No skip categories: SPSs comparison.

CRediT Author Statement

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Ilaria Battarra	Data curation, Writing – Review and editing, Data Presentation and Visualization
Beatrice Guidani	Data curation, Writing – Review and editing, Data Presentation and Visualization
Riccardo Manzini	Supervision, Project Administrator
Michele Ronzoni	Data curation, Writing – Review and editing, Data Presentation and Visualization
Luca Volpe	Formal Analysis

Graphical Abstract