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COMPARATIVE LIFE CYCLE ASSESSMENT (LCA) PACKAGING SOLUTIONS FOR THE FOOD

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COMPARATIVE LIFE CYCLE ASSESSMENT (LCA) PACKAGING SOLUTIONS FOR THE FOOD SEGMENT

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Disclaimer(s)	**Decimal commas are used throughout the report**

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ABBREVIATIONS

Acd	Acidification
ADP	Abiotic resource depletion
AE	Accumulated Exceedance
B2B	Business-to-Business
CB	Corrugated box
CC	Climate Change
CTUe	Comparative Toxic Unit for ecosystems
CFF	Circular Footprint Formula
CTUh	Comparative Toxic Unit for human
DI	disease incidence
EoL	End-of-Life
EF	Environmental Footprint
EcoF	Ecotoxicity Freshwater
EPD	Environmental Product Declaration
FE	Freshwater Eutrophication
GHG	Greenhouse Gas
GWP	Global Warming Potential
HT-C	Human toxicity, cancer
HT-NC	Human toxicity, non cancer
IR	Ionizing Radiation
kBq U235 eq.	kilobecquerels of Uranium-235 equivalents
kg CFC-11 eq.	kilograms of trichlorofluoromethane equivalents
kg CO2 eq.	kilograms of carbon dioxide equivalents
kg N eq.	kilograms of nitrogen equivalents
kg NMVOC eq.	kilograms of non-methane volatile organic compounds equivalents
kg P eq.	kilograms of phosphorus equivalents
kg Sb eq.	kilograms of antimony equivalents
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LU	Land Use
m^3 world eq.	cubic meters world equivalents
ME	Marine Eutrophication
MJ	megajoule

mol H+ eq.	moles of charge equivalent
mol N eq.	moles of nitrogen equivalent
OD	Ozone Depletion
ODP	Ozone Depletion Potential
PEF	Product Environmental Footprint
PM	Particulate Matter
POF	Photochemical Ozone Formation
(R)PC	(Reusable) plastic crate/container
RU-F	Resource Use (fossil)
RU-M	Resource Use (mineral and metals)
TE	Terrestrial Eutrophication
WU	Water Use

0. EXECUTIVE SUMMARY

Ramboll has been appointed by the European Federation of corrugated Board Manufacturers (FEFCO or the Client) as technical consultant for conducting a peer reviewed comparative Life Cycle Assessment (LCA) study for B2B transport packaging solutions for the food segment—a recyclable corrugated solution and a reusable plastic crate—in accordance with ISO standards 14040 and 14044. This is conducted as a basis for discussion with authority representatives on the current legal developments within the European Union regarding circular economy and waste prevention.

The functional unit was the provision of delivery, containment, and display for 1 ton of vegetables (fresh product) by means of functionally equivalent transport containers (either single-use corrugated board boxes, or multiple-use plastic crates) over a transport distance of 840 km from producer to retailer in the EU in a manner that maintains the safety of the produce and that is consistent with established commercial supply chains.

A systems perspective is used to reflect both systems and compare equal functions of single-use and multiple-use product items. The LCA is performed according to relevant ISO standards 14040 and 14044 and discusses the impacts on a set of fourteen environmental impact categories. The generic exclusion of potentially relevant impact categories for both systems is an unavoidable limitation of this study which needs to be taken into account when interpreting overall results and making decisions in this regard.

For the comparative assessment, two fundamentally distinct systems are taken into consideration:

- Corrugated box (single-use system) made of 53% Kraftliner and 47% Semi-chemical (fluting);
- Plastic crate (multiple-use system) made of a mixture of two polymers (58% high density polyethylene and 42% polypropylene) formed through injection moulding.

The selected specific scenario is deemed representative for the (non-refrigerated) shipping of generic fruits and vegetables by average means of transport (i.e. truck) and by considering one of the most preferred routes in Europe in terms of volume of transported goods (based on recent statistical data). To the extent possible, hygiene standards and parameters for the specific goods are acknowledged.

The geographical scope of the baseline comparison is Europe (EU-27+UK). This geographical boundary is reflected in the assumptions around the systems (e.g. recycling rates) and background datasets (e.g. electricity from grid) as inventory data.
For the **baseline scenarios** the following key assumptions have been made:

Single-use system:

- Corrugated board products manufacturing refers to the respective geographical context of the paper mill or manufacturer from FEFCO (European Database for Corrugated Board Life Cycle Studies, 2018);
- Corrugated products are made of primary and recycled fibers;
- Loading capacity: 15 kg;
- Filling rate: 70%;
- End-of-life (paper products): Recycling rate 82,9%, rest incineration with energy recovery.

For modeling environmental burdens of the recycling process, data present in the FEFCO LCI database is adapted considering information presented in the “Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board” (Suhr *et al.*, 2015). This data was compiled by RISE on behalf of CEPI and FEFCO during 2021 as part of a specific project and a pre-publication version of the results was provided for use in this assignment. The data has been checked by a major producer of recycled corrugated case materials, considering operating experiences.

Multiple-use system:

- Plastic manufacturing in Europe;
- Loading capacity: 15 kg;
- Filling rate: 70%;
- Average reuse: 24 rotations;
- Average breakage rate: 2.5%
- Distance from distribution center to service center (washing and sanitizing): 165 km
- End-of-life (Plastic products): Recycling rate 41,8%, rest incineration with energy recovery.

The aggregated total impacts of the baseline systems are summarised in the following table.

Life cycle impact assessment results of the baseline comparison of the single-use and multiple-use systems.

EF Impact category	**Avoided burdens (baseline)**	
	Single use	**Multiple use**
EF Acidification [Mole of H+ eq.]	0,14	0,10
EF Climate Change, total [kg CO2 eq.]	34,70	47,94
EF Climate Change, biogenic [kg CO2 eq.]	-0,25	0,12
EF Climate Change, fossil [kg CO2 eq.]	34,76	45,76
EF Climate Change, land use and land use change [kg CO2 eq.]	0,18	1,98
EF Ecotoxicity, freshwater [CTUe]	3,62	16,99
EF Eutrophication, freshwater [kg P eq.]	-1,83E-02	1,35E-03
EF Eutrophication, marine [kg N eq.]	0,11	0,05
EF Eutrophication, terrestrial [Mole of N eq.]	0,97	0,39
EF Human toxicity, cancer [CTUh]	-3,39E-07	3,13E-07
EF Human toxicity, non-cancer [CTUh]	-5,83E-07	1,66E-06
EF Ionising radiation, human health [kBq U235 eq.]	-7,03	0,68
EF Ozone depletion [kg CFC-11 eq.]	-2,16E-06	1,72E-07

EF Particulate matter [Disease incidences]	3,04E-06	8,00E-07
EF Photochemical ozone formation - human health [kg NMVOC eq.]	0,32	0,09
EF Resource use, fossils [MJ]	238,37	476,23
EF Resource use, mineral and metals [kg Sb eq.]	-1,14E-04	4,15E-05
EF Water use [m^3 world equiv.]	-13,20	10,83

The following overarching conclusions can be drawn from the comparative assessment for the baseline scenario:

- single-use system shows benefits for the following impact categories: Climate change, total; Ecotoxicity, freshwater; Eutrophication, freshwater; Human toxicity, cancer; Human toxicity, non-cancer; Ionizing radiation, human health; Ozone depletion; Resource use, fossils; Resource use, mineral and metals; and Water use;
- multiple-use system shows benefits for the following impact categories: Acidification; Eutrophication, marine; Eutrophication, terrestrial; Particulate matter; Photochemical ozone formation - human health.
- The Break-even analysis highlights that for a number of RPC rotations lower than the break-even point (~63 rotations), the single-use system has lower environmental impacts in the category Climate Change, total impact category.

To test decisive assumptions in the respective systems, several sensitivity scenarios are analysed, details of the investigated parameters are summarized in the following table. Note: only one parameter (or assumption) is changed per system.

Sensitivity scenario	System affected	Value in the baseline	Variation
EoL allocation - 0:100 approach (cut-off)	SU / MU	Avoided burden	Cut-off
EoL allocation - 50:50 approach	SU / MU	Avoided burden	Approach 50:50
EoL allocation - Avoided emissions (78% chemical, 22% mechanical)	SU	Pulp products as avoided emissions: 53% sulphate pulp, 47% mechanical pulps (TMP, CTMP, stone groundwood)	Pulp products as avoided emissions: 78% sulphate pulp, 22% mechanical pulps (TMP, CTMP, stone groundwood)
EoL allocation - Avoided emissions (wet pumpable pulp)	SU	Pulp products as market dry pulp	Pulp products as wet pulp (1000 kWh is required to dry off the water)
Energy mix - EU28	SU / MU	Residual Energy grid mix EU-28	Energy grid mix EU28
Energy mix - Future scenario EU-28 (2030)	SU / MU	Residual Energy grid mix EU-28	Future scenario grid mix EU-28 (2030)
Energy mix - Green electricity grid mix	SU / MU	Residual Energy grid mix EU-28	Green electricity grid mix
EoL treatment - Wastepaper reycling (secondary data)	SU	Wastepaper recycling via FEFCO's LCI re-work (Appendix 1)	Wastepaper recycling via Ecoinvent dataset
EoL treatment - Recycling 70% both systems	SU / MU	Recycling shares, SU: 82,9%; MU: 41,8%	Recycling shares, SU: 70%%; MU: 70%%
Manufacturing - Recycled content (rec40%)	MU	Recycled content RPC: 10%	Recycled content RPC: 40%
Breakage rate - BR_0,5%	MU	Breackage rate: 2,5%	Breackage rate: 0,5%
Breakage rate - BR_5%	MU	Breackage rate: 2,5%	Breackage rate: 5%
Washing - optimized detergents	MU	Detergent composition as database set	Detergent composition following Tua et al. (2019)
Washing - Min demand	MU	Washing demand: 0,0374 kWh electricity, 0,3011 liter water, 0,0044 kg detergents	Washing demand: 0,0274 kWh electricity, 0,0958 liter water, 0,0017 kg detergents
Transport - Transport -50% (both systems)	SU / MU	Transport distances as Appendix 2	Transport distances of Appendix 2 decreased by 50%
Transport - Transport +50% (both systems)	SU / MU	Transport distances as Appendix 2	Transport distances of Appendix 2 increased by 50%
Transport - Less challenging transport for MU (-25%)	MU	Transport distances as Appendix 2	Transport distances of Appendix 2 (only for MU) decreased by 25%

Under consideration of identified uncertainties and sensitivities of impact results, the following overarching conclusions can be drawn from the comparative assessment:

- For Climate change, total, Ecotoxicity, freshwater, Human toxicity, cancer, Human toxicity, non-cancer, Ozone depletion, Ionizing radiation, human health, Resource use, fossil, Resource use, mineral and metals and Water use, the single-use system shows benefits considering the comparison throughout most of the sensitivity analyses.
- In cases allocating 70% recycling end of life for both systems, the environmental benefits for the single-use system become even higher. Different EoL allocations (e.g. avoided emissions with wet pumpable pulp) can reduce the delta between the systems, and reduce the benefits in many impact categories. This is due to the assumptions that further energy demand is required to dry off the water from the market dry pulp products allocated at the point of substitution (i.e. 1000 kWh of energy demand).

- In the cut-off scenario, in all categories excluding Human toxicity, cancer and Ozone depletion no environmental benefits are highlighted. However, this scenario is considered in this study only for comparison purposes, since the Avoided burdens approach is the recommended one by ISO 14044:2006 and ISO 14044:2020, and in general this method gives incentives to develop recyclable products and to recycle them after use[1].
- For Acidification, Eutrophication, marine, Eutrophication, terrestrial, Particulate matter and Photochemical ozone formation - human health, the single-use system shows no benefits in all of the sensitivity analyses.
- By considering a conservative recycling process, the delta between the two systems is reduced, by lowering the benefit of the single-use system. This is due to the higher energy demand accounted in the process via secondary dataset (whose inputs are however older than 10 years).
- In general, by changing assumptions on the electricity grid mix, no sensible variation on the results can be drawn. This is due to the low dependency of unit processes to this parameter. Specifically, it should be noted that as manufacturing processes are implemented in the model as aggregated datasets, energy grid mix variation influence only the recycling process in the single-use system and the washing stage in the multiple-use system. However, both unit processes occur each cycle/rotation, and it could be considered a symmetrical situation.
- In the single-use system, avoided emissions of pulp products have a great influence on the results (with consequent credits in the overall aggregated results). This is mainly due to avoided impacts of mechanical pulp products, such as CTMP, TMP and stone groundwood processes.
- The Resource use, fossil impact category in the Cut-off approach deserves further explanation. The findings of this study suggest that the single-use system shows no benefits in this scenario. However, this depends to the energy mix used for wastepaper recycling (one of the main contributors to the impacts), which is related to fossil energy sources (e.g., heavy fuel oil, light fuel oil, diesel, coal). This energy mix is used *in situ* at recycling facilities for generating energy. Certainly, a different energy mix with a greater contribution from renewable sources and a lower presence of fossil fuel, could produce different results, with beneficial effects on the Resource use, fossil category for the single-use system. This aspect was investigated by many authors.
- Although studies in literature have based their models and assumptions on secondary data for the life cycle of multiple-use plastic crates (as in this study), a potential step forward would be collecting primary data at industry level. This might be relevant in future works.
- The implementation of water assessment via Water use impact category in the Environmental Footprint (EF) methodology is subject to some limitations, as explained in Sphera documentation (last documentation, year 2018)[2]. As sources of uncertainties still remain in the application of the "available water remaining" (AWaRe) methodology in the EF Water use impact category in GaBi software, results in this impact category of this study could be therefore used as potential uncertain. This can be seen as a limitation in

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[1] See: (Eberhardt *et al.*, 2020)

[2] Source: https://gabi.sphera.com/fileadmin/Documents/Introduction_to_Water_Assessment_V2.2_03.pdf

this study. These results are shown in this study for the sake of completeness. Further analysis is strongly envisaged in future studies.

This comparative LCA has been conducted in accordance with ISO standards 14040 and 14044, however an assessment of the most relevant EF categories using as a reference "Impact categories cumulatively contributing at least 80% of the total environmental impact (excluding toxicity related impact categories)" has been performed according to the Product Environmental Footprint Category Rules Guidance (version 6.3):

- **SU system:** the most relevant impact categories are Climate Change, total, Eutrophication, freshwater, Eutrophication, terrestrial, Particulate matter, Photochemical ozone formation, human health and Resource use, fossils. These categories have a cumulative contribution of 80.1% of the total impact, based on the normalized and weighted results, and excluding the toxicity related impacts,
- **MU system**: the most relevant impact categories are Climate Change, total, Particulate matter and Resource use, fossils. These categories have a cumulative contribution of 80.3% of the total impact, based on the normalized and weighted results, and excluding the toxicity related impacts.

In conclusion, total impacts as well as the comparison between the single and the multiple-use systems are strongly dependent on underlying assumptions with regard to the EoL allocation method. In general, LCA results of comparative analysis are influenced by uncertain data on the waste management (e.g. wastepaper recycling) and the avoided virgin materials production, whose consideration can affect the findings of a LCA (Ekvall *et al.*, 2020).

External review

This executive summary is based on an ISO-compliant full LCA report that was subject to a third-party review.

1. INTRODUCTION

Ramboll has been appointed by the European Federation of corrugated Board Manufacturers (FEFCO or the Client) as technical consultant for conducting a peer reviewed comparative Life Cycle Assessment (LCA) study for B2B transport packaging solutions for the food segment—a recyclable corrugated solution and a reusable plastic crate—in accordance with ISO standards 14040 and 14044. This is conducted as a basis for discussion with authority representatives on the current legal developments within the European Union regarding circular economy and waste prevention.

To meet client expectation, Ramboll performed the activities that are summarized in the following sections of the report:

- Context and Rationale of the study;
- Description of the used methodological approach;
- Literature and Data Screening;
- Description of the performed Comparative Life Cycle Assessment;
- Conclusions and recommendations;
- Critical Review.

1.1 Context and rationale for study

With the review of the Packaging and Packaging Waste Directive (Directive 94/62/EC of 20 December 1994), the Commission is planning to present specific prevention measures that might set requirements for single-use packaging like corrugated board. Yet, recyclable and recycled corrugated board packaging originating from a renewable source generally meets the aspiration of the EU Green Deal and the Circular Economy Action Plan ambitions. By means of scientific assessment methods, new evidence (facts and figures) is gathered on the situation of corrugated board packaging.

It is understood that this assessment is embedded in an ongoing debate around the environmental performance of single-use and multiple-use products or systems. Consequently, there is already a mature body of knowledge concerning several products and applications within the two domains. Next, taking into account previous findings, this study seeks to adopt a holistic perspective on the comparison of single-use (SU) and multiple-use (MU) systems in a specific context.

For the goal and scope of this assessment as well as subsequent interpretation of results it is important to bear in mind that corrugated board production and recycling of fibers into further product life cycles are integral parts of a continuous (global) paper life cycle system (see Figure 1).

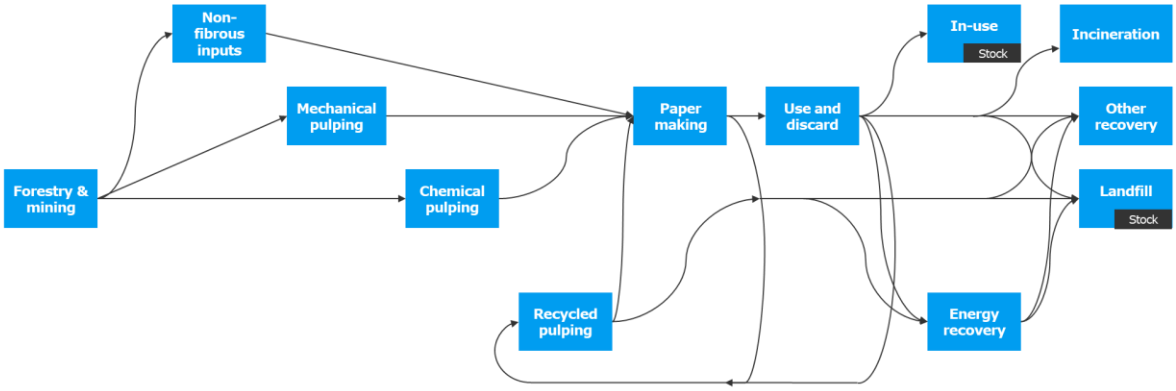

Figure 1: Simplified representation of the (global) paper system (own figure based on van Ewijk, Stegemann and Ekins (2021))

Consequently, disentangling respective processes, applications/uses, and life cycle stages poses several methodological challenges, mostly with regards to allocation of environmental burdens and credits between subsequent life cycles. Therefore, it is an important complementary goal of this study to elaborate and interpret such allocation issues in detail and to investigate the effect of methodological choices on the overall comparison. In conclusion, it is important to acknowledge that a model is always a simplified representation of the reality.

1.2 Methodological Approach

Currently, LCA provides the best and most mature framework for assessing the potential environmental impacts of products and services according to the European Commission (European Commission, 2019). One of the most frequent applications of LCA studies is the comparison of specific goods or services (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010). Several results of life-cycle based assessments are already being used in relation to certain EU policies (e.g. Ecolabel Regulation, Green Product Procurement, Ecodesign Directive). Given the method’s standardized framework, maturity and methodological adaptation to policy needs, the consideration of LCA studies in policymaking is expected to increase (European Commission, 2017). A very prominent example of the use of LCA in EU policies and impact assessment is the justification of possible changes in the waste hierarchy due to environmental concerns (European Commission, 2017). Given the previously outlined context and rationale for this study, it is important to acknowledge LCA as an iterative and continuous learning process rather than a mere calculation tool. As such, the modelling choices should be tailor-made to facilitate an efficient learning process and generate as much knowledge as possible about the specific case (Ekvall *et al.*, 2020).

1.2.1 Life Cycle Assessment for policy purposes and external communication

This LCA may be applied to a pre-policy situation and as such it seeks to generate part of the basis for potential policy decisions. Depending on the specific context and use of the LCA, different approaches to modelling might be appropriate (e.g. modelling choices regarding recycling). Most importantly, methodological decision are transparently documented and explained as to facilitate a dialogue with various policymakers and stakeholders. Therefore, different modelling choices and assumptions are adopted, as general recommendations cannot be made. This LCA study applies several different modelling choices in parallel so as to communicate and interpret the sensitivity of the results and comparison with regard to e.g. different applicable allocation procedures.

When using this LCA for external communication purposes it is crucial to acknowledge and highlight that it is a tailor-made and case-specific ISO-compliant comparative assertion (this is in contrast to more standardized approaches such as EPDs and PEFs). As a consequence, results from this study are not directly comparable with other sources and results (as would be the case if this study would adhere to more standardized approaches) but need further interpretation and discussion. Lastly, this technical report aims to present results in a disaggregated (as far as possible) and transparent manner as to allow the audience to interpret the study and adjust the modelling choices individually.

1.2.2 Literature and Database Screening

A focused literature and database research aims at identifying relevant products or processes in order to provide data and information on the specific systems. Potential problems in carrying out LCA analysis (e.g. data gaps) as well as adopted modeling approaches and methods (e.g. EoL allocation methods) are identified. Literature studies are selected based on previous knowledge and by searching specific terms (e.g. LCA, Life cycle Assessment, environmental impact, carbon footprint, comparison, recycling, plastic, waste management, packaging, end-of-life options, environmental sustainability).

The following further criteria or boundaries of the study have been applied:

- studies publicly available or provided by the FEFCO steering board;
- comparative assertion;
- studies based on the LCA methodology or adopting a life cycle perspective.

1.2.3 Life Cycle Assessment

For the quantitative assessment of relevant systems from an ecological point of view, the methodology of Life Cycle Assessment (LCA) is suitable (in accordance with relevant ISO standards 14040 and 14044). The general methodology for LCA aims to assess identified and generated Life Cycle Inventories (LCIs), consisting of quantified elementary flows referring to the functional unit, in relation to their potential impact on the natural environment, human health, and issues related to natural resource use (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010).

LCA is a well-established four-step methodology. These steps are iterative and involve the following tasks (Guinée *et al.*, 2001):

1) Goal and scope definition: object and aim of the study are described, as well as system boundaries, functional unit and data sources; impact categories, indicators and characterization models are selected.
2) Inventory analysis: this phase collects and quantifies data-based processes of inputs (e.g. fuel demand, energy demand, raw materials weights, air emissions, waste weights) in the whole life cycle of a system or product – as defined in step 1.
3) Impact assessment: inventory analysis results are assigned to the selected impact categories by means of established, scientific impact assessment methods; category indicator results are then calculated; the results can be evaluated by varying relevant parameter within a sensitivity analysis.
4) Interpretation: this phase analyses and interprets the results of the impact assessment, tries to highlight uncertainties and paths for improvement of the system.

1.2.3.1 Modelling

The LCA model for this study is developed with GaBi Professional software[3] using background data primarily from the associated GaBi Professional database (version 2021.2), Ecoinvent[4] (version 3.7.1), European Database for Corrugated Board Life Cycle Studies[5], and available public or

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[3] http://www.gabi-software.com

[4] https://www.ecoinvent.org

[5] https://www.fefco.org/lca

commercial extension databases (e.g. LCI datasets from the PEF pilot). In addition, primary data about paperboard recycling process have been collected through FEFCO members. It should be noted that decimal units in this study are given with comma.

2. LITERATURE AND DATA SCREENING

2.1 Summary of findings from literature screening

A desk-based literature screening was performed. The following findings are gathered:

- Analyzed papers most often compare cardboard boxes, reusable plastic crates and sometimes wooden boxes;
- All the publications reported are based on the commonly accepted LCA methodology. Therefore, they always consider impacts due to material extraction and manufacturing. Moreover, all the publications consider impacts related to reverse logistics and washing processes for the reusable plastic containers;
- In the majority of the analyzed studies, reusable plastic containers (RPCs) showed lower environmental impacts in most of the assessed categories. This overarching tendency is based on the following findings:
    - Main relative contribution to environmental impacts for CB-based system are associated with manufacturing phase, due to the inherently greater mass volume of the packages required per declared functional unit, while a lower number of RPCs are needed due to the characteristic reuse of single items (Levi *et al.*, 2011a; Albrecht *et al.*, 2013; Accorsi *et al.*, 2014; Abejón *et al.*, 2020a)
    - RPCs can be reused several times which could reduce the impacts of the production phase per use cycle (Fraunhofer Institute for Building Physics IBP, 2018; Del Borghi *et al.*, 2021).
    - One study suggested that virgin polypropylene boxes could have lower GWP impacts after 100 reuse cycles (Levi *et al.*, 2011a) than corrugated cardboard boxes. However, many studies have assumed lower reuse cycles as more realistic (e.g. 50 cycles) and have extended their analysis up to a maximum of 100 reuse cycles (Capuz-Rizo *et al.*, 2005; Albrecht *et al.*, 2013; Fraunhofer Institute for Building Physics IBP, 2018; Zimmermann and Bliklen, 2020; Del Borghi *et al.*, 2021; Lo-Iacono-ferreira *et al.*, 2021)[6].

Other potentially relevant findings have been highlighted, such as:

- The assumed number of recycling loops one paper fiber can undergo ranges from 3 (Abejón *et al.*, 2020b) to 25 (Putz and Schabel, 2018) in the screened studies;
- Transportation has potentially a great influence on the results: CBs could present less environmental impacts (in terms of GWP) than RPCs if the one-way transport distance (excluding return logistics) is greater than 600 km (Levi *et al.*, 2011b). This possibility is supported in another study (Levi, Vezzoli and Cortesi, 2008) where CBs show better performances with respect to RPCs, when longer distances are considered. It is further postulated that the assumed transport distance is a critical parameter in evaluating the potential environmental impacts of the respective packaging solutions and it is further found that cardboard containers are preferred for longer distances (Lo-Iacono-ferreira *et al.*, 2021).
- Some studies reported that CBs have lower environmental impacts in different categories with respect to RPCs (Koskela *et al.*, 2014; Thorbecke *et al.*, 2019); based on US geographical context CBs are associated with lower impacts for e.g. global warming, non-renewable energy use (Thorbecke *et al.*, 2019);

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[6] ARECO (Association of Logistical Operators of Reusable Elements Ecosostenibles) in Spain reports a maximum reuse rate of 100 cycles for plastic crates (source: https://areco.org.es/en/sustainability/)

  - One source suggested that protection systems for perishable products have not been considered due to lack of data, but they might "potentially push the advantage in one direction or the other if a significant difference exists" (Thorbecke *et al.*, 2019).

These selected studies, their implications, assumptions and criteria set the context of this study and are used as a source of information and data, as reported along the text.

3. COMPARATIVE LIFE CYCLE ASSESSMENT

3.1 Goal and Scope

3.1.1 Goal of the assessment and intended audience

Currently, there are two different ways of transporting fresh products (mainly fruit and vegetable items) in the B2B food segment in Europe (also referred as *systems)*:

- a recyclable single-use corrugated board solution; and
- a multiple-use plastic crate.

The main goal of the study is to **compare the environmental performance of recyclable single-use corrugated boxes (CB) and multiple-use plastic crates (RPC) in Europe, used in the food segment.** To this end, a Life Cycle Assessment (LCA) study according to the ISO 14040/44 standards is carried out. Key parameters and environmentally important life-cycle stages of the systems are identified and analyzed. Further, the influence of certain key variables for the results is evaluated.

In accordance with the ISO 14040/44 standards the equivalence of the two distinct systems (single-use and multiple-use) is evaluated to ensure a fair comparison. This applies to the performance (i.e. the functions obtained from respective products), system boundaries, data quality (i.e. equivalent and appropriate implementation of foreground and background data), allocation procedures and impact assessment categories of respective product systems.

In general, this study follows the principles of an attributional analysis, meaning that a specified and static state of a system or product is examined (Guinée *et al.*, 2001). Thus, average data (representing average environmental burden from a specific activity or production volume) is incorporated in this assessment and results refer to an unambiguously defined current system. However, the analysis also comprises consequential perspectives and approaches. This means that both recycling and energy recovery are modeled with assumed substitution (i.e. avoided energy or material provision). This approach is widely established practice and particularly used in consequential LCAs to estimate how the global environmental impacts are affected by a decision. In this regard it is important to acknowledge the comparative nature of this assessment in which different options fulfilling the same function are considered. These options are made of different processes along the life cycle (e.g., raw materials extraction, manufacturing of boxes, transport, end-of-life stage).

Different stakeholders along the investigated B2B supply chain are considered the intended audience of this study. This entails:

- raw material producers;
- manufacturers of corrugated board solutions;
- transport companies;
- retailers; and

- respective service providers necessary for reprocessing plastic crates (including washing operations).

The study sheds further light on the understanding of potential environmental implications relating to single-use and multiple-use solutions for transporting goods in the food segment in Europe. Therefore, all affected companies and associations are considered as potential target audiences. Ultimately, potential environmental hotspots are evaluated to derive reduction potentials and areas for improvement, although this is not the main goal of this comparative assessment.

3.1.2 Short description of the investigated scenario and product systems

The comparison of the two different systems is based on a representative case study (i.e. **baseline scenario**). This baseline scenario is used as a general, average scenario to illustrate potential implications on B2B transportation in Europe. Most importantly, potentially decisive parameters, assumptions, data, etc. around the respective systems are identified. The baseline comparison should therefore be understood as an evidence-based reference for deriving potential boundary conditions under which one or the other system may be preferable in terms of certain environmental impacts. With this information at hand, potential additional cases worth further investigation may be defined.

The selected specific scenario is deemed representative for the (non-refrigerated) shipping of generic fruits and vegetables by average means of transport (i.e. truck) and by considering one of the most preferred routes in Europe in terms of volume of transported goods (based on recent statistical data). To the extent possible, hygiene standards and parameters for the specific goods are acknowledged.

The two applicable *systems*, CB and RPC, are intended for the transportation of vegetables in a B2B context, therefore from the manufacturer to the retailer. Table 1 summarizes important aspects and variables relating to the two systems, taking functional equivalence into account. In this table, two parameters (number of reuses and average breakage rate) are used in the model for the RPCs. In literature, different assumptions regarding these two parameters are made (see section 2.1). The number of reuses (or rotations) for the RPC system are assumed by considering a comparative study on single-use CBs and RPCs (Thorbecke *et al.*, 2019). The authors assumed 24 rotations for RPCs on the basis of RPCs industry experts. It is assumed that RPCs have a rotation every 3-4 months for a lifespan of 5-6 years. In a conservative approach, RPCs are then assumed to be returned 4 times per year with a lifespan of 6 years, with a consequent total number of reuses of 24. Since this a debated parameter in literature (see, e.g., Lo-Iacono-ferreira *et al.* 2021), section 3.4.2 presents a break-even analysis for the impact category Climate change, total.

Table 1: Description of the systems and key parameters for the baseline comparison

Aspect	Recyclable single-use corrugated box (CB)	Multiple-use plastic crate (RPC)
Raw material and subsequent processing/ manufacturing	Corrugated cardboard made of 53% Kraftliner and 47% Semi-chemical (fluting)	Mixture of two polymers (58% HDPE / 42% PP) formed though injection moulding
Type of use	Single-use	Multiple-use (foldable crate)

Aspect	Recyclable single-use corrugated box (CB)	Multiple-use plastic crate (RPC)
Number of reuses/rotations[7]	n.a.	24
Return rate	n.a.	100 %
Average breakage rate	0[8]	2.5%[9]
Dimensions (mm)	600x400x210	
Max. load capacity (kg)	15	
Container weight (kg)	0,77	1,82
Transport	Distance from food producer to distribution center: 840 km (average distances for intermediate transports are assumed within Europe, see further details in section 3.2.3.2 and detailed description in Appendix 2)	
	-	Distance from distribution center to service center (washing and sanitizing): 165 km
Preparation for reuse (i.e. distribution, inspection, washing)	n.a.	After each use, RPCs are sent to reconditioning facilities, where they are washed and then reused up to a certain number of cycles, which determines their lifespan. Average transport distance to the reconditioning facilities is considered
End-of-life	Recycling rate 82,9%[10], rest incineration with energy recovery	Recycling rate 41,8%[11], rest incineration with energy recovery
*Needed for preparation for reuse (i.e., distribution, inspection, washing)		

3.1.3 Functional unit

Based on the described scenario above and key parameters of the respective systems the following functional unit is adopted for this assessment:

> **Provision of delivery, containment, and display for 1 ton of vegetables (fresh product) by means of functionally equivalent transport containers (either single-use corrugated board boxes, or multiple-use plastic crates) over a transport**

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[7] It is important to highlight that the comparison is made by considering the life cycle of a single-use system for 24 times and the life cycle of a multiple-use system by taking into account 24 reuses/rotations.

[8] Source: personal communication with FEFCO. Even if it breaks after one trip it has already fulfilled its purpose unless the product gets damaged.

[9] This assumption is based on values reported in literature for breakage rate of plastic crates. An average value (2,5%) is considered in this study, between a minimum value (no breakage rate = 0%), and a maximum value (5%, source Thorbecke *et al.*, 2019). This assumption is further suggested in Lo-Iacono-ferreira *et al.* (2021). The authors presented a screening of studies regarding this aspect. They conducted a comparative LCA study on CBs and RPCs by using a value between 1% and 5%.

[10] Source: https://ec.europa.eu/eurostat/databrowser/view/ENV_WASPACR__custom_1226307/default/table?lang=en EU–28 countries, year 2018, waste category "paper and carboard packaging"

[11] Source: https://ec.europa.eu/eurostat/databrowser/view/ENV_WASPACR__custom_1226307/default/table?lang=en EU–28 countries, year 2018, waste category "plastic packaging"

> **distance of 840 km from producer to retailer in the EU in a manner that maintains the safety of the produce and that is consistent with established commercial supply chains.**

Consequently, great attention is given to the evaluation of the functional equivalency of single-use and multiple-use solutions and potential functional/quality differences are disclosed in either quantitative or qualitative terms. In this respect, food safety requirements are fulfilled by both systems, which means that, for example, the multiple-use containers are sanitized between every use cycle for food contact application. Moreover, consistency and symmetry in assumptions and modelling choices between both products and associated life cycles is ensured.

3.1.4 System boundaries

The system boundaries for both systems comprise all life cycle stages from cradle-to-grave/cradle, including resource extraction, production of the packaging solution, logistics, use and end of life, including recycling and incinerating of the corrugated solution[12], washing of the plastic solution after each use, recycling and incinerating of the plastic crates after lifespan[13], as well as transport for recycling and transport of empty load returns of the plastic crates and the storage space needed for the reusable crates during idle periods.

Figure 2 shows the system boundaries for the recyclable single-use corrugated box (CB) system as adopted for the baseline comparison (see further details on the depicted life cycle stages and processes in section 0).

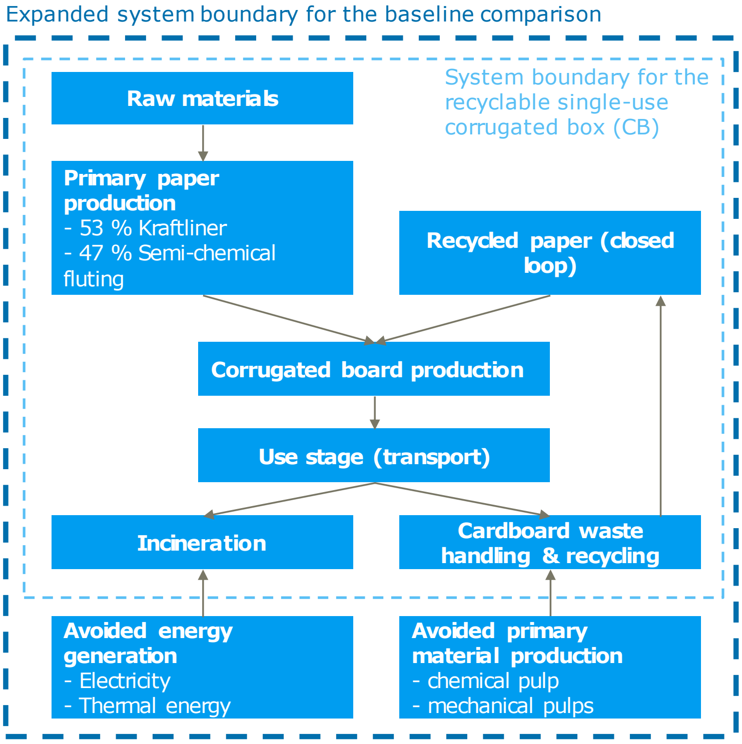

Figure 2: Simplified representation of the system boundaries for the recyclable single-use corrugated box (CB) system in the baseline scenario

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[12] Shares of recycling and incinerating are shown in Table 1.

[13] Shares of recycling and incinerating are shown in Table 1.

Figure 3 shows the system boundaries for the multiple-use plastic crate (RPC) system as adopted for the baseline comparison (see further details on the depicted life cycle stages and processes in section 0).

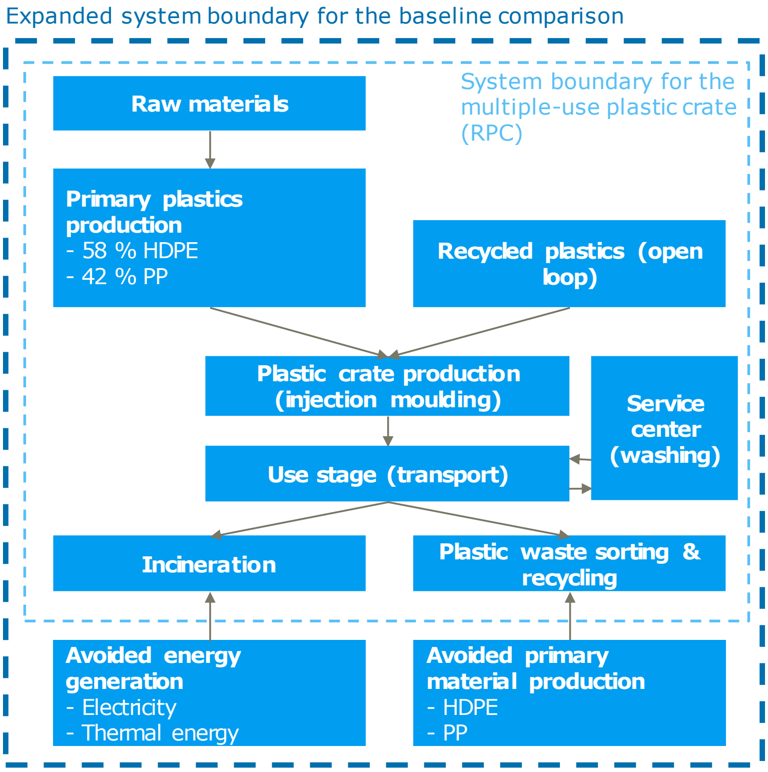

Figure 3: Simplified representation of the system boundaries for the multiple-use plastic crate (RPC) system in the baseline scenario

3.1.4.1 Geographical Scope

The geographical scope of the comparison is EU (EU-27 + UK). The analysis of a specific scenario is to comprise statistical data about transportation in the EU[14].

This geographical boundary mostly is reflected in the assumptions around the foreground systems and assumptions (e.g. transport distance, recycling rates) and background datasets (e.g. electricity from grid) as inventory data for the manufacturing stage of certain products, as well as washing processes for the multiple-use system, is site-specific, and hence they represent average production supply chains in Europe (e.g. mainly EU or EU Member States; global, if no other data is available). The geographical scope of all background processes is documented transparently.

3.1.4.2 Time boundary

Primary data[15] for the single-use system is retrieved for the manufacturing and recycling process of the corrugated packaging solution. The most recent data is referred to the year 2018 (see CEPI and FEFCO, 2018). Personal communication with FEFCO is referred to the year 2021 and early 2022.

Secondary data is retrieved for the plastic crate solution, when possible, from the past 5 years (2017-2021). In general, for both solutions, if no data can be retrieved in the past 5 years, the research is extended to the past 10 years, especially for the secondary data of the multiple-use system which is mainly based on desk-research findings.

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[14] Further information regarding transportation routes in Europe is collected among some FEFCO's members.

[15] This data can be considered as primary data since it represents specific data collected among manufacturers associated to FEFCO.

3.1.5 Handling and modelling of end-of-life stage

Recycling of material from one product system to another constitutes an omnipresent methodological challenge (i.e. allocation problem) in LCA studies, because the same material is used in at least two different products (Hauschild, 2017). This is mainly due to the aspiration of analyzing individual product systems based on the main function they provide despite their real-world implications and interrelations with potential other functions or processes. The increasing popularity and adoption of the concepts of a Circular Economy (CE) further intensify the need for consistent handling of multifunctionality-related challenges with regard to e.g. cascading use of resources and quality changes during recycling.

In order to deal with such issues, the ISO standard 14044 presents a hierarchy of procedures. These procedures are a prerequisite for comparative assertions between different product systems and allow for a hotspot analysis of a single product system. In general, the ISO hierarchy for solving multifunctionality is as follows (Hauschild, 2017):

1. Perform sub-division of the affected process, i.e. cut off subprocesses providing secondary functions;
2. Perform system expansion, i.e. integrate the secondary function into the system boundaries (displacement/avoidance of impacts or crediting for avoided production);
3. Perform allocation using physical causality, representative physical parameter, or another parameter (e.g. economic) (in this order), i.e. partition the environmental flows and associated impacts between the primary and secondary functions and cut off the part related to the secondary functions.

First, it is important to ensure consistency and symmetry in assumptions and modelling choices between both systems and associated life cycles. For the selection of an appropriate modelling approach, it is therefore important to differentiate whether recycling is characterized as a closed-loop or an open-loop. In general, open-loop recycling refers to material being recycled from one product into another, while closed-loop recycling applies when a material is recycled into the same product system, or when it is recycled into another product system without changes in the properties of the material. Arguably, paper recycling can occurs in an open-loop due to the decreasing length of recycled fibers during consequent recycling of the same fibers, ultimately reducing its quality and altering inherent properties when compared to virgin fibers (Hohenthal *et al.*, 2019) – arguably this argumentation can equally be applied to the plastics industry (Volk *et al.*, 2021). Although an open-loop assumption can be considered realistic at B2C level, this study investigates B2B transport packaging. At B2B level, paperboard recycling is mostly a closed-loop process in paperboard industry[16].

In order to represent recycling situations in LCA studies, several allocation methods have been developed and can be applied depending on the goal and scope of the assessment. With respect to the goal and scope of this assessment as well as in order to fulfill the ISO requirements (i.e. at least two variants of the allocation of credits from energy or material recovery have to be considered for comparative LCA studies) applicable allocation methods are presented in Table 2.

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[16] Paper cycle at B2B level is almost completely closed, as reported by FEFCO's LCI (2018), as well as many industry reports (see, e.g., KCPK "Recycling of paper and board in the Netherlands in 2019" available at: https://circpack.eu/fileadmin/user_upload/Recycling_of_Paper_and_Board_in_The_Netherlands_in_2019_-_final.pdf, where it is stated that

Table 2: Overview of applicable allocation methods for this study (list based on Ekvall *u. a.*, (2020) and Heijungs *u. a.* (2021))

Allocation method/ approach	Alternative/ frequently used terms	Recommended by	Evaluation considering goal and scope of this assessment
Avoided burden approach – *baseline scenario*	• Closed-loop approximation • 0/100 method • End-of-life approach • Recyclability substitution • Value of scrap approach • Allocation to material losses • System expansion	• ISO 14044:2006 • ISO 14044:2020 • ISO 14067 • ISO 20915 • GHG Protocol • PAS 2050	(+) Recommended approach when the product service life is short and/or well known (+) Relatively easy to apply (+) does not require additional data or significant modelling choices (+) Comprehensible (+) Adopted approach in European Database for Corrugated Board (CEPI and FEFCO, 2018) (-) Does not differentiate between virgin and recycled material and different quality of material (-) does not take into account how often a material is recycled (-) less reproducible
Simple cut-off – *sensitivity scenario*	• Recycled content approach • 100/0 method	• EPD system • GHG Protocol • PAS 2050	(+) Easy to apply as only the recycling process needs to be allocated between product systems (+) Comprehensible to large audience (+) Often used supplementary to closed-loop-approximation (-) Does not reflect decisive characteristics of the system (e.g. provision of secondary raw materials, different qualities of materials)
50/50 method – *sensitivity scenario*	-	• Nordic Guidelines on LCA • German Environment Protection Agency	(+) Fairly easy to use and understand (+) No need for data on quality or price (-) Additional collection of data on virgin material use or disposal are needed for the product life cycles where no virgin material is used or no disposal occurs, respectively

Allocation method/ approach	Alternative/ frequently used terms	Recommended by	Evaluation considering goal and scope of this assessment
Circular Footprint Formula (CFF) – *sensitivity scenario*	- PEF approach	- Product Environmental Footprint Guide	(+) Differentiates between virgin and recycled material, between different fate of recovered resources and the different quality of material (-) Difficult to apply due to incorporation of several additional factors (e.g. factors to quantify the quality of the recycled materials) (-) complex to explain and illustrate (-) impeded reproducibility due to complexity
REFFIBRE (Hohenthal *et al.*, 2019) **–** *not considered in this assessment*	-	- Based on ISO 14067	(+) Considers the number of subsequent uses of recycled fibers and the recycled fiber age (-) Readily applicable only for paper products; applicability to plastic products would need to be investigated for symmetry reasons

According to the ISO hierarchy (and the latest amendment 2, ISO 14044:2020) system expansion (i.e. avoided burden approach) is the preferred approach for solving multifunctionality in several end-of-life scenarios (e.g. open- or closed-loop recycling, incineration with energy recovery) (Hauschild, 2017). More specifically, material outputs from recycling processes are credited based on the assumed reduced requirement of virgin material production. Similarly, incineration of some materials in the EoL stage produces heat and electricity, which is credited using average energy equivalents (e.g. residual energy mix from grid) based on the assumption that respective primary energy generation is substituted. The adopted approach does not account for the alternative waste disposal avoided through recycling and is therefore aligned with the guidance underpinning the CFF.

The system expansion (avoided burden) approach is also the most recognized method to solve consequential end-of-life multifunctionality. Hence, this allocation method can be described as a consequential approach that includes avoided activities but is nevertheless applicable to attributional assessments (Ekvall *et al.*, 2020). The attributional and consequential versions of this method both reflect the view that material lost from the technosphere must be replaced through virgin material production. From a policy perspective, this approach leads to a focus on recycling at the end-of-life and promotes the concept of the circular economy (Ekvall *et al.*, 2020; Nilsson *et al.*, 2021), while the so-called cut-off approach (or: recycled content approach) leads to a focus on increasing the percentage of recycled materials in a new product.
The cut-off approach is not considered appropriate for biogenic materials such as paper, since this approach may lead to the conclusion that waste disposal can even have a net positive impact on

the environment. This can be the case if the disposal is, for example, incineration with energy recovery of paper and other biogenic materials. In these cases, the simple cut-off gives an incentive not to recycle the biogenic material, even if recycling is good for the environment. Hence, a drawback of the simple cut-off is that it does not give incentives for recycling after use, when the final disposal has little or positive net environmental burdens (Ekvall *et al.*, 2020).

System expansion approach and closed-loop recycling are chosen for the baseline comparison in both systems. This is in line with several other relevant LCAs, as identified in the Literature Screening (see also section 1.2.2). The following LCA studies adopted an avoided burden approach (system expansion) for either the baseline scenario or as part of the sensitivity analysis:

- Lo-Iacono-Ferreira et al. (2021): Carbon Footprint Comparative Analysis of Cardboard and Plastic Containers Used for the International Transport of Spanish Tomatoes. *Sustainability*[17]
- López-Gálvez et al. (2021): Reusable Plastic Crates (RPCs) for Fresh Produce (Case Study on Cauliflowers): Sustainable Packaging but Potential Salmonella Survival and Risk of Cross-Contamination. *Foods*
- Abejón et a. (2020): When plastic packaging should be preferred: Life cycle analysis of packages for fruit and vegetable distribution in the Spanish peninsular market. *Resources, Conservation & Recycling*
- Thorbecke et al. (2019): Life Cycle Assessment of Corrugated Containers and Reusable Plastic Containers for Produce Transport and Display
- Stiftung Initiative Mehrweg [Foundation for Reusable Systems] (2018): Carbon Footprint of Packaging Systems for Fruit and Vegetable Transports in Europe
- Koskela et al. (2014): Reusable plastic crate or recyclable cardboard box? A comparison of two delivery systems. *Journal of Cleaner Production*

The modeling approach for the baseline comparison in this study therefore ensures comparability with existing studies. Adhering to the ISO 14044 requirements, different applicable methods for the allocation of credits resulting from energy or material recovery are also considered (see Table 2). This is ensured by a sensitivity analysis (see section 3.3.4).

Lastly, it is important to bear in mind that the ISO standard does not specify any exact formula or approach to model the recycling stage, while the EU harmonized Product Environmental Footprint (PEF) methodology proposes the use of the so-called Circular Footprint Formula (CFF) (see Table 2 above). While the formula addresses some important aspects for a fair comparison between different product systems (e.g. introduction of a factor to allocate burdens and credits between two life cycles) it comes also with some shortcomings: e.g. not considering how often a material is recycled, potentially inadequate and too generic quality correction factors. When modelling closed-loop systems, the PEF methodology is even in conflict with the ISO 14044 standard as only up to 80% of credits can be assigned by using the CFF, whereas ISO allows for 100% of the credits to be allocated to the product system. It is even argued that the PEF methodology is rather applicable to internal product and process optimization purposes but not suitable for fair comparative assertions (Bach *et al.*, 2018).

In December 2021 the European Commission (EC) published a "revised Recommendation on the use of Environmental Footprint (EF) methods, helping companies to calculate their environmental

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[17] This study was referenced in an official newsletter of the European Commission (https://ec.europa.eu/environment/integration/research/newsalert/pdf/569na1_en-1313_lca-of-agricultural-tomato-packaging-boxes-for-climate-impact_v2.pdf)

performance based on reliable, verifiable and comparable information, and for other actors”[18]. Following the EC recommendation, with the aim at helping industry to know and eventually reduce environmental emissions of its products, the CFF is applied in this study along with the Avoided burden approach. Results of these two methodologies are transparently reported in Section 3.3.3.

3.1.5.1 Inherent allocation at process level

Datasets adopted from existing databases (e.g. Ecoinvent, GaBi Professional database) for the modelling of background processes adhere to inherent allocation procedures. The respective datasets coming from databases are transparently documented for the affected processes.

3.1.6 Impact categories and assessment method (LCIA)

This study is conducted in accordance with ISO 14000/14040, and the comparative assessment is expressed via Environmental Footprint (EF) impact categories. A general requirement for comparative life cycle assessments disclosed to the public is that the choice of environmental categories shall be as complete as possible, as well as appropriate and reasonable in relation to the goal of the study so that a fair comparison is facilitated. All EF impact categories are included in this study with the exception of the EF Land Use [Pt] impact category, which is excluded due to intrinsic difficulties in interpreting results due to the following reasons (which are part of the ongoing scientific research): inconsistency between databases (the use of both GaBi professional and Ecoinvent), insufficient data on relevant parameters (e.g. land management parameters such as crop or forest management and conservation practices), lack of common agreement on a cause-effect chain for modelling impacts, risk of overestimating or underestimating impacts in large countries. Table 3 gives an overview of the impact categories covered by the PEF methodology and used in this assessment.

Table 3: List of selected EF impact categories (source: PEF guide[19])

EF Impact category	Impact Category Indicator	Unit
Acidification	Accumulated Exceedance (AE)	mol H+ equivalent
Climate Change, total[20]	Radiative forcing as Global Warming Potential (GWP100)	kg CO2 equivalent
Climate Change, biogenic	*Radiative forcing as Global Warming Potential (GWP100)*	*kg CO2 equivalent*
Climate Change, land use and land use change	*Radiative forcing as Global Warming Potential (GWP100)*	*kg CO2 equivalent*
Climate Change, fossil	*Radiative forcing as Global Warming Potential (GWP100)*	*kg CO2 equivalent*
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems	CTUe
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P equivalent

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[18] Source: https://ec.europa.eu/environment/eussd/smgp/ef_methods.htm

[19] https://ec.europa.eu/environment/eussd/smgp/pdf/PEF%20webinar%20Nov%202020_Data%20and%20Impact_Final_.pdf

[20] The impact category “Climate Change, total” is constituted of three sub-impact categories: Climate Change, fossil, Climate Change, biogenic, Climate Change, land use and land use change. For the sake of transparency, all these three sub-categories are included in this study and disclosed. However, only Climate Change, total is discussed in the interpretation of the results in the charts.

EF Impact category	Impact Category Indicator	Unit
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N eq
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N equivalent
Human toxicity, cancer	Comparative Toxic Unit for humans	CTUh
Human toxicity, non-cancer	Comparative Toxic Unit for humans	CTUh
Ionising radiation, human health	Human exposure efficiency relative to U235	kBq U235 equivalent
Ozone Depletion	Ozone Depletion Potential (ODP)	kg CFC-11 equivalent
Particulate matter	Impact on human health	disease incidence
Photochemical ozone formation - human health	Tropospheric ozone concentration increase	kg NMVOC equivalent
Resource use, fossils	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb equivalent
Water use	User deprivation potential (deprivation-weighted water consumption)	m³ world equiv.

Impacts are presented by splitting life cycle stages to facilitate disclosure and interpretations of relative contributions. For both systems, the following life cycle stages are separated (with indication of the respective system):

- Raw material production and manufacturing [CB; RPC]
- Transport [CB; RPC]
- Service center (washing) [RPC]
- EoL of post-consumer product: incineration [CB; RPC]
- EoL of post-consumer product: recycling [CB; RPC]
- Avoided emissions: material [CB; RPC]
- Avoided emissions: energy (electrical and thermal) [CB; RPC]

3.1.7 Data quality requirements

According to ISO 14044 data quality requirements must be included for the following aspects:

- **Time-related coverage:** Primary datasets and inventories are not older than 2018 for the CB system. Only for the RPC system, secondary data older than 2018 (2017-2021) is considered (see section 3.1.4.2). Crucial life cycle stages and processes refer to the most recent literature or otherwise publicly available information and have been discussed with market experts in order to ensure applicability. At the time of modelling latest available secondary data is implemented for background processes (Ecoinvent 3.7.1 as well as GaBi Professional database 2021.2).

- **Geographical coverage:** In general, all data and assumptions refer to or are applicable to an average EU context, as long as data availability allows. Geographical coverage is, however, dependent on the available data. Geographical coverage of primary and secondary data is disclosed in the respective inventories in section 0.
- **Technological coverage (i.e. technological standard of production, distribution, use and EoL processes):** Primary data and information covers state-of-the-art paper production, corrugated box manufacturing, and recycling and is therefore considered representative of the current technology level. Other secondary data represents average technologies used in the EU, as described in respective background datasets.
- **Precision:** Representative and precise primary data is used to the extent possible. The influence of unavoidable variability in key parameters is tested by means of sensitivity analyses.
- **Completeness:** Completeness of data is achieved through the iterative process of data collection and modelling. Data gaps are disclosed transparently but not expected to have significant influence on the results and comparative assertion. Simple validation checks (e.g. mass or energy balances) are performed. Moreover, primary data as well as results are benchmarked with literature data, as far as possible.
- **Representativeness:** The degree to which data and assumptions reflect an average EU situation is addressed under time-related, geographical, and technological coverage. The study represents whole packaging and transport systems comprised of clearly defined product items.
- **Consistency:** Consistency in the assumptions, modelling choices, and the selection of data sources is of utmost importance for this comparative assessment (see also sections 3.1.3 and 3.1.5). In the absence of unambiguous data or references for critical assumptions equal assumptions or references are applied to both systems. The LCA methodology is uniformly applied to both systems and sub-systems and it is ensured that modelling and methodological choices do not affect the results and conclusions. If so, respective modelling and methodological choices are reflected in the sensitivity analysis. It is evident from previous LCA studies on paper products that environmental credits associated with the assumed avoided production of materials or energy can play a significant role for the total results and comparison. This holds particularly true when high-material volume systems (i.e. single-use) are compared with low-material volume systems (i.e. multiple-use). Inconsistent use of data for the upstream (i.e. raw material extraction and processing) and downstream (i.e. recycling and avoided production) can potentially cause an over- or underestimation of environmental benefits from recycling. This study therefore ensures consistency between the datasets used for both raw material processing and EoL crediting by adopting a closed-loop approximation for both systems. This assumption is tested by means of sensitivity analysis.
- **Reproducibility:** Primary data is confidential, but context information and reference flows are disclosed to the extent possible. All other assumptions as well as implementation of secondary data is documented in a way that allows for reproduction of the underlying models.
- **Uncertainty of information:** Major uncertainties are addressed by means of a sensitivity analysis as well as qualitative discussions. Remaining uncertainties are taken into consideration when interpreting results. In particular, uncertainty on information for the manufacturing of a plastic crate solution is due to lack of primary data. Therefore, secondary data is used (see section 3.1.4.2), and this can be seen as a limitation of this study.

3.1.8 General assumptions and exclusions form the assessment

The following overarching assumptions and simplifications are made:

- Capital goods and infrastructures (e.g. for the reconditioning of plastic crates; recycling facilities) as well as auxiliary processes (e.g. refrigeration of infrastructure) are not considered, except in cases where the selected inventory data incorporates this information as part of an aggregated dataset;
- Additional and/or deviating space requirements for storage of containers are neglected;
- Additional quantities of excess plastic crates (i.e. float) in order to ensure a stable and flexible system are not considered; The effect of an additional stock of plastic crates is assumed to be negligible as a larger stock would also mean that individual plastic crates are less frequently used and therefore would lead to a lower average reuse rate of a certain stock; This observation is assuming the functional unit to be fixed (i.e. transporting 1 ton of fresh produce), hence individual crates would need to be moved less frequently to meet the same function/service. This obviously means that this larger stock can be used longer, which again would mean that only a fraction of this stock would need to be allocated to the functional unit of this assessment. In conclusion, assuming a larger stock would not make any difference from a purely analytical perspective. Any organizational aspects that may have to be factored in are beyond the scope of this assessment;
- Potential implications and effects on the contained food (e.g. protection of food) due to the respective packaging solution are not taken into account;
- Potential implications due to the inherent thermal properties of the containers are excluded due to lack of data.

Any additional assumptions and limitations are reported in the respective sections.

3.1.9 Normalization and weighting

According to ISO 14040, normalization and weighting are optional parts of the life cycle impact assessment procedure. In this study, they are not taken into account.

3.2 Life Cycle Inventory Analysis

This section provides a detailed and transparent description and discussion of data quality, assumptions, allocation procedures, data gaps, and accompanying calculations. Necessary data and information are collected through different sources and hence can be classified as:

- **Primary data:** data collected/measured directly by a company; e.g. raw material demand, energy (electricity, natural gas, etc.), wastes (emissions as well as solid waste) inputs and outputs for a particular process or product. Data are collected and maintained by subject-matter experts such as material and product engineers, research and development managers, or LCA experts.
- **Secondary data:** data collected through publications, scientific literature, statistics, and LCI databases.

Primary or secondary data can entail full LCI datasets/LCIA results, input-output tables (e.g. bill of materials), assumptions, and certain reference flows or values. The respective classification of incorporated inventory data is marked in section0.

3.2.1 Data collection

3.2.1.1 Data collection from industry

Primary data collected from manufacturers is implemented through either complete LCIA results or own modelling based on received input/output sheets (i.e. connecting reference flows and values with applicable datasets and flows from LCI databases). All data and information received are checked for applicability, completeness, consistency, and plausibility. Data and information obtained are disclosed to the extent confidentiality agreements allow.

3.2.1.2 Data collection from literature sources and LCI databases

In case primary data is not available nor accessible, secondary data from literature or LCI databases are incorporated and documented. As is common practice in comprehensive LCA studies, LCI datasets (e.g. electricity from grid) are required to integrate primary information from e.g. input-output sheets for processes. Moreover, it is assured that the use of secondary data is applicable and representative in light of the goal and scope of this assessment.

LCI of corrugated board, commissioned by FEFCO in 2018

FEFCO conducted a LCI study to evaluate inputs and outputs for average corrugated board manufacturing. This study adheres to the system boundaries adopted in the LCI study conducted by FEFCO (CEPI and FEFCO, 2018), as reported in Figure 4, where a closed-loop corrugated board packaging system is assumed.

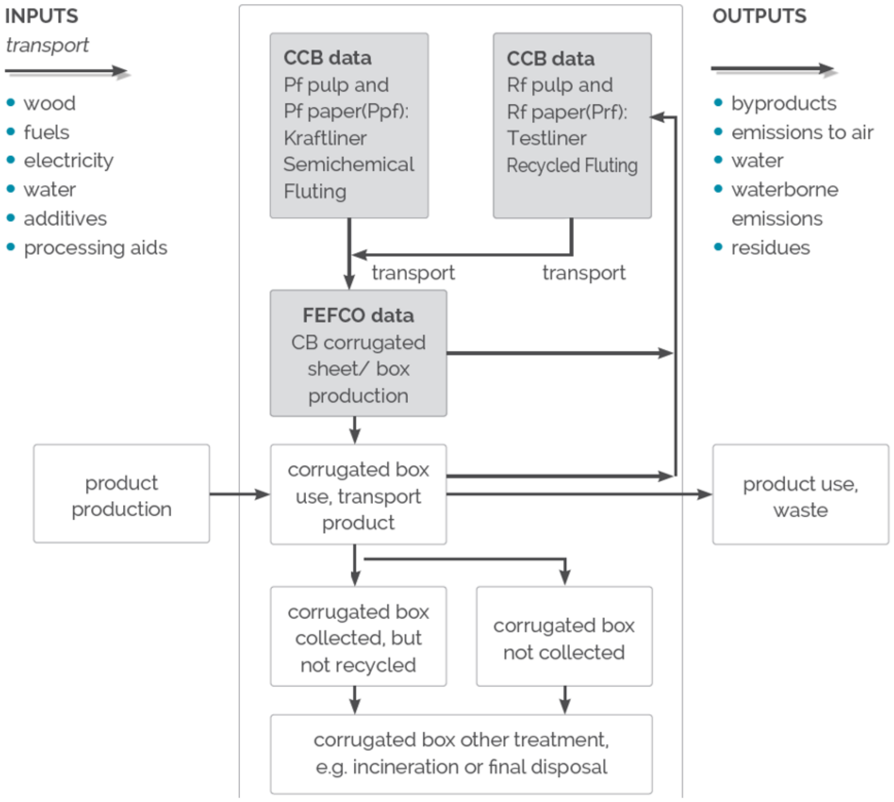

Figure 4: Flow chart of unit processes involved in the LCI of FEFCO[21]

LCI of wastepaper to pulp production

For modeling environmental burdens of the recycling process, data present in the FEFCO LCI database is adapted considering information presented in the "Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board" (Suhr *et al.*, 2015). This data was compiled by RISE on behalf of CEPI and FEFCO during 2021 as part of a specific project and a pre-publication version of the results was provided for use in this assignment. The data has been checked by a major producer of recycled corrugated case materials, considering operating

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[21] https://www.fefco.org/lca/dscription-of-production-system/paper-production

experiences. This data can be considered a "hybrid" of primary and secondary data. Assumptions made for this LCI are reported in section 3.2.3.4. and LCI data used in the model is reported in Appendix 1.

3.2.2 Product systems and process flowcharts

The following table defines the characteristics of both systems for the model. A typical RPC model retrieved from a website source of RPC manufacturer is considered as reference for the RPC system. Its weight is adapted to have the same functionality as the CB model. Source of data are reported in the table and as footnotes.

Table 4: Description of the modelled solutions

	Single-use corrugated box (CB)	Multiple-use plastic crate (RPC)	
	Modelled reference	Model 6421	Modelled reference
Material	corrugated board	HDPE	HDPE/PP
Mass of one box/crate (kg)	0,77	1,98	1,82
External dimension (mm)	600x400x210	600x400x229	600x400x210
Max loading capacity (kg)	15	20	15
Source of data	Personal communication with FEFCO (2021)	CPR system[22]	-

By considering modelled references in the previous table, the following Table 5 shows number of CBs and RPCs used in the model (with calculation), as well as mass of one CB/RPC and mass of all CBs/RPCs. The comparison is therefore made by considering the manufacture of 73,33 kg of CB manufactured and 7,22 kg of RPC. Total mass of RPC is calculated considering number of rotations assumed in the baseline scenario (24 rotations); therefore, number of RPCs needed for transporting 1 ton of goods is divided by 24.

Table 5: Description of parameters used in the model

	Single-use corrugated box (CB)	Multiple-use plastic crate (RPC)
	Modelled reference	Modelled reference
Mass of good transported	1 ton of transported vegetables	
Max loading capacity (kg)	15	
Loading capacity (real) assumed[23]	70%	
Number of CBs/RPCs	1.000 / (15 kg * 70%) = 95,23 boxes	(1.000 / (15 kg * 70%))/24 = 3,96 crates
Mass of one CB/RPC (kg)	0,77	1,82
Mass of all CBs/RPCs (kg)	73,3	7,2
Overall distance of one CB/RPC (km)	1.145	1.537,5

Overall transport distance of one RPC is also calculated considering number of rotations, as described in the followjng table

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[22] https://www.cprsystem.it/wp-content/uploads/2021/08/CPR_Rev3_Scheda-informativa-Casse-Ortofrutta.pdf

[23] A realistic loading weight (70%) of the maximum capacity is assumed for both systems (arbitrary)

Table 6: Overall transport distances

	Single-use system (CB)			Multiple-use system (RPC)		
	distances (km)	n-times	distances (km) per f.u.	distances (km)	n-times	distances (km) per f.u.
Transport routes						
manufacturer - food producer	55	1	55	370	1/24	15,42
food producer - distribution center	840	1	840	840	1	840
distribution - retailer	50	1	50	50	1	50
retailer - distribution center	n.a.	1	n.a.	50	1	50
distribution - service center (washing and sanitizing)	n.a.	1	n.a.	165	1	165
service center - food producer	n.a.	1	n.a.	380	1	380
Transport routes (EoL)						
EoL recycling (CB: after each use; RPC: after the last route at end of lifespan)	150	1	150	840	1/24	35,00
EoL incineration (CB: after each use; RPC: after the last route at end of lifespan)	50	1	50	50	1/24	2,08
Overall distances of one box / crate (km)			1.145,0			1.537,5

3.2.3 Data sources

3.2.3.1 Raw material acquisition and processing

Single-use system (CB)
The general sequence of a paper production process is depicted in Figure 5.

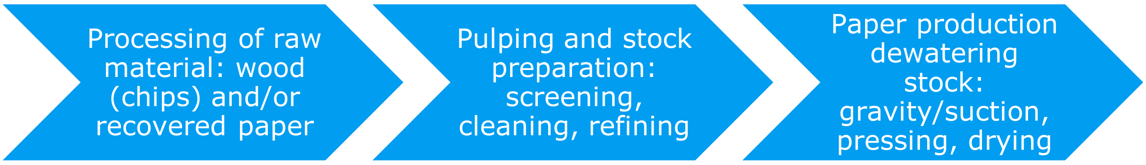

Figure 5: Paper production process (own depiction based on FEFCO[24])

The life cycle reported in FEFCO LCI (2018) starts from the forest operations, extraction of fuels, and acquisition of other raw materials, and ends at the corrugated box production's gate. The dataset covers all relevant process steps / technologies over the supply chain of the represented cradle-to-gate inventory. All upstream operations, such as production and transportation of used chemicals, and production of purchased energy are included. This dataset has variable paper inputs, and the type of paper can be chosen individually. Following the information given by FEFCO members regarding the composition of the CB, the LCI is adapted to the specific situation, as shown in Table 4.

Table 7: Description of the paper grades used in the single-use system (source FEFCO LCI, 2018)

Single-use corrugated box (CB)	Kraftliner	Semi-chemical fluting

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[24] https://www.fefco.org/lca/dscription-of-production-system/paper-production

Recycled content[25]	0,35 kg waste paper input per kg Kraftliner	0,09 kg waste paper input per kg Semichemical Fluting
Cut-off rules for each unit process	Coverage of at least 95% of mass and energy of the input and output flows, and 98% of their environmental relevance (according to expert judgment)	

The CB production is modelled with average composition for the scope of the study. This information is gathered among FEFCO members. Hence, a composition (by weight, input material) of 53% kraftliner and 47% semi-chemical fluting is considered. In the production process, around 1.1 kg of paper input is required to obtain 1 kg of CB. The manufacturing process follows the indications reported in the FEFCO LCI (2018): "Corrugated Board is manufactured from a number of specially conditioned layers of recycled and/or virgin papers, called Fluting Medium and Linerboard. Reels of Fluting Medium and Linerboard are fed into a machine called a Corrugator. The Fluting Medium paper is conditioned with heat and steam and fed between large corrugating rolls that give the paper its fluted shape. Starch is applied to the tips of the flutes on one side and the inner liner is glued to the fluting. The corrugated fluting medium with one liner attached to it is called single face web and travels along the machine towards the Double Backer where the single face web meets the outer liner and forms corrugated board. A number of layers of single faced web may be built up to produce double and triple wall corrugated board. The corrugated board is slit into the required widths and cut into sheets which are then stacked or pelletized. The final stage of the process consists of printing and then slotting, folding and gluing the corrugated board to manufacture a corrugated box." All these steps are included in the LCI. The manufacturing process of both paper grades and CB is modelled by using database entries as reported in Table 8.

Table 8: Secondary data for paper grades and corrugated box production

Provider process	Data classification	Source	Geographical coverage
Kraftliner (2018)	Secondary data	FEFCO[26]	EU-28
Semichemical Fluting (2018)	Secondary data	FEFCO	EU-28
Corrugated board excl. paper production (2018), open paper input	Secondary data	FEFCO	EU-28

Multiple-use system (RPC)

The RPC manufacturing stage is based on the composition reported in Del Borghi *et al.* (2021). According to the study developed by the University of Stuttgart, the plastic crate analyzed in this study is made of a polymer granulate mix of high-density polyethylene (HDPE) and polypropylene (PP) with a proportion of 58.4% and 41.6% by weight, respectively.

This composition is adopted in the model and a fixed recycled content of 10% by weight is assumed. The recycled content for plastic crates with focus on fruits and vegetables in the past five years in Europe is investigated with a desktop-based screening. To determine the percentage of recycled HDPE and PP in plastic crates the legislation around recycled content in packaging directly in contact with food is taken into consideration, as follows:

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[25] From FEFCO, Cepi Container Board: European database for corrugated board life cycle studies LCI (2018): "based on mostly primary fiber and a smaller part of waste paper/recovered paper".

[26] All these database entries are considered by Sphera: "interpretation of FEFCO LCI (2018)".

- EU has strict legislation around plastics in contact with food, and the use of recycled plastics needs to be approved by EFSA[27]
- Based on the EFSA publication registry – only 5 companies have received this certification by mid-2021 for HDPE and PP relevant to the scope.

In addition, websites of eleven providers[28] in Europe were visited to determine if there were indications of recycled vs. virgin content. Based on this research it is evident that virgin material is the default due to food safety reasons, but a few firms advocate for providing options made from recycled materials upon request. It is therefore assumed that no more than 10% recycled content is found in plastic crates for food contact.

Plastic waste fractions[29] occurring during the production process are assumed to be entirely incinerated with energy recovery.

The selected database entries for the manufacturing of plastic crates are shown in Table 9

Table 9: Secondary data for RPC manufacturing

Provider process	Data classification	Source	Geographical coverage
Polyethylene, HDPE, granulate	Secondary data	PlasticsEurope	EU-28
Polypropylene, PP, granulate	Secondary data	PlasticsEurope	EU-28
Market for polyethylene, high density, granulate, recycled	Secondary data	Ecoinvent 3.7.1	Europe (RER)
Plastic injection molding	Secondary data	Sphera	EU-28
Electricity grid mix	Secondary data	Sphera	EU-28
Polyethylene (PE) in waste incineration plant	Secondary data	Sphera	EU-28

3.2.3.2 Transport

Transport is assumed to represent an average distance for distribution within Europe. The approach is illustrated in Figure 6 for partial distances between manufactures to retailers.

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[27] https://ec.europa.eu/food/safety/chemical-safety/food-contact-materials/legislation_en

[28] Providers: Paviplast (Greece), PSAplast (Portugal), CargoPlast® GmbH (Germany), Boxline (Germany), Bekuplast (Germany), Svenska retursystem (Sweden), morssinkhofplastics (The Netherlands), Tepsa (Spain), Conip (Italy), Obal centrum (Check Republic), Schoeller Allibert (Sweden)

[29] A standard value (3%) for plastic material losses within the injection molding process is accounted (source: Sphera).

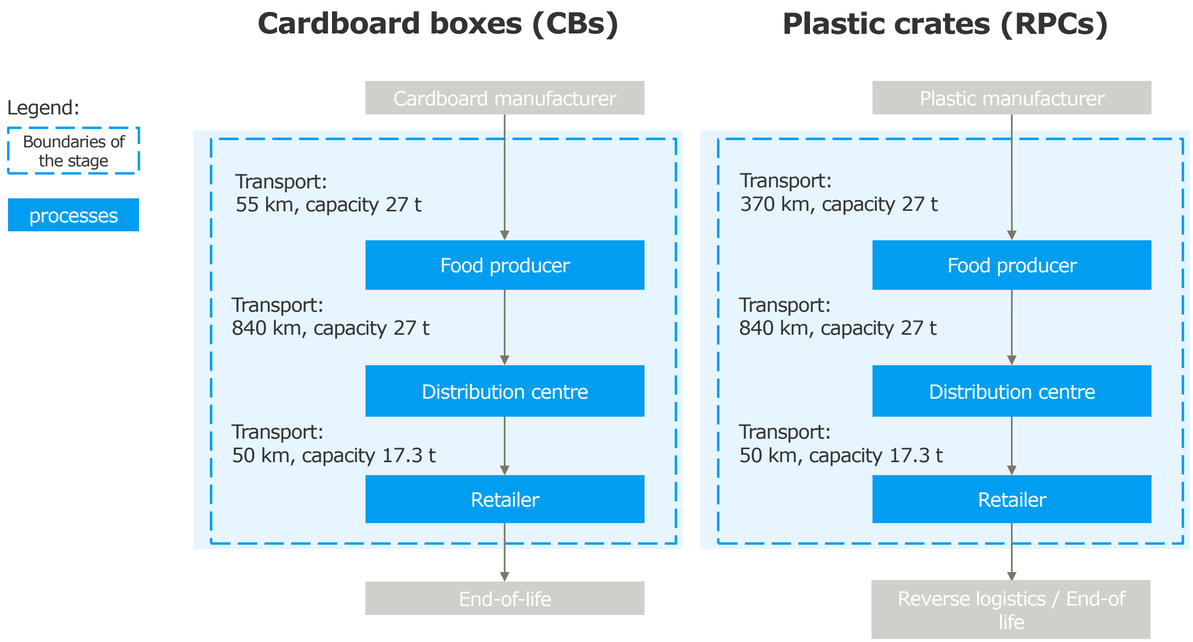

Figure 6: Scheme of the transport life cycle stage

Distances, calculations, and respective references adopted in the model are thoroughly described and reported in Appendix 2.
Regarding the means of transportation, transport between manufacturers and food producers is modelled with a generic articulated lorry, while the transport between food producers and distributions centres, as well as all other transports, are modelled as 50% truck EURO 5 and 50% truck EURO 6. Table 10 reports the database entries adopted in the model.

Table 10: Secondary data for transport

Provider process	Data classification	Source	Geographical coverage
Articulated lorry transport incl. fuel, Euro 0-6 mix, 40 t total weight, 27 t max payload	Secondary data	Sphera	EU-28
Truck-trailer, Euro 6, 34 - 40t gross weight / 27t payload capacity	Secondary data	Sphera	GLO
Truck-trailer, Euro 5, 34 - 40t gross weight / 27t payload capacity	Secondary data	Sphera	GLO

3.2.3.3 Service center (washing) in the Multiple-use system (RPC)

Modeling potential environmental impacts within a service center implies considering the steps in the washing process of plastic crates, in general, as described in Table 11.

Table 11: General steps in a service centre for washing plastic crates[30]

Steps of the service centre	Description of the process
Visual control of plastic crates	RPCs are sorted out based on their optical and functional quality

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[30] These steps and their description are adapted from https://www.elpress.com/products/industrial-washing-systems/washing-systems/crate-washers/ and https://www.boonsfis.com/en/blog/the-advantages-of-a-crate-washer/30 and https://www.elpress.com/products/industrial-washing-systems/washing-systems/crate-washers/

Steps of the service centre	Description of the process
Pre-washing	Spray nozzles clean the crates at a low water temperature (approx. 30-40 °C). This removes residues from the crates.
Washing (control temperature and chemical concentrations)	In the main wash zone, spray nozzles clean the crates with hot water (approx. 50-65 °C). Fats and bacterial contaminants are removed in combination with the right chemicals. This keeps the germ count in the wash tank as low as possible.
Rinsing	The products are rinsed with fresh cold or hot water, with the aim of effectively removing the cleaning/disinfectant agent. Rinsing with hot water helps with the drying of the crates. The assumed crate washers are designed as to enable optimal re-use of the rinse water containing the chemical residue.
Drying	In the blow off unit, air is blown over the crates by means of fans. In general, air is heated up to approx. 50 °C.

For modeling potential environmental impacts, a recent LCA study in the EU on plastic crates (Tua *et al.*, 2019) is used as reference for the steps involved. Post-consumer plastic crates are washed and dried with specified inputs to the process (i.e. water demand, heat demand, electricity demand, detergent demand). Organic residues are incinerated, and wastewater is treated in municipal treatment facilities. It is assumed that RPCs are sorted out based on their optical and functional quality. Discarded crates per cycle (2.5%[31]) are recycled – the percentage of broken/discarded crates is referred to as "breakage rate". New RPCs are consequently required for compensating the assumed breakage rate. The steps involved in the reverse logistics, as well as their relative unit processes, are shown in Figure 7.

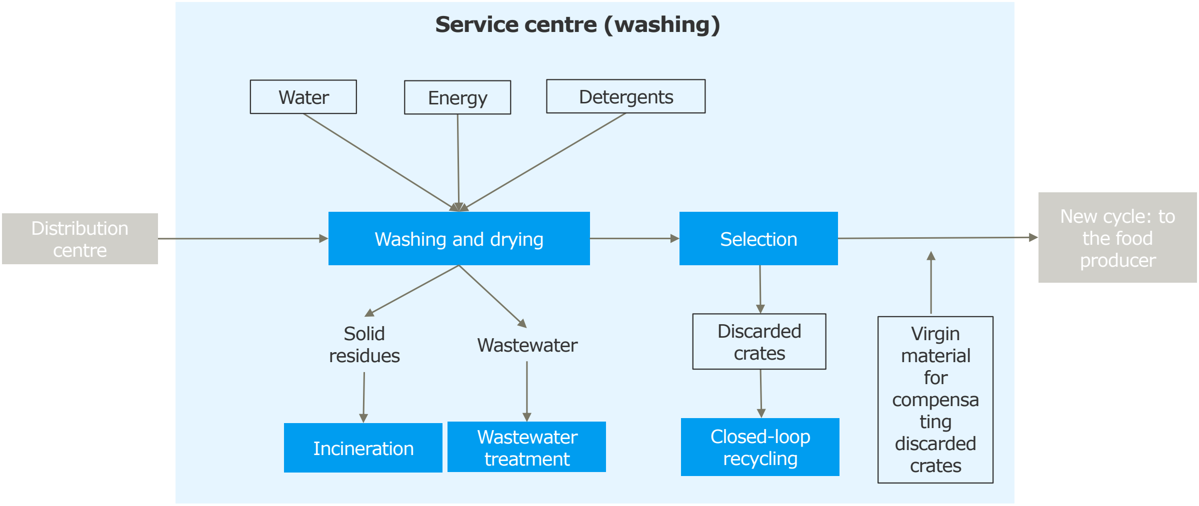

Figure 7: Scheme of the service center (washing) life cycle stage

Inputs for the washing and drying process are retrieved from literature. Table 12 presents the results of a literature screening of plastic crates washing processes in the last five years.

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[31] This is an average value, sources: (Tua *et al.*, 2017; Thorbecke *et al.*, 2019)

Table 12: Literature screening of service centre (washing) – values given per plastic crate (reference weight of a plastic crate is 1,82 kg, as reported in Table 1)

Parameter	**Datasheet**[32]	(Tua *et al.*, 2019)	(Thorbecke *et al.*, 2019)	(Lo-Iacono-ferreira *et al.*, 2021)
Energy demand [kWh]	0,077	-	0,077	0,050
Water demand [liters]	0,40	0,67	0,17	0,93
Combined detergents and rinse demand [g]	-	3,50	3,06	17,3

An average value from the reported values is calculated for 1 kg of RPC. Table 13 shows these parameters.

Table 13: Parameters used in the model for the service centre (washing) life cycle stage for RPC system

Parameter	**Average value per kg of plastic crate (RPC)**[33]
Energy demand [kWh]	0,037
Water demand [liters]	0,301
Combined detergents and rinse demand [g]	4,4

Table 14 reports the database entries adopted in the model. Discarded RPCs within this life cycle stage are assumed to be recycled, in accordance with relevant literature.

Table 14: Secondary data for service centre (washing)

Provider process	**Data classification**	**Source**	**Geographical coverage**
Market for non-ionic surfactant	Secondary data	Ecoinvent 3.7.1	GLO
Residual grid mix	Secondary data	Sphera	EU-28+3
Tap water from groundwater	Secondary data	Sphera	EU-28
Municipal waste in waste incineration plant	Secondary data	Sphera	EU-28
Municipal wastewater treatment	Secondary data	Sphera	EU-28

3.2.3.4 Post-consumer EoL

For the EoL treatment of both systems, assumptions are made due to the lack of reliable information regarding material flows of disposable packaging items. It is assumed that post-consumer CBs and RPCs are recycled, and therefore EU statistical data in the baseline scenario is used for modelling the impacts at EoL (see Table 15).

Table 15: Statistical data for EoL treatment[34]

EU28 (from 2020) - Eurostat 2018	**recycling rate (%)**	**assumed incineration (%)**

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[32] Source: Reich firm (2021), available at http://reich-gmbh.net/wp-content/uploads/2016/05/Metzger-ENG-Flyer-Waschmaschine_V08-eMail.pdf

[33] Weight of the modelled multiple-use plastic crate is reported in Table 4.

[34] Source: https://ec.europa.eu/eurostat/databrowser/view/ENV_WASPACR__custom_1226307/default/table?lang=en EU–28 countries, year 2018, waste categories "paper and carboard packaging" and "plastic packaging"

paper and cardboard packaging	82,9	17,1
plastic packaging	41,8	58,2

Boundaries for both systems and unit processes are shown in Figure 8 and Figure 9.

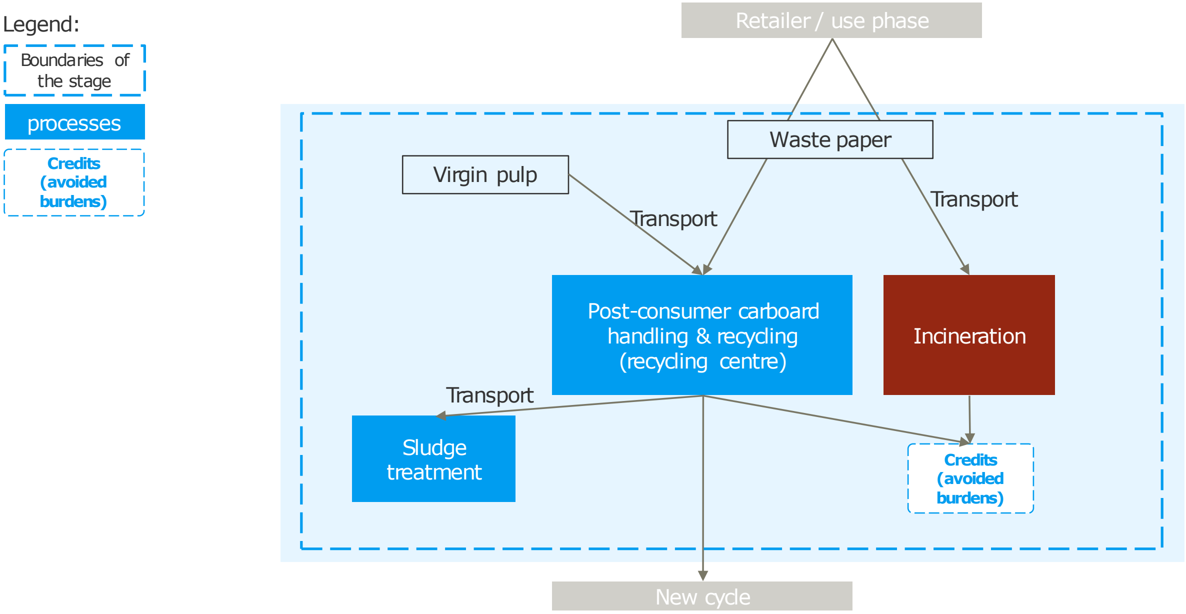

Figure 8: Scheme of the EoL life cycle stage for CBs

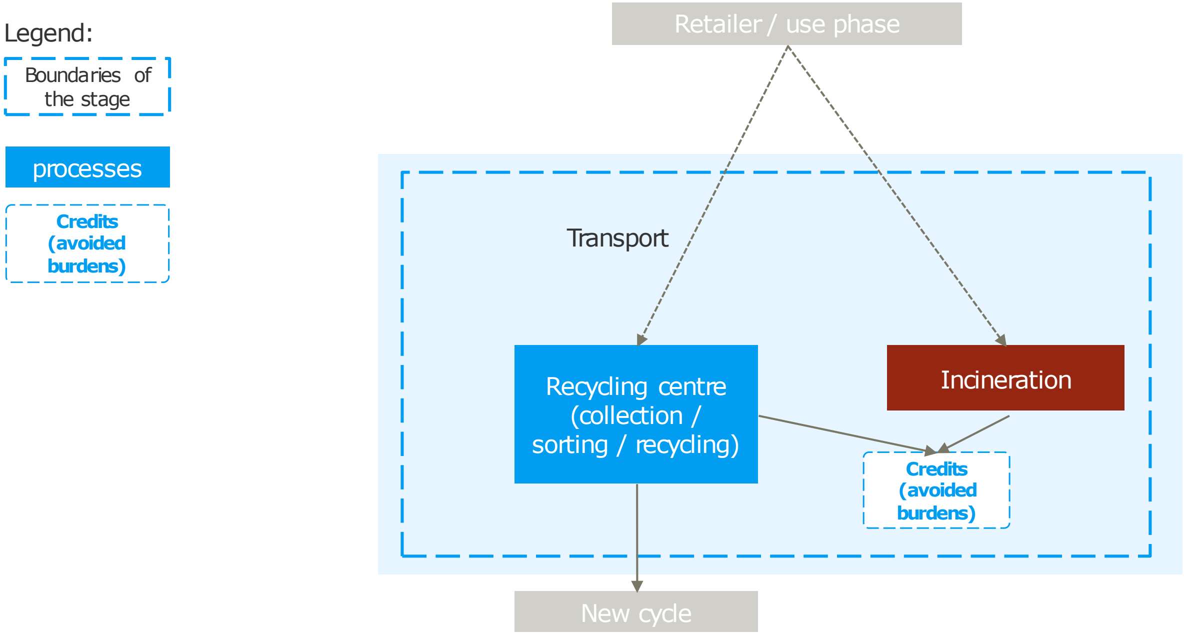

Figure 9: Scheme of the EoL life cycle stage for RPCs

In general, following the indications of Table 15, it is assumed for both systems that:

- environmental credits associated with the avoided production of virgin pulps and avoided production of virgin granulate plastics are entirely attributed to the systems (Avoided burdens approach – baseline). The explanation regarding the approach taken for avoided emissions is reported in the following paragraph “Approach for credits”

- Remainder of wastepaper material fractions and waste plastics are entirely incinerated with energy recovery. Environmental credits associated with the avoided provision of average electricity from grid and thermal energy are entirely attributed to the systems.

Recycling

To represent an appropriate recycling scenario as well as to account for environmental credits of recycling in the single-use system, gate-to-gate inventory data of a dedicated recycling process for wastepaper recycling is implemented by using a hybrid approach, as introduced in section 3.2.1.2. For the calculation of the repulping of wastepaper, FEFCO’s LCI is divided in two inputs: one related to the pulp production, and the other related to the paper machine.
For the first input, 150 kWh electricity per ton of pulp is considered (see Table 6.1 in Suhr *et al.*, 2015). For the second input, 550 kWh electrical energy demand per ton is considered (see Table 7.11 in Suhr *et al.*, 2015), and 403 kWh thermal energy demand per ton (see Table 2.9 in Suhr *et al.*, 2015). By using these shares, the total share of purchased electricity demand for recovered pulp production is estimated at around 37 kWh/ton with a self-generated energy demand estimated at around 526 kWh/ton. Therefore, the share of fossil fuels used for internal energy demand is estimated at around 552 MJ/ton. The latter is therefore assumed to be required to have 1 ton of fiber in an integrated mill process. Wastepaper is therefore recycled to wet pumpable pulp, which is identified as output of this process.

The resultant LCI describes the recycling of wastepaper from placing the recovered wastepaper into the pulper to recovered pulp (see Table 16). This LCI considers mechanical and agitation processes and refers to 1 ton of recovered pulp – details of the LCI are reported in appendix (see Appendix 1).

Table 16: Primary data for wastepaper paper recycling implemented by means of inventory data and own modelling

Provider process name	Data classification	Source	Geographical coverage	Reference value
Wastepaper recycling to wet pulp	Hybrid data (primary and secondary)	Calculations and expert judgment	Europe	1,000 kg

Table 17 reports the database entries adopted in the model.

Table 17: Secondary data for for wastepaper paper recycling

Provider process	Data classification	Source	Geographical coverage
Residual grid mix	Secondary data	Sphera	EU-28+3
Hard coal mix	Secondary data	Sphera	EU-28
Lignite mix	Secondary data	Sphera	EU-28
Diesel mix at refinery	Secondary data	Sphera	EU-28
Light fuel oil at refinery	Secondary data	Sphera	EU-28

Provider process	Data classification	Source	Geographical coverage
Natural gas mix	Secondary data	Sphera	EU-28
Heavy fuel oil at refinery	Secondary data	Sphera	EU-28
Hydrogen peroxide	Secondary data	Sphera	EU-28
Thermal energy from biomass	Secondary data	Sphera	EU-28
Maize starch production	Secondary data	Ecoinvent 3.7.1	DE
market for alkylketene dimer sizing agent, for paper production	Secondary data	Ecoinvent 3.7.1	RER (EU)
Municipal waste in waste incineration plant	Secondary data	Sphera	EU-28
Municipal wastewater treatment (sludge incineration)	Secondary data	Sphera	EU-28
Paper and board (water 0%) in waste incineration plant	Secondary data	Sphera	EU-28
Tap water from groundwater	Secondary data	Sphera	EU-28
Municipal wastewater treatment (mix)	Secondary data	Sphera	EU-28

Secondary inventory data is implemented to represent a recycling scenario in the multiple-use system, as reported with database entries adopted in the model in Table 18.

Table 18: Secondary data for for plastic crates recycling

Provider process	Data classification	Source	Geographical coverage
Residual grid mix	Secondary data	Sphera	EU-28+3
treatment of waste polyethylene, for recycling, unsorted, sorting	Secondary data	Ecoinvent 3.7.1	CH
Plastic granulate secondary	Secondary data	Sphera	EU-28

Approach for credits

By adopting a closed-loop approximation for the EoL modelling (as done consistently for both systems and introduced in Section 3.1.5) it is assumed that the system is not affecting the secondary material market by potentially displacing recycled materials from other products. Therefore, this assumption is less disputable and circumvents the open-loop allocation problem (see also section 3.1.5).

To model the avoided environmental emissions in the multiple-use system, the same composition of granulated plastic is used for the RPC (see section 3.2.3.1: Multiple-use system).

To model the avoided environmental emissions in the single-use system (CB system), the following approach is taken:

- It is assumed that the recycled pulp as output of the wastepaper recycling is substituted by virgin pulp
- The point of substitution (functional equivalence) of the CB life cycle following the wastepaper recycling process is *wet pulp* ready to pump onto the paper machine. However, the available data for virgin pulp in database sets (e.g., Ecoinvent) is linked to the production of market pulp (*dry market pulp*). Therefore, dry market pulp is considered in the baseline scenario. Therefore, dry market pulp is considered in the baseline scenario, since it is line with the current PEFCR[35] guidelines for paper intermediate products. For full transparency, a sensitivity analysis is presented by assuming wet pulp as different point of substitution (see 3.3.4 section for further description)[36].
- It is assumed in the baseline scenario that credits for avoided emissions of virgin pulp products are assigned by considering similar paper grades that compose a CB: 53% kraftliner and 47% semi-chemical fluting (see section 3.2.3.1: Single-use system).
- The following dry market virgin pulps are considered: 53% chemical pulp and 47% mechanical pulp.
- The chemical pulp is assumed to be sulphate pulp.
- The mechanical pulp is assumed to consist of one third stone groundwood pulp, one third thermo-mechanical pulp and one third chemi-thermomechanical pulp. This assumption is made to create a technology mix, given a lack of more detailed information on the semi-chemical fluting part and due to lack of information regarding semi-chemical pulp production in databases. For these three virgin pulp production products, life cycle inventory datasets are available in the Ecoinvent database.
- Inputs of the model are shown in Table 19.

Table 19: Secondary data for virgin pulp production

Provider process	Data classification	Source	Geographical coverage
Sulfate pulp production, from softwood, unbleached	Secondary data	ecoinvent 3.7.1	Europe (RER)
Stone groundwood pulp production	Secondary data	ecoinvent 3.7.1	Europe (RER)
Thermo-mechanical pulp production	Secondary data	ecoinvent 3.7.1	Europe (RER)
Chemi-thermomechanical pulp production	Secondary data	ecoinvent 3.7.1	Europe (RER)

In order to evaluate this approach against other virgin paper grades, a sensitivity analysis is conducted by considering different scenarios, described in Section 3.3.4.

Incineration

Wastepaper and plastic waste incineration processes are implemented next to inventory data on the recycling process, distinct (see Table 20).

Table 20: Secondary data for waste incineration processes

Provider process	Data classification	Source	Geographical coverage
Paper and board (water 0%) in waste incineration plant	Secondary data	Sphera	EU-28

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[35] https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_Intermediate%20paper%20product_Feb%202020.pdf

[36] This approach takes into account indications for improvement by the third-party review panel.

Provider process	Data classification	Source	Geographical coverage
Polyethylene (PE) in waste incineration plant	Secondary data	Sphera	EU-28

In order to account for environmental benefits associated with the recovered energy during incineration processes, electricity as well as thermal energy are implemented as avoided burdens (see Table 21).

Table 21: Secondary data for avoided provision of energy due to energy recovery from waste incineration

Provider process	Data classification	Source	Geographical coverage
Residual grid mix	Secondary data	Sphera	EU-28+3
Thermal energy from natural gas	Secondary data	Sphera	EU-28

Transport processes during EoL treatment are implemented with the entry reported in Table 22.

Table 22: Secondary data for transport in EoL treatment

Provider process	Data classification	Source	Geographical coverage
Truck-trailer, Euro 5, 34 - 40t gross weight / 27t payload capacity	Secondary data	Sphera	GLO

3.3 Impact assessment results

By using the baseline models for both systems, impact results are provided, and main contributors to the results are presented per each impact category. The relevant comparative assertion is shown as “aggregated total” values in the respective figures (see dashed bars and absolute numbers in figures), thus accounting for all positive and negative impact contributions within a system.

3.3.1 Baseline comparison results[37]

The following sections present the potential impacts per category and allow for a comparison between the two systems. Moreover, a contribution analysis is facilitated by showing contributions from certain life cycle stages within the respective systems. For dealing with negative values, the approach suggested in the PEFCR[38] is taken: the percentage impact contribution for any process is calculated by using absolute values (i.e., the minus sign is ignored). This procedure allows to consider the relevance of any credits (e.g., from avoided emissions at EoL) to be identified. Consequently, the total impact score is recalculated including the converted negative scores and set to 100%. Percentage impact contribution for any process is assessed to this new total impact score.

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[37] Results for the raw material production and manufacturing life cycle stage in the single-use system are differentiated between kraftliner production, semi-chemical fluting production, and corrugated board production (which exclude paperboard manufacturing, accounted in their relative contributions).

[38] Source: PEFCR Guidance, available at https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_guidance_v6.3.pdf

3.3.1.1 Acidification

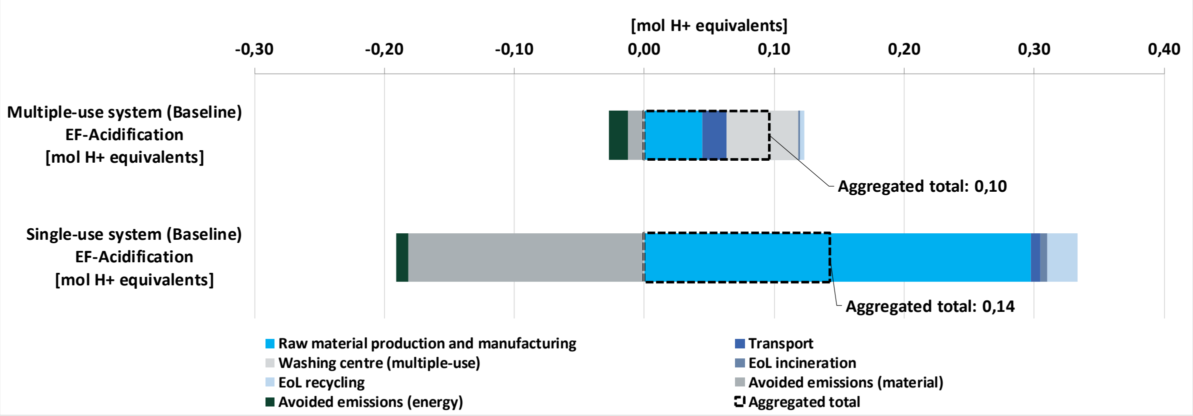

Figure 10: EF-Acidification [mol H+ equivalents], Functional unit, for transporting 1 ton of good: SU system: 73,3 kg of CB, MU system: 7,2 kg of RPC

The most relevant sources of emissions to the Acidification impact category in the CB system are:

- Nitrogen oxides (42,4%), with the most relevant processes as kraftliner and corrugated board production (38,3%)
- Sulphur dioxide (30,9%), with the most relevant processes as semi-chemical fluting manufacturing (14,5%) and avoided emissions of mechanical pulp products (14,6%, this is considered a credit, and it can be noted that chemical pulp plays a minor role in this category).

The most relevant sources of emissions to the Acidification impact category in the RPC system are:

- Sulphur dioxide (48,4%), with the most relevant process as raw material production and manufacturing (RPC) (32,2%, mainly due to HDPE granulate production, followed by PP granulate production)
- Nitrogen oxides (40,8%), with the most relevant process as raw material production and manufacturing (RPC) (24,6%, mainly due to HDPE granulate production, followed by PP granulate production)

3.3.1.2 Climate Change, total

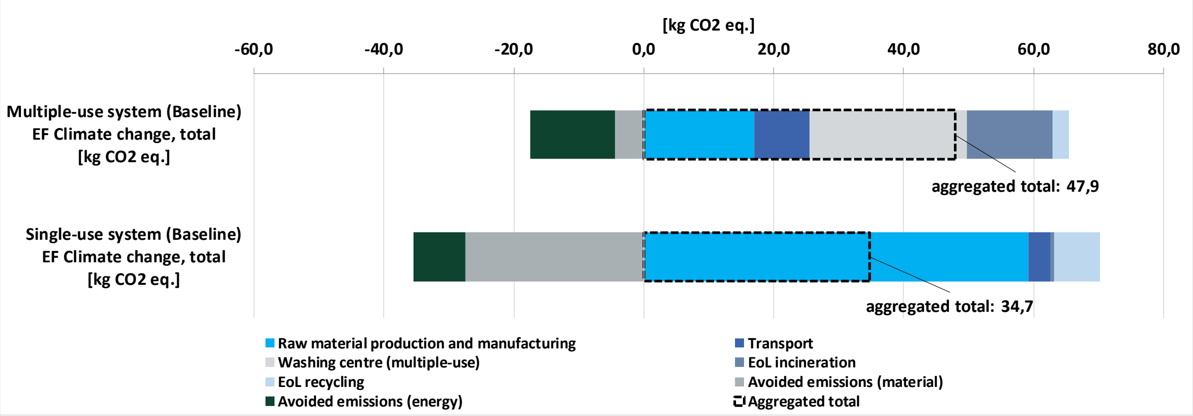

Figure 11: EF-Climate change, total [kg CO2 Equivalents], Functional unit, for transporting 1 ton of good: SU system: 73,3 kg of CB, MU system: 7,2 kg of RPC

The most relevant sources of emissions to the Climate change, total impact category in the CB system are:

- Carbon dioxide (91,7%), with the most relevant processes as semi-chemical fluting (18,2%), board production (17,5%), kraftliner production (16%), and avoided emissions (material) (23,5%, with main contributions of CTMP with 7,3% and TMP with 6,8% – this is considered a credit, it can be noted that chemical pulp play a minor role in this category)
- Methane (group VOC to air) (4,9%), with the most relevant processes: with the most relevant processes as raw material production and manufacturing (CB) (2,5%, mainly due to corrugated board production).

The most relevant sources of emissions to the Climate change, total impact category in the RPC system are:

- Carbon dioxide (95,0%), with the most relevant processes as raw material production and manufacturing (RPC) (34,4%, mainly due to HDPE granulate production, followed by PP granulate production) and EoL incineration (28,5%).
- Methane (group VOC to air) (4,1%), with the most relevant processes as raw material production and manufacturing (RPC) (2,0%, mainly due to HDPE granulate production, followed by PP granulate production).

3.3.1.3 Ecotoxicity, freshwater

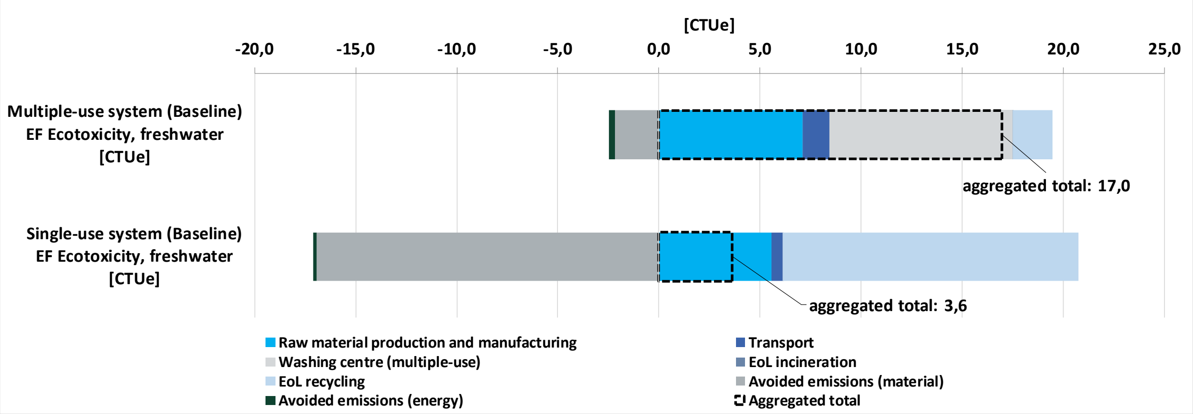

Figure 12: Ecotoxicity, freshwater [CTUe], Functional unit, for transporting 1 ton of good: SU system: 73,3 kg of CB, MU system: 7,2 kg of RPC

The most relevant sources of emissions to the Ecotoxicity, freshwater impact category in the CB system are:

- Terbutylazine (Pesticides to agricultural soil) (15,4%) with the most relevant processes as EoL recycling (15,4%)
- Chromium (+VI) (heavy metals emissions to fresh water) (12,9%) with the most relevant processes as avoided emissions of mechanical pulp (CTMP with 3,1%, TMP with 3%, stone groundwood with 2,5%) – this is considered a credit, and it can be noted that chemical pulp play a minor role in this category

The most relevant sources of emissions to the Ecotoxicity, freshwater impact category in the RPC system are:

- Zinc (heavy metals to fresh water) (31,4%) with the most relevant processes as raw material production and manufacturing (RPC) (22,9%, mainly due to HDPE granulate production, followed by PP granulate production)
- Chromium (+VI) (14,0%) with the most relevant processes as EoL recycling (6,6%)

3.3.1.4 Eutrophication, freshwater

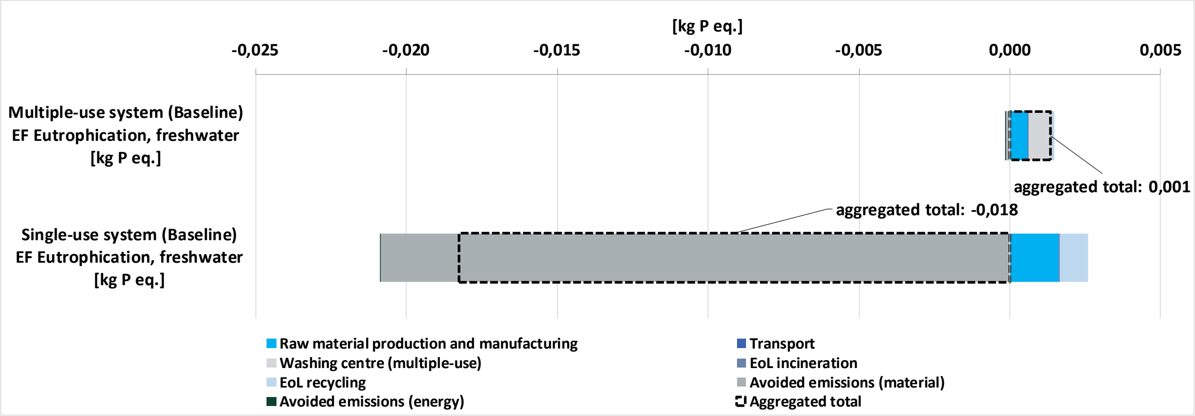

Figure 13: EF-Eutrophication, freshwater [kg P eq.], Functional unit, for transporting 1 ton of good: SU system: 73,3 kg of CB, MU system: 7,2 kg of RPC

The most relevant sources of emissions to the Eutrophication, freshwater impact category in the CB system are:

- Phosphate (emissions to fresh water) (79,2%), with the most relevant processes as avoided emissions of mechanical pulp products (CTMP with 25%, TMP with 26,6%, stone groundwood with 22,2%) – this is considered a credit, it can be noted that chemical pulp play a minor role in this category (with 3,2% share)
- Phosphate (inorganic emissions to fresh water) (12,4%), with the most relevant processes as avoided emissions (material) (10,1%)

The most relevant sources of emissions to the Eutrophication, freshwater impact category in the RPC system are:

- Phosphate (emissions to fresh water) (95,0%), with the most relevant processes as raw material production and manufacturing (RPC) (65,6%, mainly due to HDPE granulate production, followed by PP granulate production) and avoided emissions (material) (15,1%)

3.3.1.5 Eutrophication marine

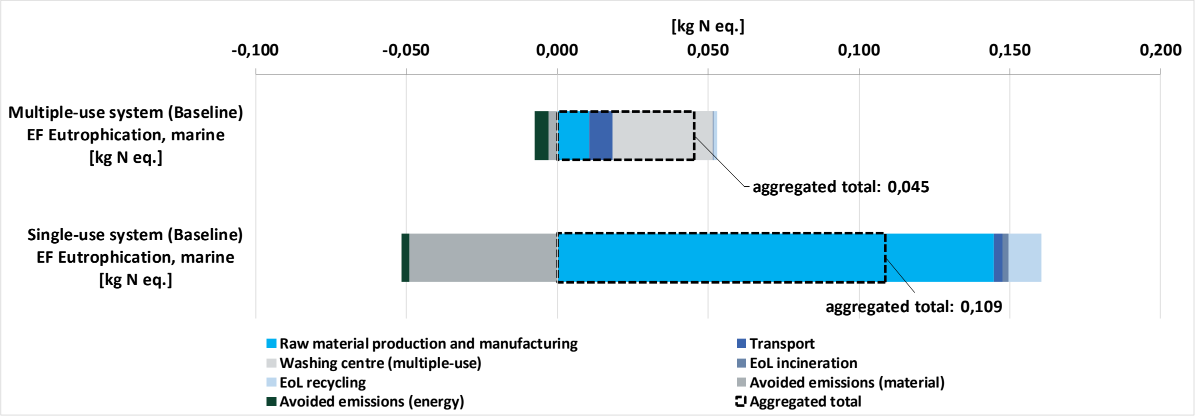

Figure 14: EF-Eutrophication marine [kg N eq.], Functional unit, for transporting 1 ton of good: SU system: 73,3 kg of CB, MU system: 7,2 kg of RPC

The most relevant sources of emissions to the Eutrophication, marine impact category in the CB system are:

- Nitrogen oxides (inorganic emissions to air) (55,2%), with the most relevant processes as corrugated board production (19,9%), kraftliner production (16,9%) and semi-chemical fluting (12,9%)
- Nitrogen (inorganic emissions to fresh water) (16,3%), with the most relevant processes as semi-chemical fluting (9,8%), kraftliner production (2,5%)

The most relevant sources of emissions to the Eutrophication, marine impact category in the RPC system are:

- Nitrogen oxides (inorganic emissions to air) (82,2%), with the most relevant processes as raw material production and manufacturing (RPC) (49,5%, mainly due to HDPE granulate production, followed by PP granulate production)
- Nitrogen monoxide (inorganic emissions to air) (7,7%), with the most relevant processes as washing center (3,5%)

3.3.1.6 Eutrophication, terrestrial

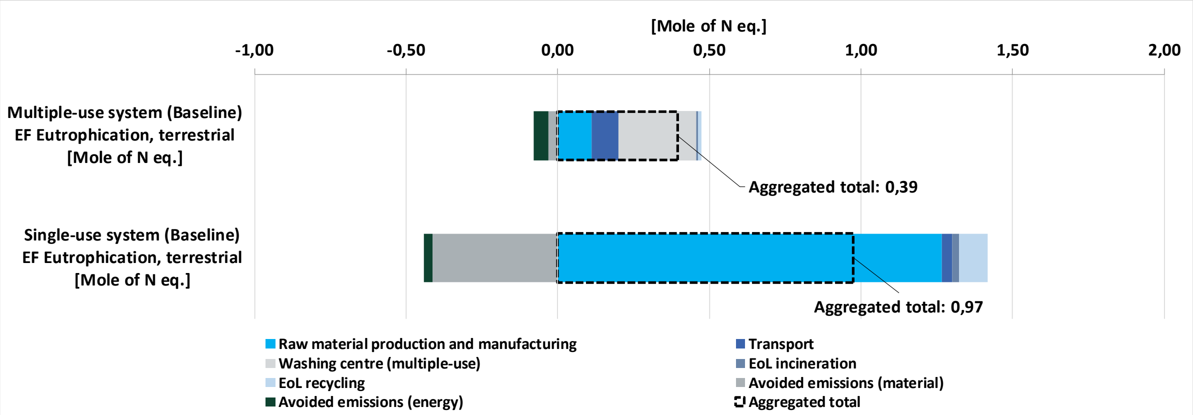

Figure 15: EF-Eutrophication, terrestrial [mol N eq.], Functional unit, for transporting 1 ton of good: SU system: 73,3 kg of CB, MU system: 7,2 kg of RPC

The most relevant sources of emissions to the Eutrophication, terrestrial impact category in the CB system are:

- Nitrogen oxides (inorganic emissions to air) (69,0%), with the most relevant processes as corrugated board production (24,9%), kraftliner production (21,2%), semi-chemical fluting production (16,1%)

The most relevant sources of emissions to the Eutrophication, terrestrial impact category in the RPC system are:

- Nitrogen oxides (inorganic emissions to air) (84,7%), with the most relevant processes as raw material production and manufacturing (RPC) (51,0%, mainly due to HDPE granulate production, followed by PP granulate production) and avoided emissions (material) (15,1%)
- Nitrogen monoxide (inorganic emissions to air) (8,0%), the most relevant processes as washing center (3,6%)

3.3.1.7 Human toxicity, cancer

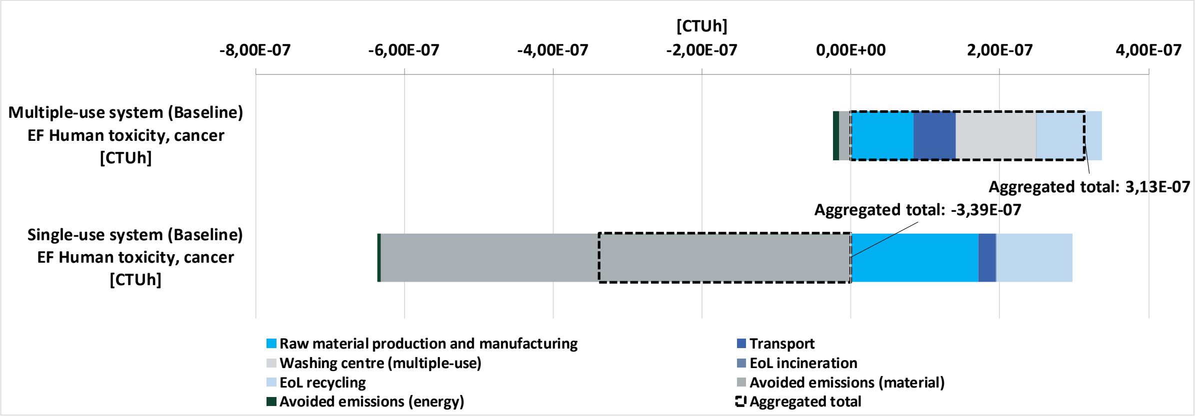

Figure 16: EF-Human toxicity, cancer [CTUh], Functional unit, for transporting 1 ton of good: SU system: 73,3 kg of CB, MU system: 7,2 kg of RPC

The most relevant sources of emissions to the Human toxicity, cancer impact category in the CB system are:

- Chromium (+VI) (heavy metals to fresh water) (52,7%) with the most relevant processes as avoided emissions (credits) of CTMP production (12,7%), TMP production (12,5%), and sulphate pulp production (12,9%)
- Chromium (heavy metals to fresh water) (17,1%) with the most relevant processes as corrugated board production (7,5%)

The most relevant sources of emissions to the Human toxicity, cancer impact category in the RPC system are:

- Chromium (+VI) (heavy metals to fresh water) (83,1%) with the most relevant processes as EoL recycling (39,4%) and raw material production and manufacturing (RPC) (35,5%, mainly due to HDPE granulate production, followed by PP granulate production)

3.3.1.8 Human toxicity, non-cancer

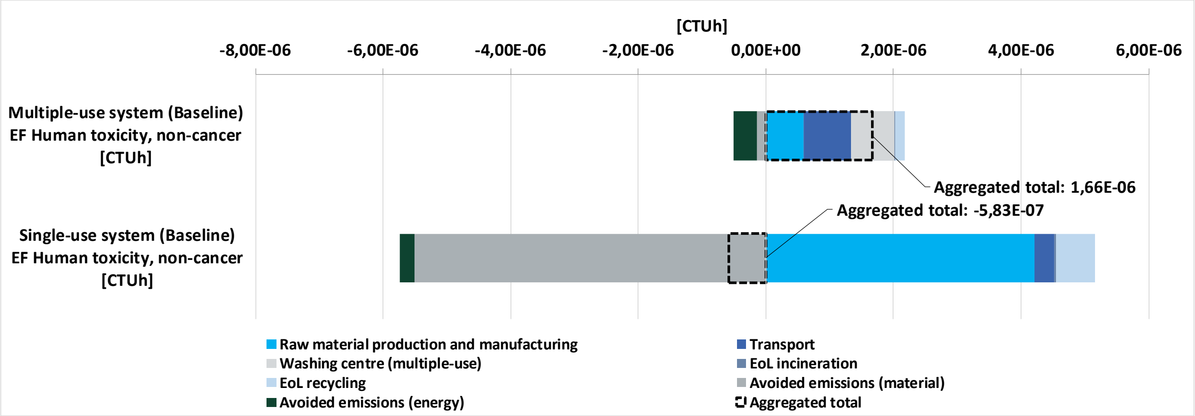

Figure 17: EF-Human toxicity, non-cancer [CTUh], Functional unit, for transporting 1 ton of good: SU system: 73,3 kg of CB, MU system: 7,2 kg of RPC

The most relevant sources of emissions to the Human toxicity, non-cancer impact category in the CB system are:

- Zinc (heavy metals to agricultural soil) (38,6%) with the most relevant processes as avoided emissions of CTMP production (8,4%), stone groundwood pulp production (5,4%)
- Mercury (heavy metals to air) (24,9%) with the most relevant processes as corrugated board production (7,5%) and kraftliner production (5%)

The most relevant sources of emissions to the Human toxicity, non-cancer impact category in the RPC system are:

- Mercury (heavy metals to air) (51,0%) with the most relevant processes as raw material production and manufacturing (RPC) (23,2%, mainly due to HDPE granulate production, followed by PP granulate production) and avoided emissions (energy) (15,3%)
- Arsenic (+V) (heavy metals to fresh water) (13,3%) with the most relevant processes as raw material production and manufacturing (RPC) (6,7%, mainly due to HDPE granulate production, followed by PP granulate production)

3.3.1.9 Ionizing radiation, human health

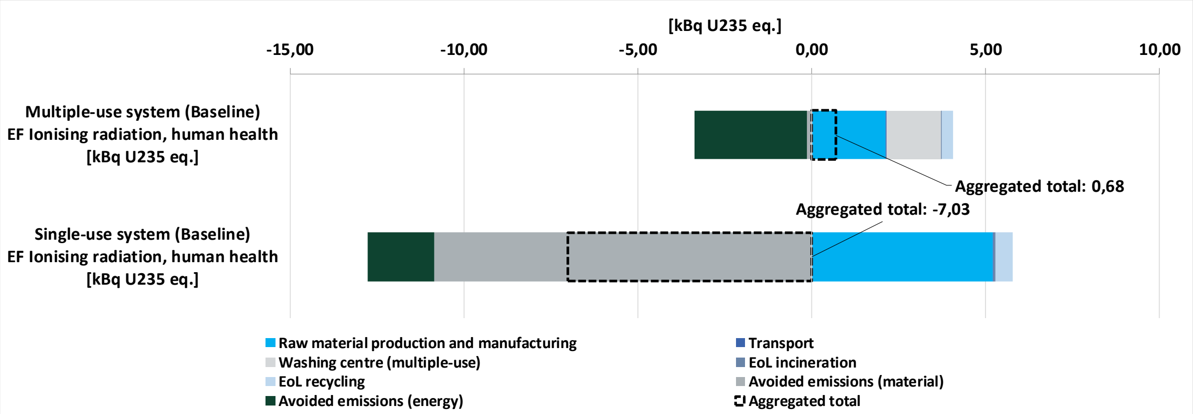

Figure 18: EF-Ionising radiation, human health [kBq U235 eq.], Functional unit, for transporting 1 ton of good: SU system: 73,3 kg of CB, MU system: 7,2 kg of RPC

The most relevant sources of emissions to the Ionizing radiation, human health impact category in the CB system are:

- Carbon (C14) (radioactive emissions to air) (58,2%), with the most relevant processes as avoided emissions (credits) of mechanical pulp production (17,6%) and kraftliner production (10,6%),

The most relevant sources of emissions to the Ionizing radiation, human health impact category in the RPC system are:

- Carbon (C14) (radioactive emissions to air) (90,4%), with the most relevant processes as raw material production and manufacturing (RPC) (41,2%, mainly due to HDPE granulate production, followed by PP granulate production) and avoided emissions (energy) (38,7%)

3.3.1.10 Ozone depletion

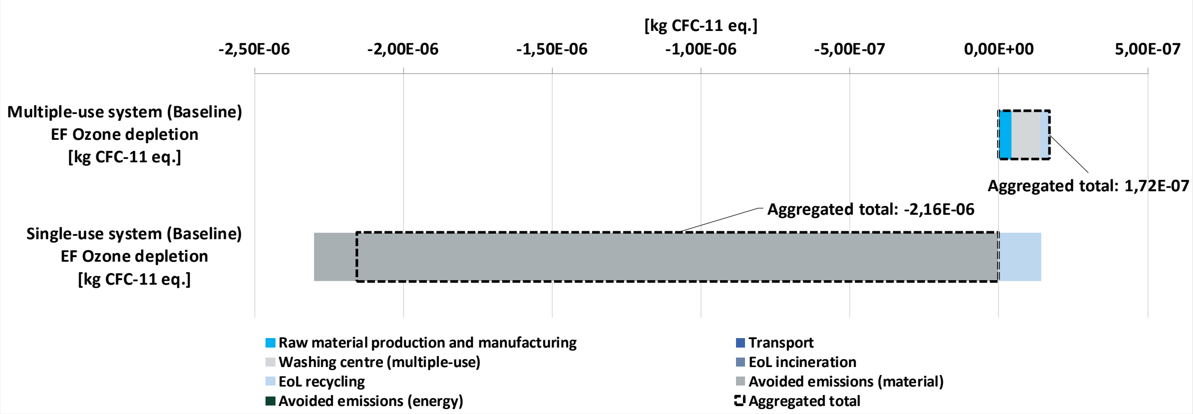

Figure 19: EF-Ozone depletion [kg CFC11 equivalents], Functional unit, for transporting 1 ton of good: SU system: 73,3 kg of CB, MU system: 7,2 kg of RPC

The most relevant sources of emissions to the Ozone depletion impact category in the Cb system are:

- Halon (1301) (halogenated organic emissions to air) (43,2%), with the most relevant processes as avoided emissions (credits) of mechanical pulp products (23,5%) and sulphate pulp (16,6%)
- Halon (1211) (halogenated organic emissions to air) (34,1%), with the most relevant processes as avoided emissions (credits) of CTMP (10,8%) and TMP (11,2%)

The most relevant sources of emissions to the Ozone depletion impact category in the RPC system are:

- Halon (1301) (halogenated organic emissions to air) (76,7%), with the most relevant processes as raw material production and manufacturing (RPC) (40,9%, mainly due to HDPE granulate production, followed by PP granulate production) and EoL recycling (30,9%)
- Halon (1211) (halogenated organic emissions to air) (34,1%), with the most relevant processes as raw material production and manufacturing (RPC) (10,5%, mainly due to HDPE granulate production, followed by PP granulate production)

3.3.1.11 Particulate matter

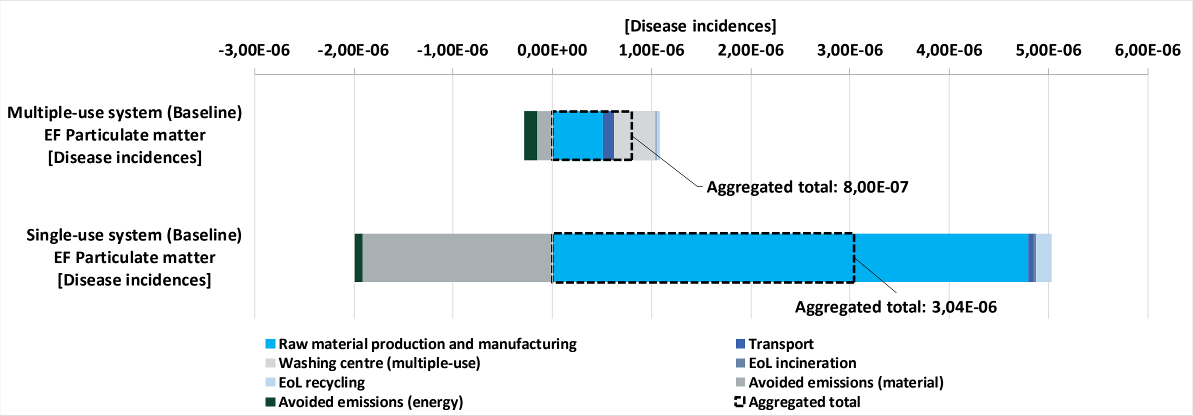

Figure 20: EF-Particulate matter [disease incidence], Functional unit, for transporting 1 ton of good: SU system: 73,3 kg of CB, MU system: 7,2 kg of RPC

The most relevant sources of emissions to the Particulate matter impact category in the CB system are:

- Dust (particles to air, PM2.5) (66,2%), with the most relevant processes as corrugated board production (32,6%) and avoided emissions of sulphate pulp (16,2%)
- Sulphur dioxide (inorganic emissions to air) (7,6%), with the most relevant processes as semi-chemical fluting (3%)

The most relevant sources of emissions to the Particulate matter impact category in the RPC system are:

- Dust (particles to air, PM2.5) (59,5%), with the most relevant processes as raw material production and manufacturing (RPC) (37,7%) and avoided emissions (material) (11,9%)
- Sulphur dioxide (inorganic emissions to air) (27,2%), with the most relevant processes as raw material production and manufacturing (RPC) (18,1%)

3.3.1.12 Photochemical ozone formation - human health

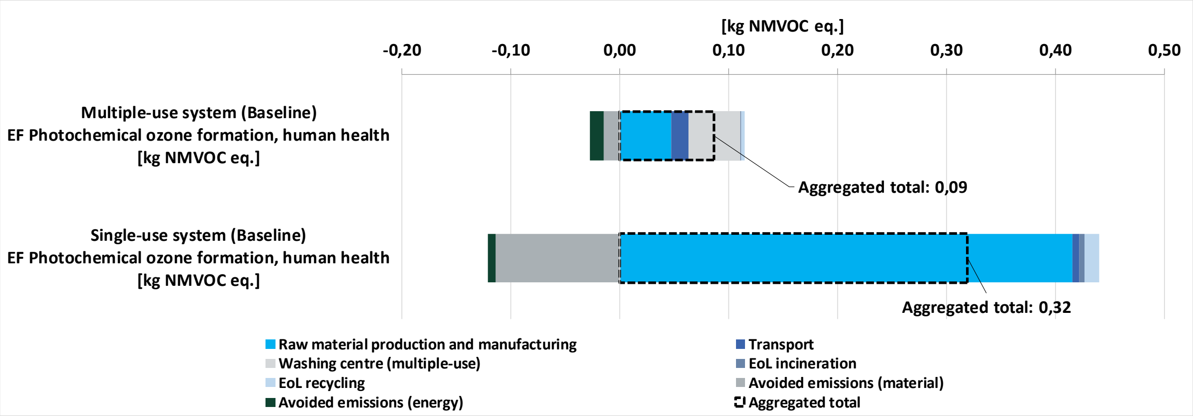

Figure 21: EF-Photochemical ozone formation - human health [kg NMVOC equivalents], Functional unit, for transporting 1 ton of good: SU system: 73,3 kg of CB, MU system: 7,2 kg of RPC

The most relevant sources of emissions to the Photochemical ozone formation – human health impact category in the CB system are:

- Nitrogen oxides (inorganic emissions to air) (53,6%) with the most relevant processes as corrugated board production (19,4%), kraftliner (16,4%)
- Organic emissions to air (group VOC - unspecified) (20,4%), with the most relevant processes as raw material production and manufacturing (CB) (18,3%)

The most relevant sources of emissions to the Photochemical ozone formation – human health impact category in the RPC system are:

- Nitrogen oxides (inorganic emissions to air) (54,1%) with the most relevant processes as raw material production and manufacturing (RPC) (32,6%) and avoided emissions (material) (9,7%)
- Organic emissions to air (group VOC - unspecified) (26,9%), with the most relevant processes as raw material production and manufacturing (RPC) (18,9%)

3.3.1.13 Resource use, fossils

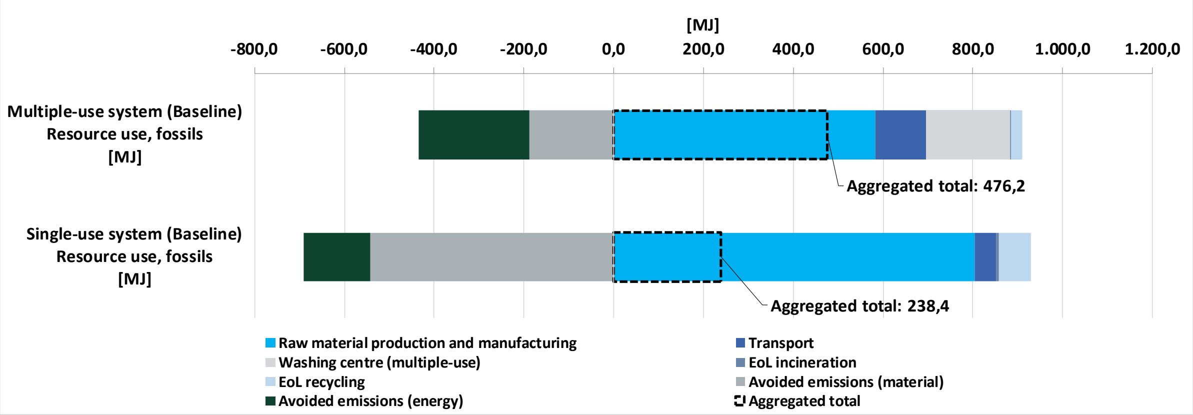

Figure 22: EF-Resource use, fossils [MJ], Functional unit, for transporting 1 ton of good: SU system: 73,3 kg of CB, MU system: 7,2 kg of RPC

The most relevant resources in the Resource use, fossils impact category in the CB system are:

- Natural gas (29,9%), with the most relevant processes as corrugated board production (7,3%)
- Crude oil (23,5%), with the most relevant processes as corrugated board production (8,4%)
- Uranium (18,9%), with the most relevant processes as avoided emissions (credits) of mechanical pulp (11%)

The most relevant resources in the Resource use, fossils impact category in the RPC system are:

- Crude oil (56,6%), with the most relevant processes as raw material production and manufacturing (RPC) (40,0%, mainly due to HDPE granulate production, followed by PP granulate production) and avoided emissions (material) (14,6%)
- Natural gas (26,8%), with the most relevant processes as raw material production and manufacturing (RPC) (12,7%) and avoided emissions (material) (6,2%)
- Uranium (8,9%), with the most relevant processes as raw material production and manufacturing (RPC) (4,3%)

3.3.1.14 Resource use, minerals and metals

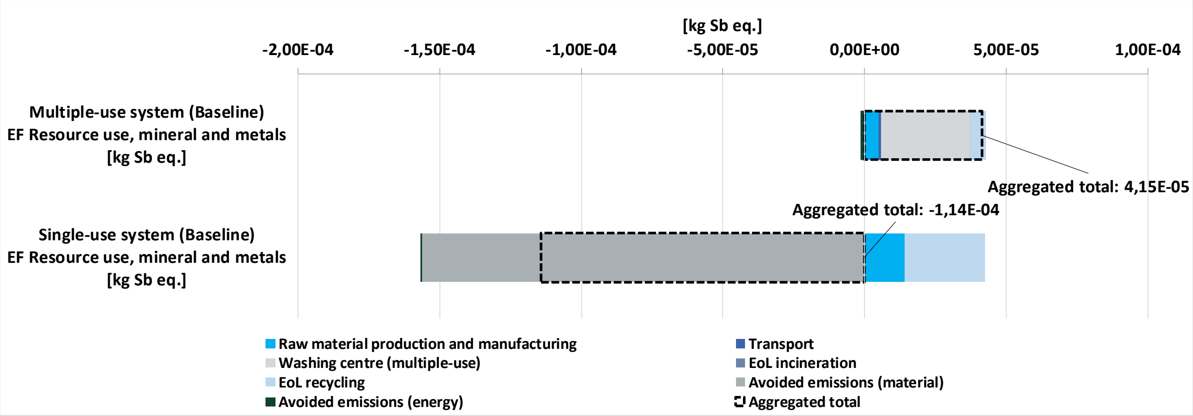

Figure 23: EF-Resource use, minerals and metals [kg Sb equivalents], Functional unit, for transporting 1 ton of good: SU system: 73,3 kg of CB, MU system: 7,2 kg of RPC

The most relevant resources in the Resource use, minerals and metals impact category in the CB system are:

- Tellurium (61,4%), with the most relevant processes as avoided emissions (credits) of mechanical pulp products (41,8%)
- Gold (11,7%), with the most relevant processes as avoided emissions (credits) of mechanical pulp products (6,7%)
- Copper (7,1%), with the most relevant processes as avoided emissions (credits) of mechanical pulp products (4,3%)

The most relevant resources in the Resource use, minerals and metals impact category in the RPC system are:

- Tellurium (53,3%), with the most relevant processes as EoL recycling (26,4%) and raw material production and manufacturing (RPC) (20,5%)
- Copper (10,5%), with the most relevant processes as raw material production and manufacturing (RPC) (5,0%) and EoL recycling (3,3%)

3.3.1.15 Water use

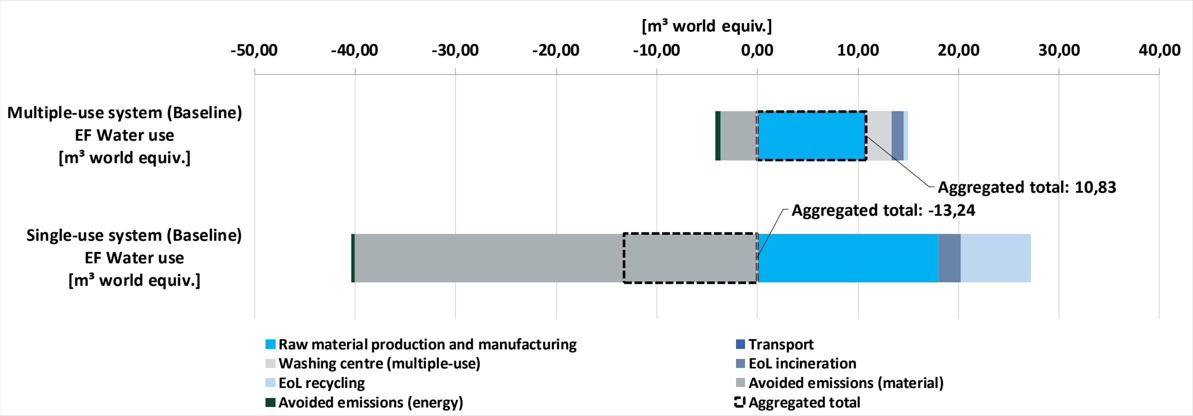

Figure 24: Water use [m3 world eq.], Functional unit, for transporting 1 ton of good: SU system: 73,3 kg of CB, MU system: 7,2 kg of RPC

The most relevant sources of emissions[39] to the Water use impact category in the CB system are:

- avoided emissions (material - credits) (59,3%)
- raw material production and manufacturing (CB) (26,6%)

The most relevant sources of emissions[40] to the Water use impact category in the RPC system are:

- raw material production and manufacturing (CB) (65,1%)
- avoided emissions (material) (22,3%).

3.3.1.16 Contribution analysis

An overview of the relevance of life cycle stages' impacts is given in Table 23 and Table 24. For dealing with negative values, the approach suggested in the PEFCR[41] is taken: the percentage impact contribution for any life cycle stage is calculated by using absolute values (i.e. the minus sign is ignored). This procedure allows to consider the relevance of any credits (e.g., from avoided

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[39] For these sources of emissions, contributions analysis is given per life cycle stage, as differentiation between different flows is not possible.

[40] For these sources of emissions, contributions analysis is given per life cycle stage, as differentiation between different flows is not possible.

[41] Source: PEFCR Guidance, available at https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_guidance_v6.3.pdf

emissions at EoL) to be identified. Consequently, the total impact score is recalculated including the converted negative scores and set to 100%. Percentage impact contribution for any life cycle stage is assessed to this new total impact score. This analysis is based on quantitative results for each life cycle stage and each category reported in Appendix 3.

Table 23: Single-use system: Contribution analysis of life cycle stages in the baseline scenario – PEF methodology

Single-use system (CB): Impact categories	Raw material production and manufacturing	Transport	EoL incineration	EoL recycling	Avoided emissions (material)	Avoided emissions (energy)
EF 2.0 Acidification [Mole of H+ eq.]	57%	1%	1%	4%	35%	2%
EF 2.0 Climate Change - total [kg CO2 eq.]	56%	3%	0%	7%	26%	8%
EF 2.0 Ecotoxicity, freshwater [CTUe]	15%	1%	0%	39%	45%	0%
EF 2.0 Eutrophication, freshwater [kg P eq.]	7%	0%	0%	4%	89%	0%
EF 2.0 Eutrophication, marine [kg N eq.]	68%	1%	1%	5%	23%	1%
EF 2.0 Eutrophication, terrestrial [Mole of N eq.]	68%	2%	1%	5%	22%	2%
EF 2.0 Human toxicity, cancer [CTUh]	18%	3%	0%	11%	68%	0%
EF 2.0 Human toxicity, non-cancer [CTUh]	39%	3%	0%	6%	51%	2%
EF 2.0 Ionising radiation, human health [kBq U235 eq.]	28%	0%	0%	3%	59%	10%
EF 2.0 Ozone depletion [kg CFC-11 eq.]	0%	0%	0%	6%	94%	0%
EF 2.0 Particulate matter [Disease incidences]	68%	1%	0%	2%	27%	1%
EF 2.0 Photochemical ozone formation, human health [kg NMVOC eq.]	74%	1%	1%	2%	20%	1%
EF 2.0 Resource use, fossils [MJ]	50%	3%	0%	4%	33%	9%
EF 2.0 Resource use, mineral and metals [kg Sb eq.]	7%	0%	0%	14%	78%	0%
EF 2.0 Water use [m^3 world equiv.]	27%	0%	3%	10%	59%	0%

Table 23 shows that the most relevant hotspots in the single-use system (CB) are:

- Raw material production and manufacturing: between 50% and 74% in categories as Acidification, Climate Change, Eutrophication (marine and terrestrial), Particulate matter, Photochemical ozone formation, Resource use fossil
- Avoided emissions (material), which is related to avoided emissions associated to market pulp products: between 51% and 94% in categories as Eutrophication freshwater, Human toxicity (cancer and non-cancer), Ionizing radiation human health, Ozone depletion, Resource use mineral and metals, Water use

The following life cycle stages are not considered hotspots:

- transport (less than 3% in all categories)
- EoL incineration (less than 3% in all categories)

It should be noted that EoL recycling has major contribution (39%) in Ecotoxicity freshwater category, and that Avoided emissions (energy) contribute maximum 10% in all categories.

Table 24: Multiple-use system: Contribution analysis of life cycle stages in the baseline scenario – PEF methodology

Multiple-use system (RPC): Impact categories	Raw material production and manufacturing	Transport	Washing centre (multiple-use)	EoL incineration	EoL recycling	Avoided emissions (material)	Avoided emissions (energy)
EF 2.0 Acidification [Mole of H+ eq.]	30%	12%	37%	1%	3%	9%	10%
EF 2.0 Climate Change - total [kg CO2 eq.]	21%	10%	29%	16%	3%	5%	16%
EF 2.0 Ecotoxicity, freshwater [CTUe]	32%	6%	41%	0%	9%	10%	1%
EF 2.0 Eutrophication, freshwater [kg P eq.]	36%	2%	46%	0%	7%	8%	0%
EF 2.0 Eutrophication, marine [kg N eq.]	17%	13%	55%	0%	2%	5%	7%
EF 2.0 Eutrophication, terrestrial [Mole of N eq.]	20%	16%	46%	1%	2%	6%	9%
EF 2.0 Human toxicity, cancer [CTUh]	23%	16%	30%	0%	24%	5%	2%
EF 2.0 Human toxicity, non-cancer [CTUh]	22%	28%	25%	0%	6%	5%	14%
EF 2.0 Ionising radiation, human health [kBq U235 eq.]	28%	0%	21%	0%	5%	2%	43%
EF 2.0 Ozone depletion [kg CFC-11 eq.]	26%	0%	55%	0%	19%	0%	0%
EF 2.0 Particulate matter [Disease incidences]	37%	8%	30%	1%	3%	11%	10%
EF 2.0 Photochemical ozone formation, human health [kg NMVOC eq.]	33%	12%	33%	1%	2%	10%	9%
EF 2.0 Resource use, fossils [MJ]	43%	8%	14%	0%	2%	14%	18%
EF 2.0 Resource use, mineral and metals [kg Sb eq.]	12%	2%	72%	0%	12%	0%	3%
EF 2.0 Water use [m^3 world equiv.]	55%	0%	14%	6%	2%	19%	3%

Table 24 shows that the most relevant hotspots in the multiple-use system (RPC) are:

- Washing centre: between 30% and 72% in categories as Acidification, Ecotoxicity freshwater, Eutrophication (all three categories), Ozone depletion, Particulate matter, Photochemical ozone formation, Resource use mineral and metals
- Raw material production and manufacturing (RPC): between 25% and 43% in categories as Acidification, Ecotoxicity freshwater, Eutrophication freshwater, Ionizing radtiation, human health, Ozone depletion, Particulate matter, Photochemical ozone formation, Resource us fossils, Water use
- Avoided emissions (energy) can be considered hotspot only for the category Ionizing radiation human health (43%)
- Transport can be considered hotspot only for the category Human toxicity non-cancer (28%)

The other life cycle stages have different contributions to the results between with a maximum contribution of 24% (i.e. EoL recycling in Human toxicity cancer category), followed by 19% (i.e. Avoided emissions, material in Water use category).

3.3.2 Modelling EoL allocation with the Circular Footprint Formula (CFF)

The CFF is used in this study to enable a comparison between the two systems. The burdens of the whole life cycle are considered, such as virgin raw materials acquisition and its pre-processing, recycled material inputs, post-consumer recycling and incineration with energy recovery, as well as disposal in landfill. Bach *et al.* (2018) reported that: on the one hand, the CFF does not arbitrarily favor incinerating over reuse and recycling; on the other hand, shortcomings and discussions has been part of the CFF development. Therefore, the authors argued that several challenges regarding ensuring fair comparability do remain, especially for the following parameters: how often a material is recycled, the estimation of qualities of primary and secondary materials, the newly introduced parameter A (which allocates burdens and credits between two life cycles). The scientific debate regarding the use of CFF is still ongoing, as Bach *et al.* (2018) pointed out with the following disclaimer: "Even though [a] company is more aware of the value choices made in the CFF, we recommend that the CFF is applied with caution. For B2B and B2C communication, we recommend not using the CFF due to its many bias assumptions. Therefore, we recommend to review and revise the quality terms and allocation factors and to consider reuse rates for all materials and products. One simple solution to improve the CFF would be to adapt the specifications of ISO for closed loop recycling." Furthermore, Ekvall *et al.* (2020) highlighted that: "The CFF itself is also complex, which increases the risk that LCA practitioners misinterpret the formula, and the risk that errors in the LCA remain undetected by reviewers or other readers of the LCA report. The LCA results can to a large extent be governed by highly uncertain data on the waste management and the avoided virgin materials production, which affects the credibility of the LCA."

Circular Footprint Formula implementation for this LCA

The implementation of the Circular Footprint Formula (as sensitivity scenario) is based on the latest available guidance[42].

The following CFF parameters are considered in the sensitivity scenario in this study:

- R1 of CB (recycled content manufacturing): based on FEFCO's LCI
- R1 of RPC (recycled content manufacturing): 0,1 (see section 3.2.3.1)
- A (burdens and credits between supplier and user of the recycled material): 0,2 (based on the PEFCR[43] value reported for corrugated board, and the same value for RPC)
- R2 of CB (recycling rate end-of-life): 0,829 (based on EUROSTAT[44])
- R2 of RPC (recycling rate end-of-life): 0,418 (based on EUROSTAT)
- Qsin/Qp and Qsout/Qp: 1 (based on the PEFCR value reported for corrugated board, and the same value for RPC)

3.3.3 Summary of baseline comparison

This section reports the baseline results (avoided burden approach) along with the CFF results.

Table 25: Summary of aggregated total impacts of the baseline scenario and Circular Footprint Formula (CFF), Functional unit, for transporting 1 ton of good: SU system: 73,3 kg of CB, MU system: 7,2 kg of RPC

EF Impact category	Avoided burdens (baseline)		Circular Footprint Formula (CFF)	
	Single use	Multiple use	Single use	Multiple use
EF Acidification [Mole of H+ eq.]	0,14	0,10	0,17	0,12
EF Climate Change, total [kg CO2 eq.]	34,70	47,94	42,20	61,86
EF Climate Change, biogenic [kg CO2 eq.]	-0,25	0,12	-0,08	0,11
EF Climate Change, fossil [kg CO2 eq.]	34,76	45,76	42,15	59,65

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[42] https://ec.europa.eu/environment/archives/eussd/pdf/footprint/PEF%20methodology%20final%20draft.pdf

[43] https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_Intermediate%20paper%20product_Feb%202020.pdf

[44] https://ec.europa.eu/eurostat/databrowser/view/ENV_WASPACR__custom_1226307/default/table?lang=en

EF Climate Change, land use and land use change [kg CO2 eq.]	0,18	1,98	0,13	1,98
EF Ecotoxicity, freshwater [CTUe]	3,62	16,99	-4,68	17,78
EF Eutrophication, freshwater [kg P eq.]	-1,83E-02	1,35E-03	-1,22E-02	1,33E-03
EF Eutrophication, marine [kg N eq.]	0,11	0,05	0,11	0,05
EF Eutrophication, terrestrial [Mole of N eq.]	0,97	0,39	0,98	0,45
EF Human toxicity, cancer [CTUh]	-3,39E-07	3,13E-07	-2,26E-07	2,98E-07
EF Human toxicity, non-cancer [CTUh]	-5,83E-07	1,66E-06	7,17E-07	2,03E-06
EF Ionising radiation, human health [kBq U235 eq.]	-7,03	0,68	-2,22	3,57
EF Ozone depletion [kg CFC-11 eq.]	-2,16E-06	1,72E-07	-1,52E-06	1,48E-07
EF Particulate matter [Disease incidences]	3,04E-06	8,00E-07	3,37E-06	9,96E-07
EF Photochemical ozone formation - human health [kg NMVOC eq.]	0,32	0,09	0,33	0,11
EF Resource use, fossils [MJ]	238,37	476,23	459,48	811,16
EF Resource use, mineral and metals [kg Sb eq.]	-1,14E-04	4,15E-05	-8,85E-05	3,99E-05
EF Water use [m^3 world equiv.]	-13,20	10,83	-8,97	13,37

Further explanation of deviations between Avoided burden approach and CFF results is given in Figure 25 (exemplary selection of four impact categories). This figure highlights results of the baseline (blue bars) and deviations between these results and the results via CFF (green error bars). Although in three categories errors are not prominent, error bars in one impact category included the figure (Resource use, fossil) indicate that impacts calculated with CFF approach are higher than the Avoided burden’s approach for both systems. In particular, impacts for the SU system calculated with the CFF are 193% higher than the Avoided burdens approach, and impacts for the MU system calculated with the CFF are 170% higher than the Avoided burdens approach.

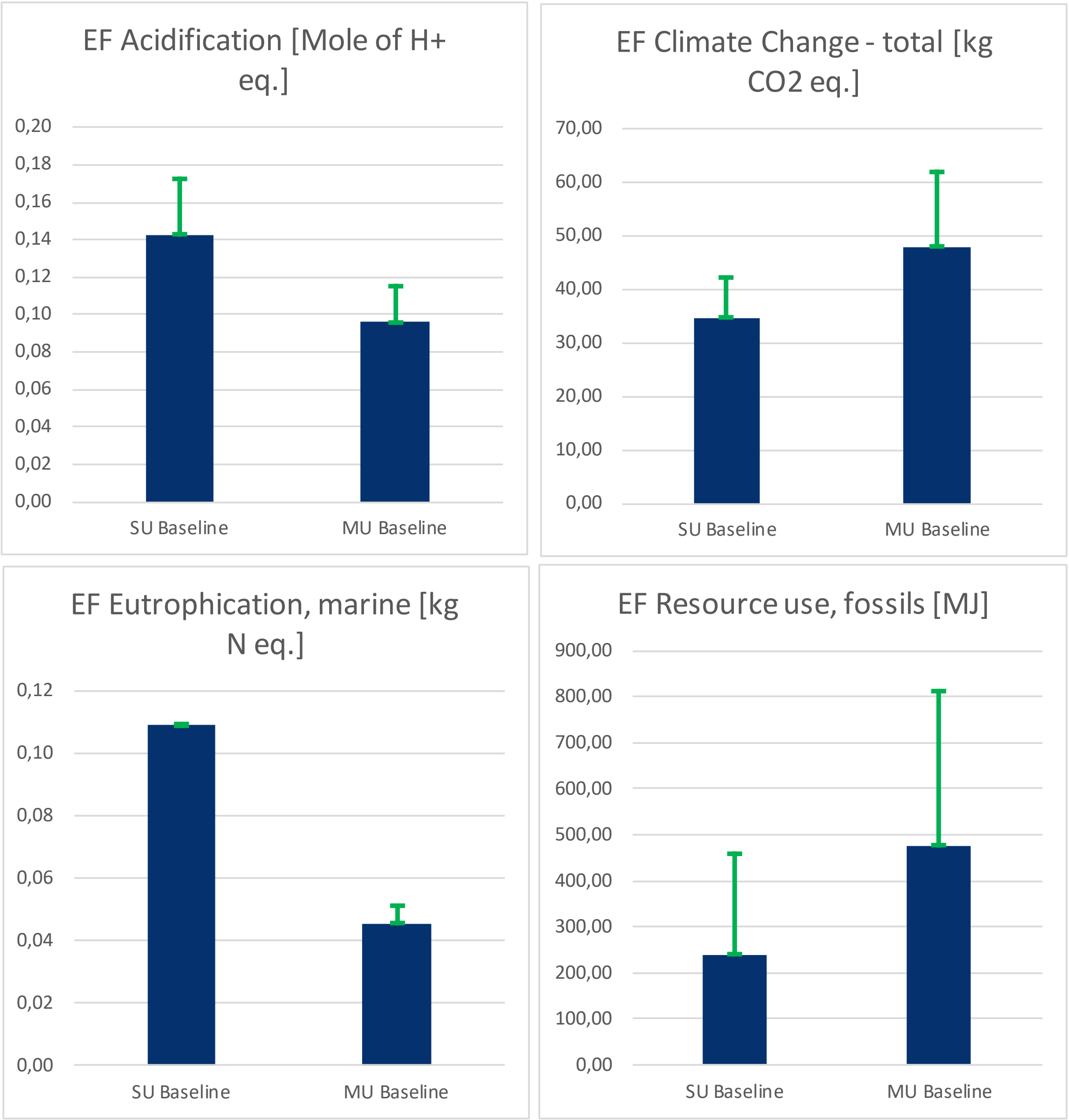

Figure 25: Deviations of results for four impact categories: Baseline (avoided burden) and Circular Footprint Formula (CFF)

3.3.4 Sensitivity Analysis

To investigate the influence of critical parameters on the results and the comparative analysis, a sensitivity analysis is presented. In this regard, only one parameter (or assumption) is changed per system. This is aimed at keeping transparency and ensure traceability of results. Critical assumptions and their potential effect on the baseline comparison are evaluated, and detailed results are presented per sensitivity scenario and compared to the baseline one. The suggested sensitivity scenarios are based on both the contribution analysis of the baseline comparison and the identified variability regarding critical parameters. As a result, certain potentially sensitive parameters or assumptions are excluded from the quantitative sensitivity analysis as they are found to impact both scenarios equally and hence do not have an effect on the comparative assertion. Table 26 gives an overview of all sensitivity analyses performed for this study.

Table 26: Summary of sensitivity analyses

	Baseline scenario	Sensitivity analysis
Manufacturing	• RPC: 10% recycled content	• RPC: 40% recycled content[45]
Breakage rate	• RPC: 2,5% (average)	• RPC: 0,5% (min)[46] • RPC: 5,0% (max)[47]
Transport	• International distances based on average data	• Distances[48]: +50% • Distances: -50% • Distances: less challenging transport route only for MU system (-25%)
EoL treatment	• CB: 82,9% recycling, rest incinerating • RPC: 41,8% recycling, rest incinerating	• 70% recycling both systems[49] • CB: Wastepaper recycling by using secondary data[50]
Washing of plastic crates[51]	• Detergent with standard composition (average energy and water demand)	• Detergent (specific composition)[52] • Min demand for detergents and energy[53]
Reuse rate of plastic crates	• Average: 24 rotations	• Break-even analysis for Climate Change, total indicator
Allocation method/approach	• Avoided burdens approach	• 0:100 approach (Cut-off)[54] • 50:50 approach[55] Avoided emissions with a different shares of virgin pulp processes[56]:

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[45] Arbitrary assumption.

[46] Source: (Tua *et al.*, 2019), (Abejón *et al.*, 2020b)

[47] Source: (Thorbecke *et al.*, 2019), (Lo-Iacono-ferreira *et al.*, 2021)

[48] Arbitrary assumption

[49] This scenario is presented to highlight symmetry between the two systems.

[50] For this scenario, secondary dataset, i.e., RER: treatment of waste paper to pulp, wet lap, totally chlorine free bleached (ecoinvent 3.7.1)

[51] Washing of plastic crates is a necessary procedure, as indicated in many studies, see., e.g., (Thorbecke *et al.*, 2019), (Lo-Iacono-ferreira *et al.*, 2021)

[52] This specific composition is modeled by using LCI for plastic crates reported in (Tua *et al.*, 2019)

[53] This assumption is made by considering optimized scenario for washing RPCs. Therefore, minimum values reported in literature are considered, as follows: energy demand (Lo-Iacono-ferreira *et al.*, 2021), water demand (Thorbecke *et al.*, 2019), surfactants/detergents (Lo-Iacono-ferreira *et al.*, 2021)

[54] This approach follows the indication by Ekvall *et al.* (2020) :"When the avoided virgin material production is highly uncertain but still important for the LCA results, a double approach might also be applied that presents two sets of results from the LCA: one without the credit for avoided virgin-material production, and one with this credit."

[55] Given the unavoidable uncertainty concerning the extent to what recovered pulp actually replaces virgin pulp and the inherent uncertainty in the underlying datasets for primary pulp production, a 50:50 allocation approach is applied to both systems. Therefore, instead of assigning the full credits, emissions are allocated 50:50 between the first and second life cycle.

[56] A different variant for the allocation of credits is considered in accordance with the requirements for comparative assertions defined in ISO 14040/14044 standards. This is important if the effects of environmental credits affect the compared single and multiple-use systems in different ways. It is assumed in the Baseline scenario that avoided emissions are modeled by using as virgin pulp: sulphate pulp (53%, by weight) and mechanical pulps (47%, by weight = composition with TMP, CTMP and stone groundwood pulp processes, as in the baseline scenario). With this sensitivity analysis, different shares of virgin pulp processes are investigated, where the composition of virgin pulp is made by sulphate pulp (78%, by weight) and mechanical pulps (22%, by weight). This assumption is made by considering statistical data in the EU for pulp consumption (see last CEPI report, 2020, Key Statistics (published Jul 8, 2021) available here: https://www.cepi.org/wp-content/uploads/2021/07/Key-Stats-2020-FINAL.pdf).

	Baseline scenario	Sensitivity analysis
		78% sulphate pulp and 22% mechanical pulps; - Avoided emissions by assuming *wet pulp* as point of substitution[57]
Electricity mix	- Residual energy mix in EU-28	- EU28 grid mix - EU28 future scenario (year 2030) - EU28 green electricity grid mix

3.4 **Interpretation**

3.4.1 Results interpretation

Environmental impacts in the single-use system are predominantly driven by the manufacturing of CBs followed by the wastepaper recycling process, while in the multiple-use system they are driven by the washing and sanitizing of RPCs. It is important to highlight that the aggregated results are significantly influenced by the assumed avoided emissions due to the assigned credits of substituted virgin pulp products and substituted granular plastics.

The use of the cut-off approach generates different results for the indicators of Climate change, total, as well as Ecotoxicity freshwater, Eutrophication freshwater, Human toxicity, non-cancer, Ionizing radtiation, Resource use fossil, Resource use, mineral and metals and Water use. This is due to the different EoL allocation in all cycles in the single-use system, and only at the end of lifespan in the multiple-use system, as expected. This situation is completely different when considering the 50:50 approach, where the emissions are similar to the Avoided burden approach (with exception of Human toxicity non cancer). The CFF increases the delta between the impacts of the two systems in many impact categories, but the overall results remain the same as the baseline scenario.

By considering different avoided emissions in the single-use system (for avoided pulp production), some categories present different potential environmental impacts than the Baseline scenario. Here the differences are highlighted for the scenario with avoided emissions of 78% sulphate and 22% mechanical pulp, where the single-use system has higher emissions in Resource use fossils. In the scenario “wet pumpable pulp”, the single-use system has higher emissions in the Climate Change, fossil category. This is due to the high contribution of the total energy demand for drying off the water from the market pulp.

EoL treatment has great influence on the results, in both sensitivity analyses:

- by using secondary data for the wastepaper recycling process, some impact categories present higher impacts for the single-use system (i.e., Human toxicity, cancer, Human toxicity, non-cancer, Ozone depletion, Resource use, mineral and metals); in general, all categories in the single-use system present higher impacts than the Bassline scenario.

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[57] See section 3.2.3.4 for explanation of this assumption: in particular, this scenario investigates the substitution by wet pumpable pulp, which is the output of the recycling process. Since database sets in Ecoinvent for pulp products are referred to market dry pulp, this sensitivity scenario hypothetically assumes that by substituting for wet pumpable pulp, the avoided emissions are calculated via air dried market pulps, and energy demand to dry off the water is considered. According to EU Ecolabel criteria (European Union, 2019), drying pulp from pumpable to air dry requires 1000 kWh of thermal energy - in line with values estimated from the BREF (Suhr *et al.*, 2015).

- By assuming symmetry in the EoL life of both systems, and therefore, for example, by assuming the same share of recycling rate (70%), the single-use systems present a beneficial effect. The following impact categories present indeed different results, with lower impacts than multiple-use system (differently than the Baseline scenario): Eutrophication, freshwater, Ionizing radiation, human health.

In general, many scenarios in the sensitivity analysis do not have relevant influence on the results, including in the following scenarios: energy grid mix, recycled content of RPCs, breakage rate of RPCs, washing (optimized detergents and optimized demand), transport distances.

A comprehensive overview of aggregated total results throughout the scenarios within both systems is disclosed in the following sections – presented per impact category. By doing so, the robustness (and potential variation) of the baseline comparison between the two systems is visualized and can be interpreted. The overall comparison of the sensitivity analyses in table form is given in Appendix 5. A summary of parameters for this sensitivity analysis is given in the following table. It should be noted that when a parameter affects only one system, graphical comparison in the following charts is shown by comparing the affected system against the baseline of the other system (e.g., in the scenario "EoL allocation – Avoided emissions (78% chemical, 22% mechanical pulps)", results related to the variation in the SU system via different pulp products (as avoided emissions) are compared against the results of the baseline of the MU system, for each impact category).

Table 27: Summary of sensitivity analyses[58] (SU: single-use system, MU: Multiple-use system)

Sensitivity scenario	System affected	Value in the baseline	Variation
EoL allocation - 0:100 approach (cut-off)	SU / MU	Avoided burden	Cut-off
EoL allocation - 50:50 approach	SU / MU	Avoided burden	Approach 50:50
EoL allocation - Avoided emissions (78% chemical, 22% mechanical)	SU	Pulp products as avoided emissions: 53% sulphate pulp, 47% mechanical pulps (TMP, CTMP, stone groundwood)	Pulp products as avoided emissions: 78% sulphate pulp, 22% mechanical pulps (TMP, CTMP, stone groundwood)
EoL allocation - Avoided emissions (wet pumpable pulp)	SU	Pulp products as market dry pulp	Pulp products as wet pulp (1000 kWh is required to dry off the water)
Energy mix - EU28	SU / MU	Residual Energy grid mix EU-28	Energy grid mix EU28
Energy mix - Future scenario EU-28 (2030)	SU / MU	Residual Energy grid mix EU-28	Future scenario grid mix EU-28 (2030)
Energy mix - Green electricity grid mix	SU / MU	Residual Energy grid mix EU-28	Green electricity grid mix
EoL treatment - Wastepaper reycling (secondary data)	SU	Wastepaper recycling via FEFCO's LCI re-work (Appendix 1)	Wastepaper recycling via Ecoinvent dataset
EoL treatment - Recycling 70% both systems	SU / MU	Recycling shares, SU: 82,9%; MU: 41,8%	Recycling shares, SU: 70%%; MU: 70%%
Manufacturing - Recycled content (rec40%)	MU	Recycled content RPC: 10%	Recycled content RPC: 40%
Breakage rate - BR_0,5%	MU	Breackage rate: 2,5%	Breackage rate: 0,5%
Breakage rate - BR_5%	MU	Breackage rate: 2,5%	Breackage rate: 5%
Washing - optimized detergents	MU	Detergent composition as database set	Detergent composition following Tua et al. (2019)
Washing - Min demand	MU	Washing demand: 0,0374 kWh electricity, 0,3011 liter water, 0,0044 kg detergents	Washing demand: 0,0274 kWh electricity, 0,0958 liter water, 0,0017 kg detergents
Transport - Transport -50% (both systems)	SU / MU	Transport distances as Appendix 2	Transport distances of Appendix 2 decreased by 50%
Transport - Transport +50% (both systems)	SU / MU	Transport distances as Appendix 2	Transport distances of Appendix 2 increased by 50%
Transport - Less challenging transport for MU (-25%)	MU	Transport distances as Appendix 2	Transport distances of Appendix 2 (only for MU) decreased by 25%

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[58] Results related to sensitivity scenarios indicated in the table are reported in Appendix 5

3.4.1.1 Acidification

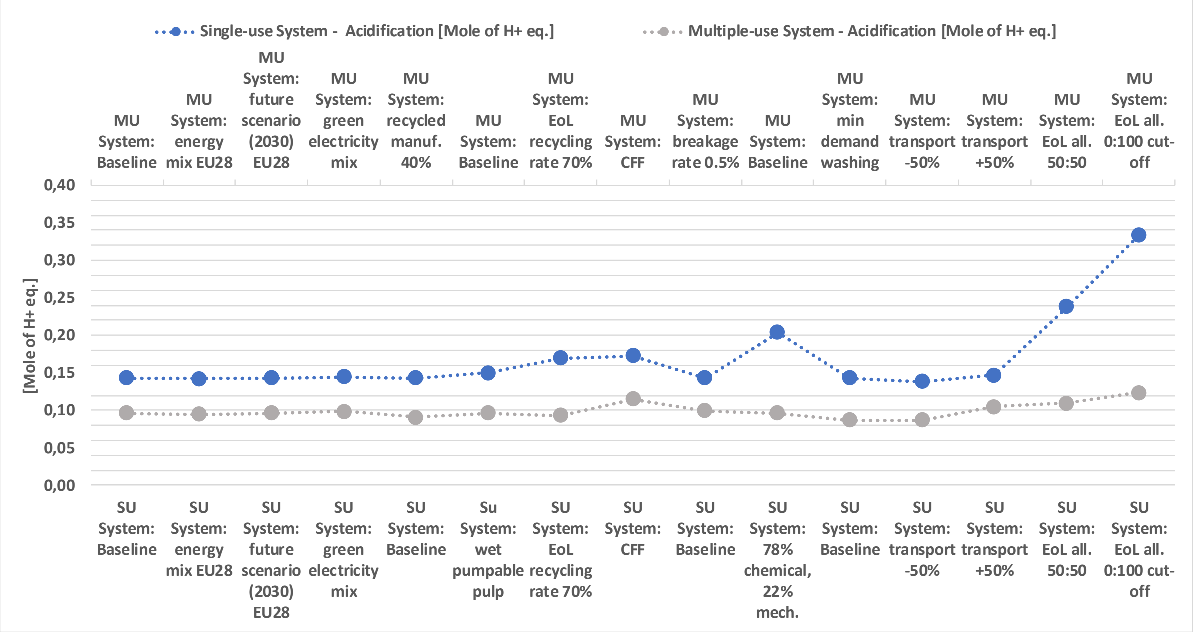

Figure 26: Summary of aggregated results for the impact category Acidification of all scenarios within both systems (only some scenarios are displayed; the rest are present in table form) - Number of reuses/rotations in the MU system = 24

3.4.1.2 Climate Change, total

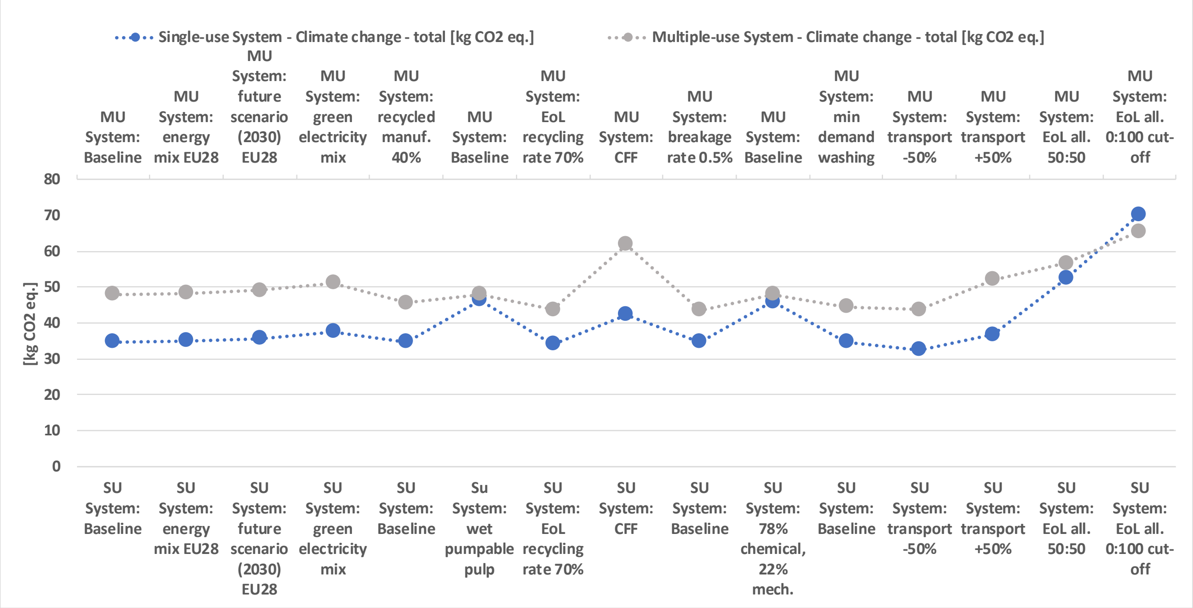

Figure 27: Summary of aggregated results for the impact category Climate Change, total of all scenarios within both systems (only some scenarios are displayed; the rest are present in table form) - Number of reuses/rotations in the MU system = 24

3.4.1.3 Ecotoxicity, freshwater

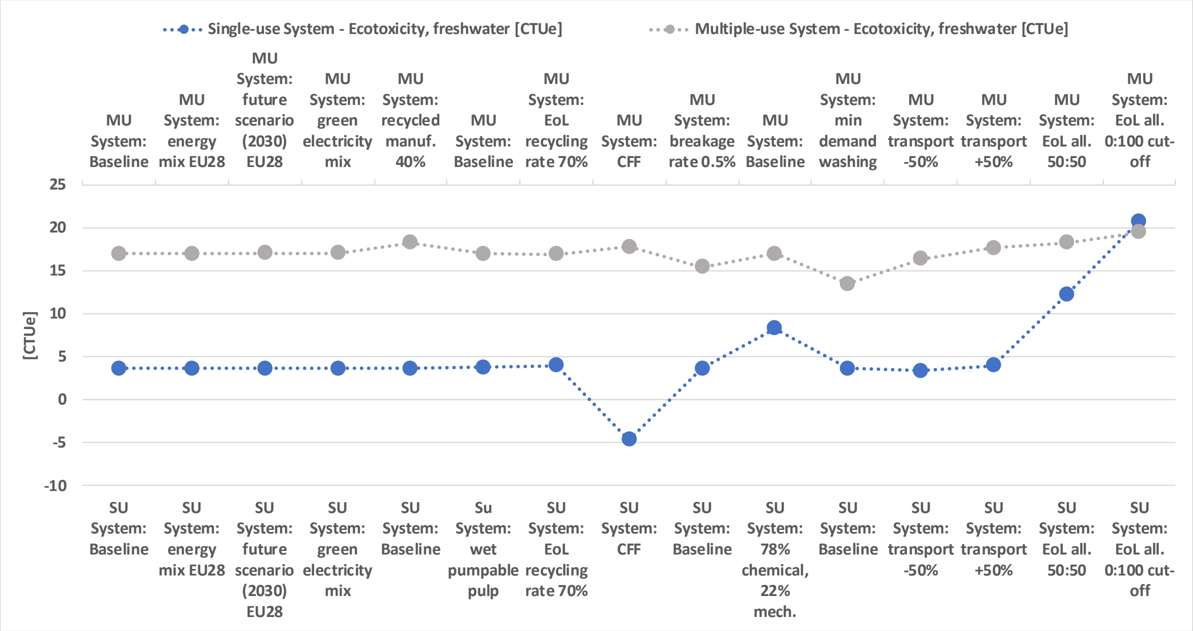

Figure 28: Summary of aggregated results for the impact category Ecotoxicity, freshwater of all scenarios within both systems (only some scenarios are displayed; the rest are present in table form) - Number of reuses/rotations in the MU system = 24

3.4.1.4 Eutrophication, freshwater

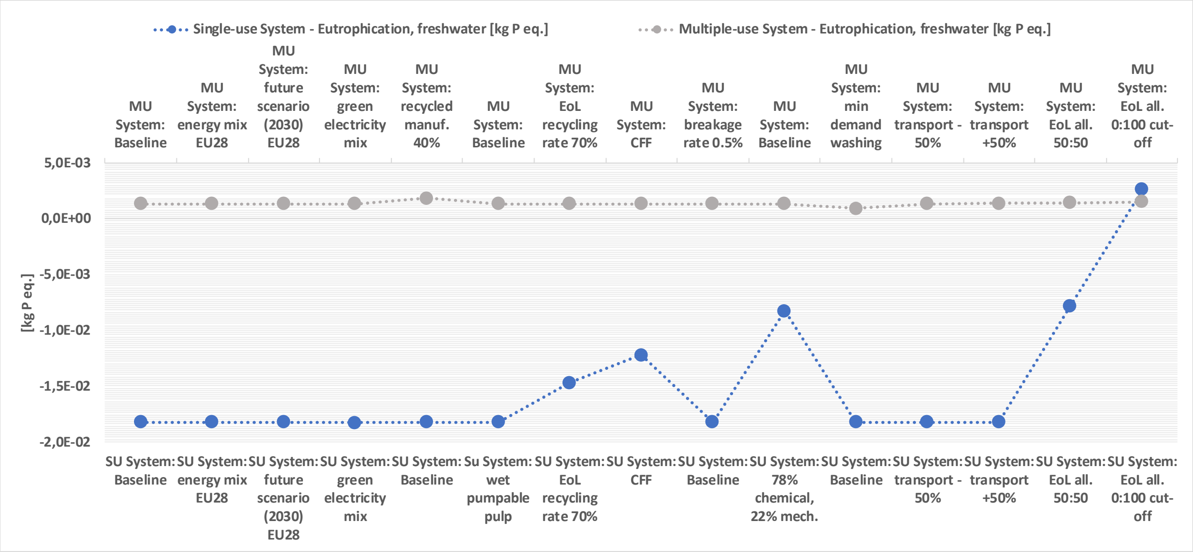

Figure 29: Summary of aggregated results for the impact category Eutrophication, freshwater of all scenarios within both systems (only some scenarios are displayed; the rest are present in table form) - Number of reuses/rotations in the MU system = 24

3.4.1.5 Eutrophication marine

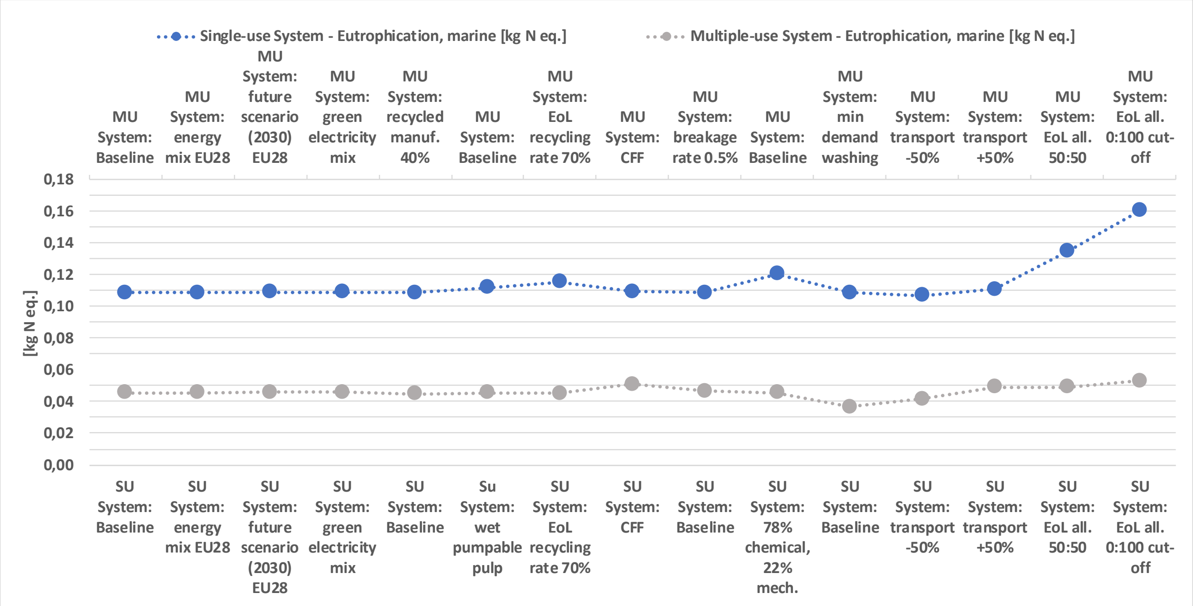

Figure 30: Summary of aggregated results for the impact category Eutrophication marine of all scenarios within both systems (only some scenarios are displayed; the rest are present in table form) - Number of reuses/rotations in the MU system = 24

3.4.1.6 Eutrophication, terrestrial

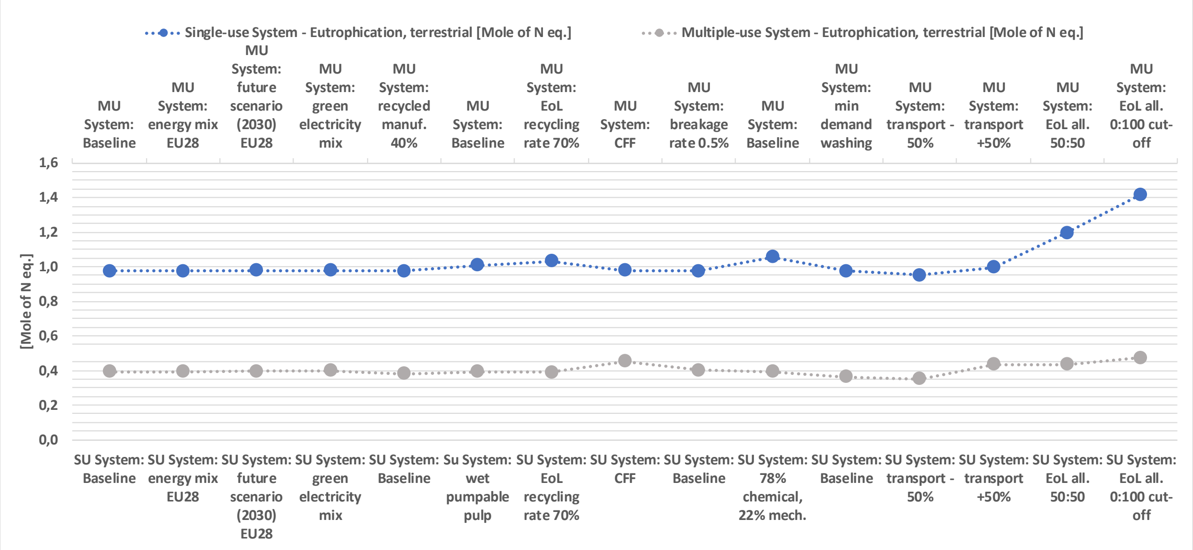

Figure 31: Summary of aggregated results for the impact category Eutrophication, terrestrial of all scenarios within both systems (only some scenarios are displayed; the rest are present in table form) - Number of reuses/rotations in the MU system = 24

3.4.1.7 Human toxicity, cancer

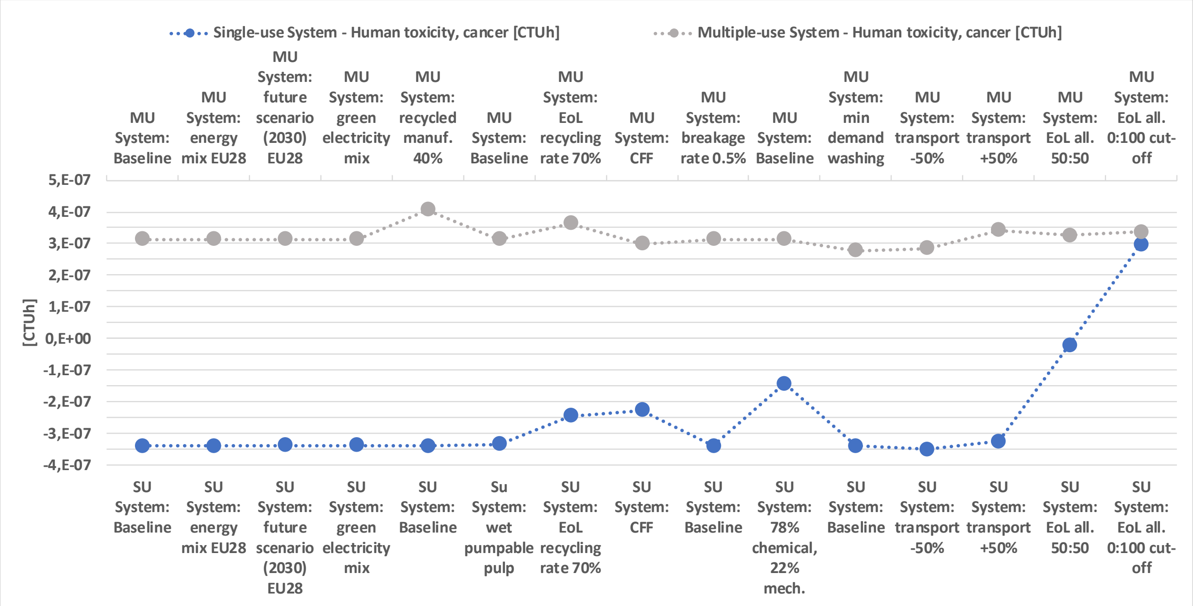

Figure 32: Summary of aggregated results for the impact category Human toxicity, cancer of all scenarios within both systems (only some scenarios are displayed; the rest are present in table form) - Number of reuses/rotations in the MU system = 24

3.4.1.8 Human toxicity, non-cancer

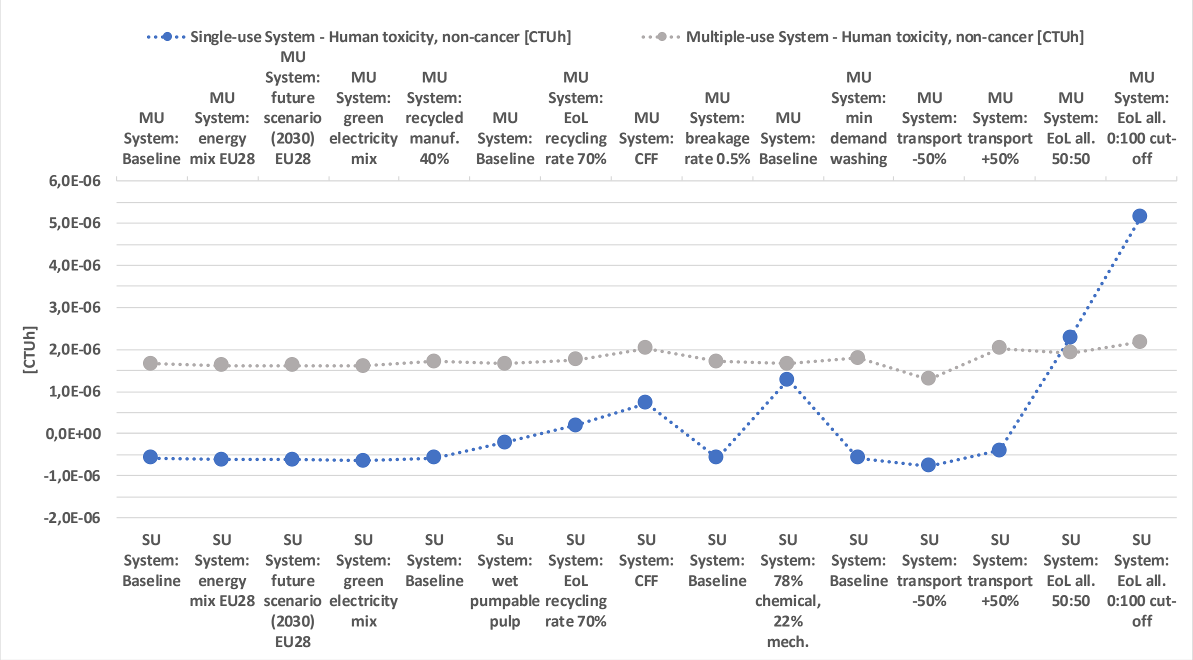

Figure 33: Summary of aggregated results for the impact category Human toxicity, non-cancer of all scenarios within both systems (only some scenarios are displayed; the rest are present in table form) - Number of reuses/rotations in the MU system = 24

3.4.1.9 Ionizing radiation, human health

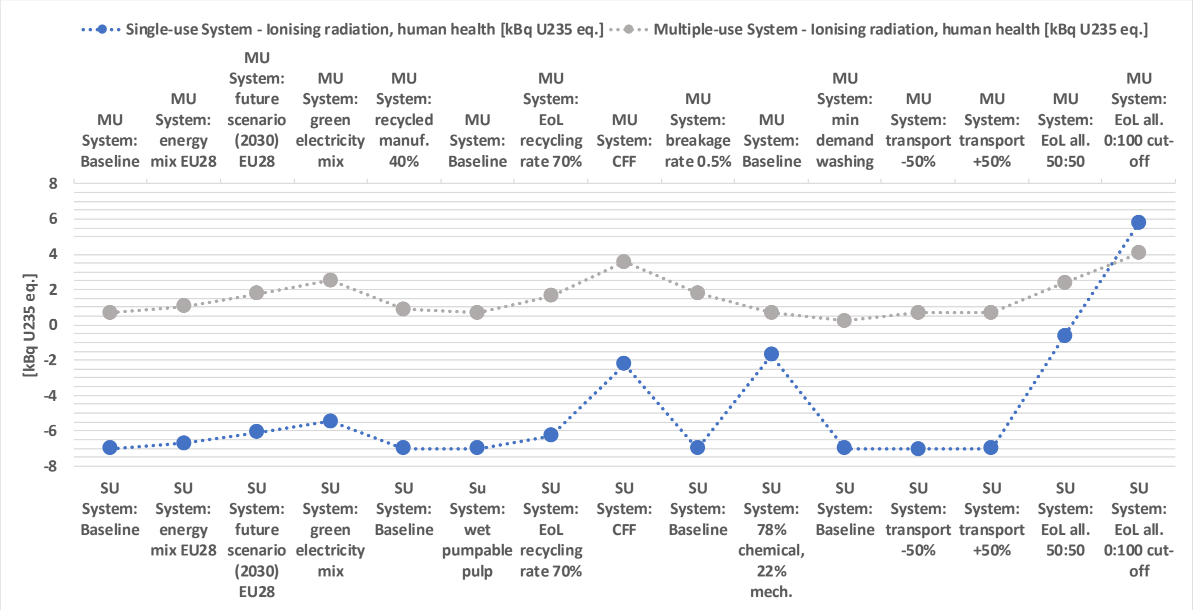

Figure 34: Summary of aggregated results for the impact category Ionizing radiation, human health of all scenarios within both systems (only some scenarios are displayed; the rest are present in table form) - Number of reuses/rotations in the MU system = 24

3.4.1.10 Ozone depletion

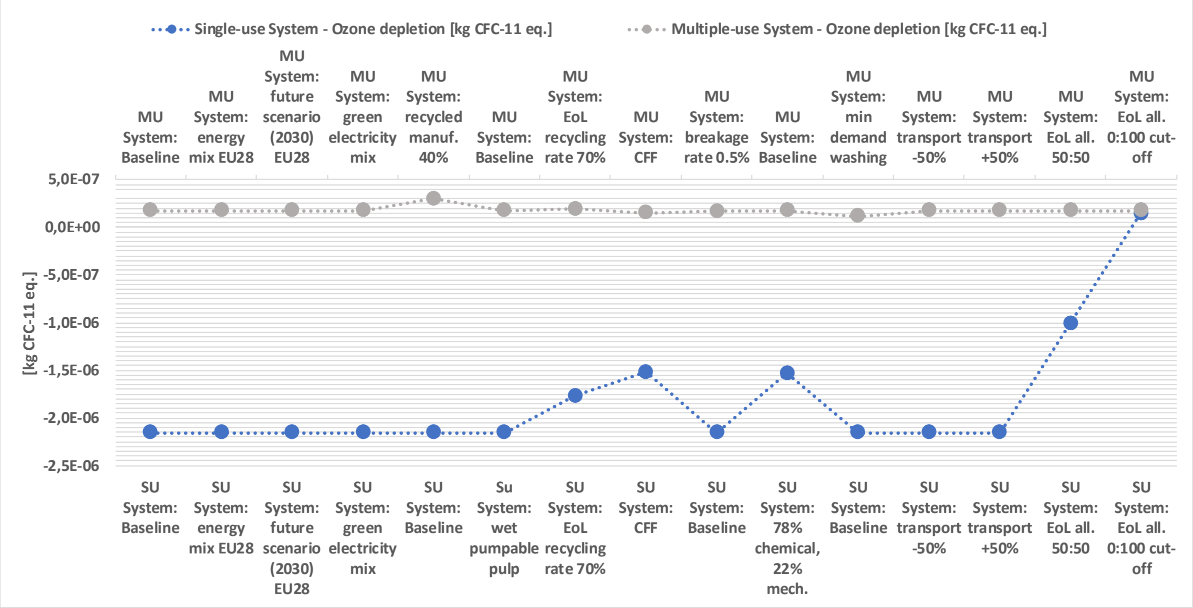

Figure 35: Summary of aggregated results for the impact category Ozone depletion of all scenarios within both systems (only some scenarios are displayed; the rest are present in table form) - Number of reuses/rotations in the MU system = 24

3.4.1.11 Particulate matter

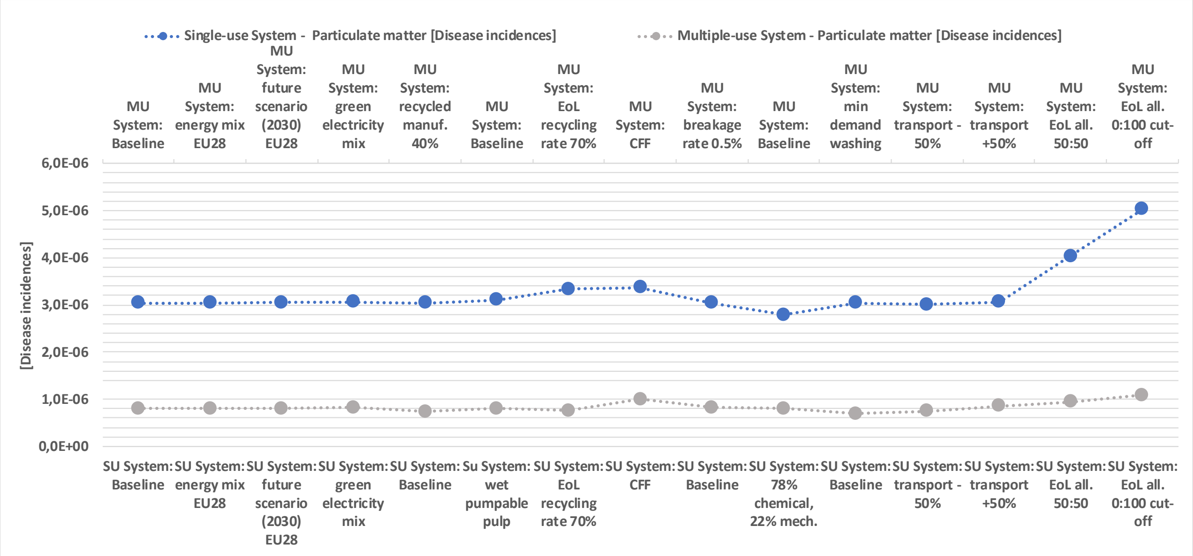

Figure 36: Summary of aggregated results for the impact category Particulate matter of all scenarios within both systems (only some scenarios are displayed; the rest are present in table form) - Number of reuses/rotations in the MU system = 24

3.4.1.12 Photochemical ozone formation - human health

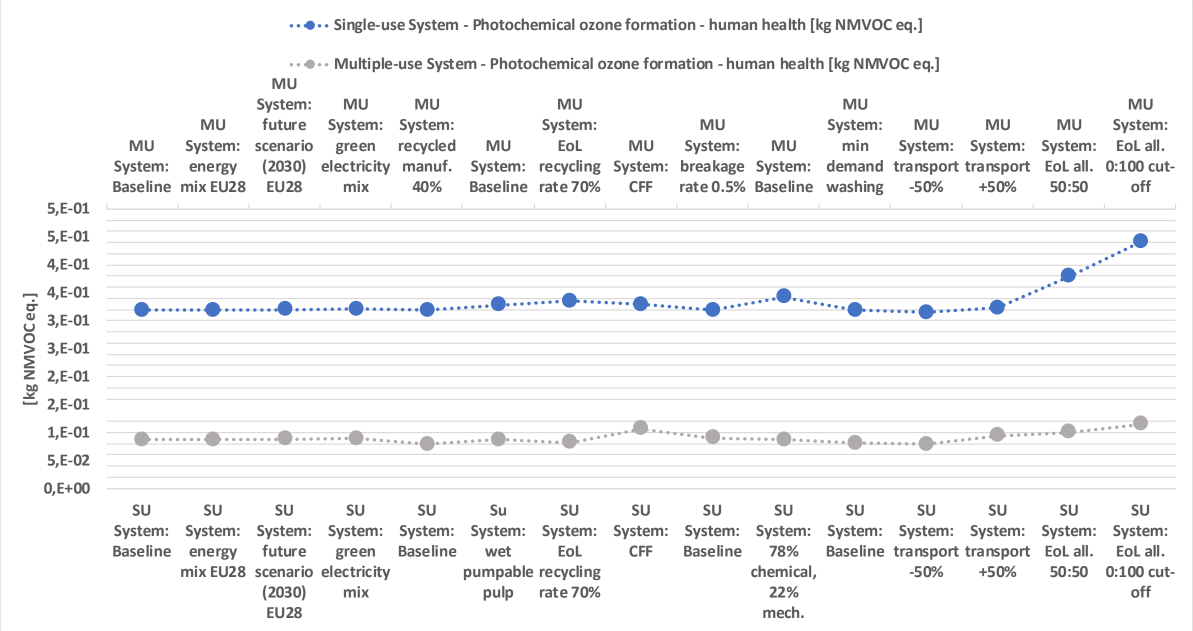

Figure 37: Summary of aggregated results for the impact category Photochemical ozone formation - human health of all scenarios within both systems (only some scenarios are displayed; the rest are present in table form) - Number of reuses/rotations in the MU system = 24

3.4.1.13 Resource use, fossils

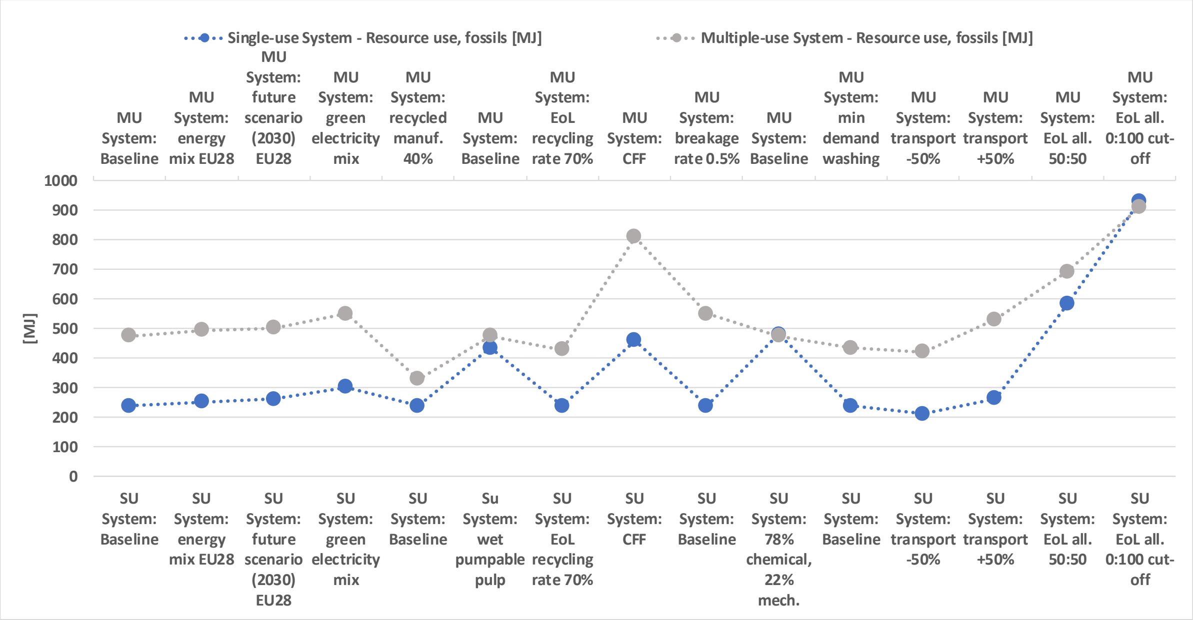

Figure 38: Summary of aggregated results for the impact category Resource use, fossil of all scenarios within both systems (only some scenarios are displayed; the rest are present in table form) - Number of reuses/rotations in the MU system = 24

3.4.1.14 Resource use, minerals and metals

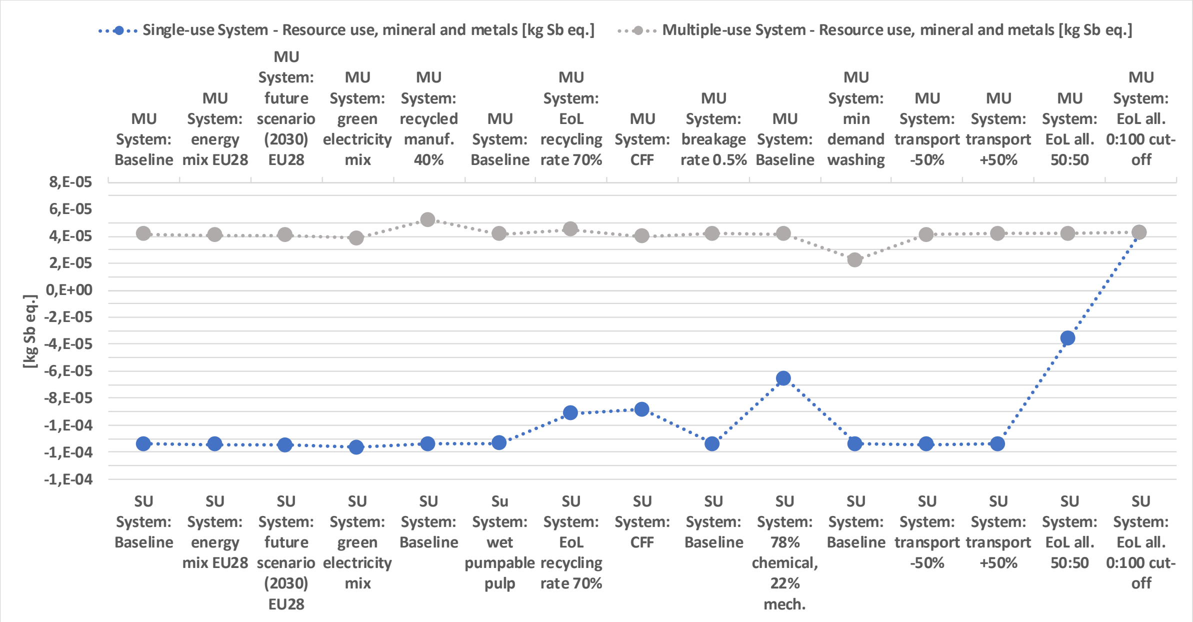

Figure 39: Summary of aggregated results for the impact category Resource use, minerals and metals of all scenarios within both systems (only some scenarios are displayed; the rest are present in table form) - Number of reuses/rotations in the MU system = 24

3.4.1.15 Water use

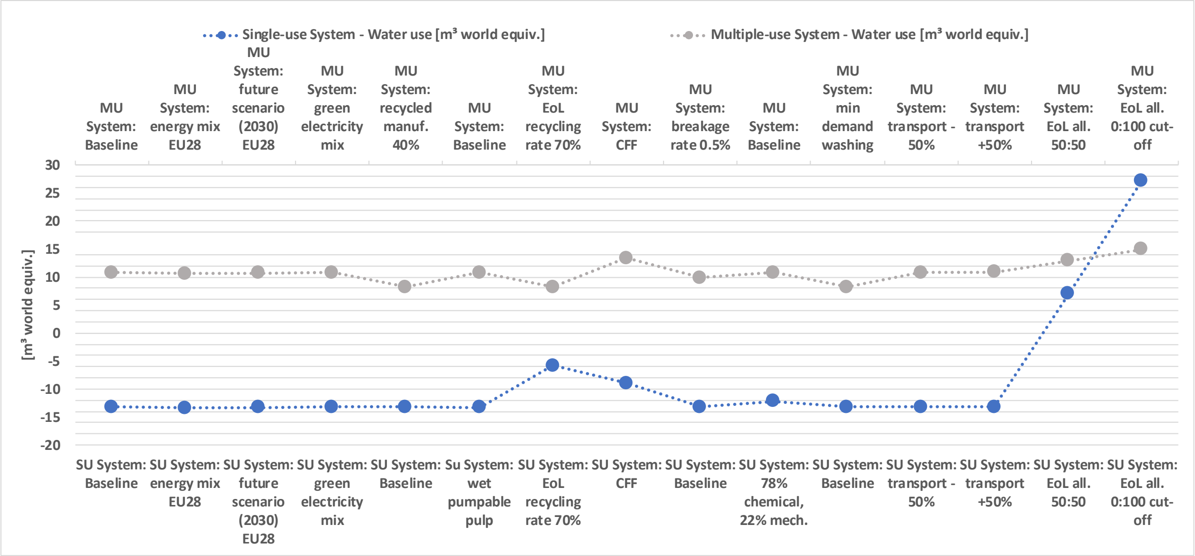

Figure 40: Summary of aggregated results for the impact category Water use of all scenarios within both systems (only some scenarios are displayed; the rest are present in table form) - Number of reuses/rotations in the MU system = 24

3.4.2 Break-even analysis

Since the number of reuses/rotations of RPCs is a relevant parameter in the present study, a break-even analysis is presented with a variable number of rotations for the Climate Change, total impact category.

It is important to acknowledge that, in general, break-even points presented by different studies are not directly comparable as they refer to different background data, geographical context, assumptions etc. However, it is deemed relevant to put the results of this study in context. In order to facilitate a better comparison between the respective break-even points, additional meta data per study is disclosed (see Table 28).

Table 28: Comparison of calculated break-even points in different studies

Source	Functional unit	Geographical context	Calculated break-even point for CO_2 eq. in number of rotations of the plastic crate
Fraunhofer Institute for Building Physics IBP (2018)	The distribution of 1.000 t of fruit or vegetables in Reusable Plastic Containers (RPC) or in single-use Cardboard Boxes (CB)	Europe	**6**
Thorbecke *et al.* (2019)	Provide containment during filling, transport and display of 907,185 kg (1.000 short tons) of grocery market produce in the United States in a manner that maintains the safety of the produce for human consumption	US	**77**

Source	Functional unit	Geographical context	Calculated break-even point for CO_2 eq. in number of rotations of the plastic crate
	and that is consistent with commercial supply chains		
Lo-Iacono-ferreira *et al.* (2021)	A packaging system to properly store and transport 1.000 t of product from the market of origin, located mainly in Almería (Spain), to the destination market (Germany)	Europe	**> 100**
This study (Baseline)	Provision of delivery, containment, and display for 1 ton of vegetables (fresh produce) by means of functionally equivalent transport containers (either corrugated board boxes or plastic crates) over a representative transport distance from producer to retailer in the EU in a manner that maintains the safety of the produce and that is consistent with established commercial supply chains.	Europe	**63**

Figure 41 shows the analysis of the break-even point for this study for the impact category Climate change, total (see Table 28). This calculation considers the consequences by variating the number of rotations of RPCs for the MU system. As the functional unit (f.u. = 1 ton of transported fresh goods **over a transport distance of 840 km from producer to retailer in the EU**) remains the same, impacts associated to the SU system are shown as a steady line (34,70 kg CO2-eq.), whereas impacts associated to the MU system depend on the number of rotations. The break-event point of impacts of SU system and MU system (~63 rotations) is between a minimum value reported in the previous table (6) and a maximum one (>100). The chart shows that for a number of RPC rotations lower than the break-even point, the single-use system has lower environmental impacts in the category Climate Change, total. For a number of RPC rotations higher than the break-even point, the multiple-use system present lower emissions. This means that if the lifespan of a plastic crate is higher than the break-even point, the MU system is preferrable over the SU system, otherwise not. Since this analysis is related to the specific assumptions of this study (e.g., boundaries of the systems, methodology, approach, functional unit, …), it cannot be generalized.

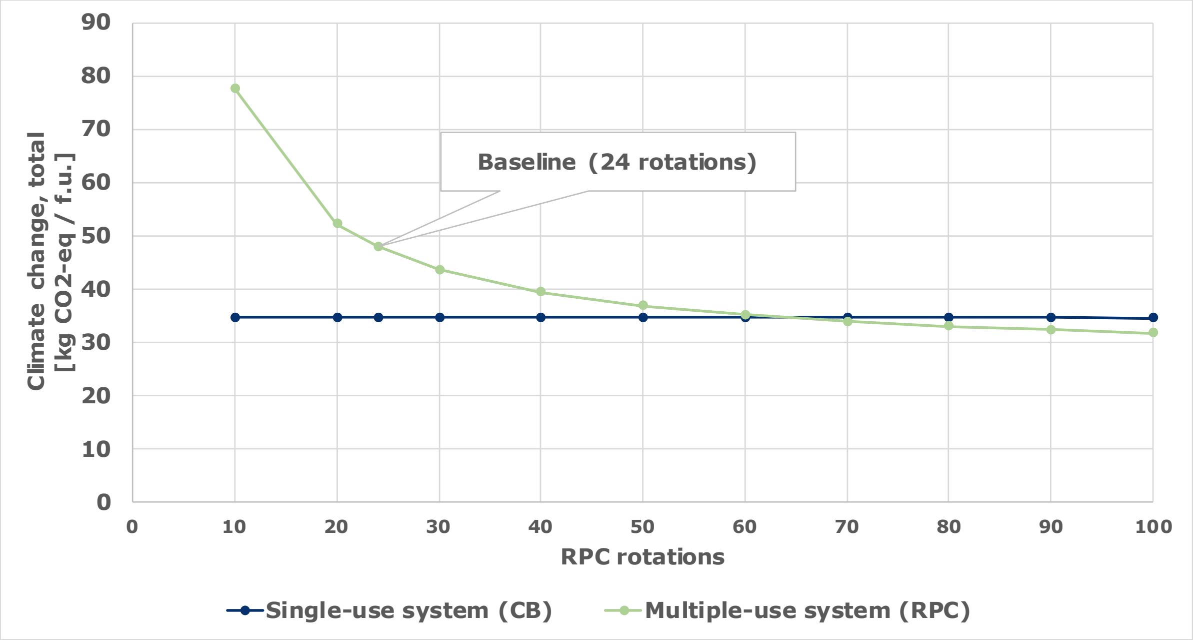

Figure 41: Break-even point for Climate change, total impact category

3.4.3 Uncertainty analysis

This section presents an overview of uncertainties due to data gaps and/or inconsistencies in the underlying databases.

Significant differences in potential environmental impacts in most of the categories are identified with regard to the **avoided emissions in the baseline scenario**. It is assumed that is mainly due to the use of datasets (i.e. Ecoinvent), which lead to high avoided emissions of mechanical pulp products. As shown in section 3.4.1, this has an effect in many categories, such as Human toxicity, cancer, Human toxicity, non-cancer, Ozone depletion, Water use, Eutrophication freshwater, Ionizing radiation, human health, Resource use, mineral and metals.

Significant differences in potential **Photochemical ozone formation - human health** and **Ozone depletion** impacts are identified with regard to the single-use system. Obtained results for this impact category appear to be overestimated for the conservative recycling (with secondary data).

3.4.4 Regarding the Avoided burden approach (and negative values)

The results presented in section 3.3.3 and results presented in 3.4.1 show significant credits calculated as avoided emissions at EoL. This is due to the approach of the baseline (Avoided burden) introduced in section 3.1.5.

The Avoided burden approach as baseline is assumed for this study for the following reasons:

- It is in line with several other relevant LCAs, as identified in the Literature Screening (see section 2.1) and therefore better suited for a debate around their respective findings[59]

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[59] To the best of our knowledge, all life cycle assessment studies on single-use corrugated board solutions versus multiple-use plastic crate solution published in the last 5 years assume a system expansion. Sensitivity analyses with different EoL allocation approaches are indeed present in the body of literature, as this study.

- It is consistent with underlying inventory data for the corrugated board (CEPI and FEFCO, 2018), i.e. closed-loop approximation; hence results are not determined by 3rd party systems (obviously this is a modelling choice and not necessarily representing the reality)
- It is the preferred approach in ISO standard and explicitly stated in latest amendment ISO 14044:2020 (i.e., expanding the system to include additional functions must be understood as subtracting avoided burdens with the substitution method)
- It ensures symmetry in assumptions (i.e., closed-loop approximation for both systems)
- It ensures comparability of systems with inherently different characteristics (i.e. system with high material volume throughput vs. system with low material volume throughput); for this reason a cut-off approach is not applicable and also a 50:50 allocation approach is highly questionable (both are nevertheless included in the sensitivity analysis to give a broader view of potential fluctuations of results); CFF is deemed the only alternative allocation method for this comparison (this is therefore included in the final results, see Table 25).

As consequence of this choice, negative results (due to avoided emissions) are shown in impact categories in the single-use system like Eutrophication freshwater, Human toxicity (cancer and non-cancer), Ionizing radiation, human health, Ozone depletion, Resource use, mineral and metals, and Water use. These avoided emissions are related to pulp products and their relative database sets. However, this is inevitable in this case, as only Ecoinvent provides data for dry market pulp products at the point of substitution.

4. CONCLUSIONS, RECOMMENDATIONS AND LIMITATIONS

The chapters above provide background information and results for B2B transport packaging solutions for the food segment—a recyclable corrugated solution and a reusable plastic crate in Europe (see description of goal and scope of the study in section 3.1).
In particular, the functional unit adopted for this assessment is:

> **Provision of delivery, containment, and display for 1 ton of vegetables (fresh product) by means of functionally equivalent transport containers (either single-use corrugated board boxes, or multiple-use plastic crates with a lifespan of 24 equivalent reuses) over a transport distance of 840 km from producer to retailer in the EU in a manner that maintains the safety of the produce and that is consistent with established commercial supply chains.**

A systems perspective is used to reflect both systems and compare equal functions of single-use and multiple-use product items (see section 3.1.2). The LCA is performed according to relevant ISO standards 14040 and 14044 and discusses the impacts on a set of fourteen environmental impact categories (see section 3.1.6). The generic exclusion of potentially relevant impact categories for both systems is an unavoidable limitation of this study which needs to be taken into account when interpreting overall results and making decisions in this regard.

With regards to data quality and appropriateness for the goal and scope of this assessment, it is important to differentiate between primary and secondary data (see section 0) as well as to acknowledge environmentally decisive life-cycle stages and processes within both systems. Therefore, the study is based on extensive data gathering in particular for the single-use system, for which primary data from paper producers and converters is incorporated to reflect the current practice of upstream manufacturing steps of single-use product items as well as their EoL treatment. For the multiple-use system, upstream and downstream processes are covered using background information available in LCI databases and extensive research is performed regarding the use phase of multiple-use items, in particular the different washing options. In conclusion, particular attention is given to environmentally decisive parameters, assumptions and processes when identifying and selecting appropriate data sources.

Overall, results of the comparative assessment of single and multiple-use systems show overall that the environmental hotspots refer to different life cycle phases in the two systems: the main contributors to the impacts in the single-use system are the raw material production and manufacturing stages and avoided emissions (material), whereas the main contributors in the multiple-use system are the washing stage and the raw material and manufacturing stage (see section 3.3.1.16 for contribution analysis).

Under consideration of identified uncertainties, the following overarching conclusions can be drawn from the comparative assessment for the baseline scenario:

- single-use system shows benefits for the following impact categories: Climate change, total; Ecotoxicity, freshwater; Eutrophication, freshwater; Human toxicity, cancer; Human toxicity, non-cancer; Ionizing radiation, human health; Ozone depletion; Resource use, fossils; Resource use, mineral and metals; and Water use;
- multiple-use system shows benefits for the following impact categories: Acidification; Eutrophication, marine; Eutrophication, terrestrial; Particulate matter; Photochemical ozone formation - human health.

- The Break-even analysis highlights that for a number of RPC rotations lower than the break-even point (~63 rotations), the single-use system has lower environmental impacts in the category Climate Change, total impact category.

To test decisive assumptions in the respective systems, several sensitivity scenarios are analysed, details of the investigated parameters are summarized in the following table. Note: only one parameter (or assumption) is changed per system. For more details see section 3.3.4 and Table 27 for an overview of scenarios.

Sensitivity scenario	**System affected**	**Value in the baseline**	**Variation**
EoL allocation - 0:100 approach (cut-off)	SU / MU	Avoided burden	Cut-off
EoL allocation - 50:50 approach	SU / MU	Avoided burden	Approach 50:50
EoL allocation - Avoided emissions (78% chemical, 22% mechanical)	SU	Pulp products as avoided emissions: 53% sulphate pulp, 47% mechanical pulps (TMP, CTMP, stone groundwood)	Pulp products as avoided emissions: 78% sulphate pulp, 22% mechanical pulps (TMP, CTMP, stone groundwood)
EoL allocation - Avoided emissions (wet pumpable pulp)	SU	Pulp products as market dry pulp	Pulp products as wet pulp (1000 kWh is required to dry off the water)
Energy mix - EU28	SU / MU	Residual Energy grid mix EU-28	Energy grid mix EU28
Energy mix - Future scenario EU-28 (2030)	SU / MU	Residual Energy grid mix EU-28	Future scenario grid mix EU-28 (2030)
Energy mix - Green electricity grid mix	SU / MU	Residual Energy grid mix EU-28	Green electricity grid mix
EoL treatment - Wastepaper reycling (secondary data)	SU	Wastepaper recycling via FEFCO's LCI re-work (Appendix 1)	Wastepaper recycling via Ecoinvent dataset
EoL treatment - Recycling 70% both systems	SU / MU	Recycling shares, SU: 82,9%; MU: 41,8%	Recycling shares, SU: 70%%; MU: 70%%
Manufacturing - Recycled content (rec40%)	MU	Recycled content RPC: 10%	Recycled content RPC: 40%
Breakage rate - BR_0,5%	MU	Breackage rate: 2,5%	Breackage rate: 0,5%
Breakage rate - BR_5%	MU	Breackage rate: 2,5%	Breackage rate: 5%
Washing - optimized detergents	MU	Detergent composition as database set	Detergent composition following Tua et al. (2019)
Washing - Min demand	MU	Washing demand: 0,0374 kWh electricity, 0,3011 liter water, 0,0044 kg detergents	Washing demand: 0,0274 kWh electricity, 0,0958 liter water, 0,0017 kg detergents
Transport - Transport -50% (both systems)	SU / MU	Transport distances as Appendix 2	Transport distances of Appendix 2 decreased by 50%
Transport - Transport +50% (both systems)	SU / MU	Transport distances as Appendix 2	Transport distances of Appendix 2 increased by 50%
Transport - Less challenging transport for MU (-25%)	MU	Transport distances as Appendix 2	Transport distances of Appendix 2 (only for MU) decreased by 25%

Under consideration of identified uncertainties and sensitivities of impact results, the following overarching conclusions can be drawn from the comparative assessment:

- For Climate change, total, Ecotoxicity, freshwater, Human toxicity, cancer, Human toxicity, non-cancer, Ozone depletion, Ionizing radiation, human health, Resource use, fossil, Resource use, mineral and metals and Water use, the single-use system shows benefits considering the comparison throughout most of the sensitivity analyses.
- In cases allocating 70% recycling end of life for both systems, the environmental benefits for the single-use system become even higher. Different EoL allocations (e.g. avoided emissions with wet pumpable pulp) can reduce the delta between the systems, and reduce the benefits in many impact categories. This is due to the assumptions that further energy demand is required to dry off the water from the market dry pulp products allocated at the point of substitution (i.e. 1000 kWh of energy demand).
- In the cut-off scenario, in all categories excluding Human toxicity, cancer and Ozone depletion no environmental benefits are highlighted. However, this scenario is considered in this study only for comparison purposes, since the Avoided burdens approach is the recommended one by ISO 14044:2006 and ISO 14044:2020 (see Table 2 and Section 3.4.4), and in general this method gives incentives to develop recyclable products and to recycle them after use[60].
- For Acidification, Eutrophication, marine, Eutrophication, terrestrial, Particulate matter and Photochemical ozone formation - human health, the single-use system shows no benefits in all of the sensitivity analyses.
- By considering a conservative recycling process, the delta between the two systems is reduced, by lowering the benefit of the single-use system. This is due to the higher energy demand accounted in the process via secondary dataset (whose inputs are however older than 10 years).
- In general, by changing assumptions on the electricity grid mix, no sensible variation on the results can be drawn. This is due to the low dependency of unit processes to this parameter. Specifically, it should be noted that as manufacturing processes are implemented in the model as aggregated datasets, energy grid mix variation influence only the recycling process in the single-use system and the washing stage in the multiple-use system. However, both unit processes occur each cycle/rotation, and it could be considered a symmetrical situation.
- In the single-use system, avoided emissions of pulp products have a great influence on the results (with consequent credits in the overall aggregated results). This is mainly due to avoided impacts of mechanical pulp products, such as CTMP, TMP and stone groundwood processes.
- The Resource use, fossil impact category in the Cut-off approach deserves further explanation. The findings of this study suggest that the single-use system shows no benefits in this scenario. However, this depends to the energy mix used for wastepaper recycling (one of the main contributors to the impacts), which is related to fossil energy sources (e.g., heavy fuel oil, light fuel oil, diesel, coal). This energy mix is used *in situ* at recycling facilities for generating energy. Certainly, a different energy mix with a greater contribution from renewable sources and a lower presence of fossil fuel, could produce different results, with beneficial effects on the Resource use, fossil category for the single-use system. This aspect was investigated by many authors. Ferrara and Feo (2021), for example, highlighted in a study about energy mix for wastepaper recycling that the choice

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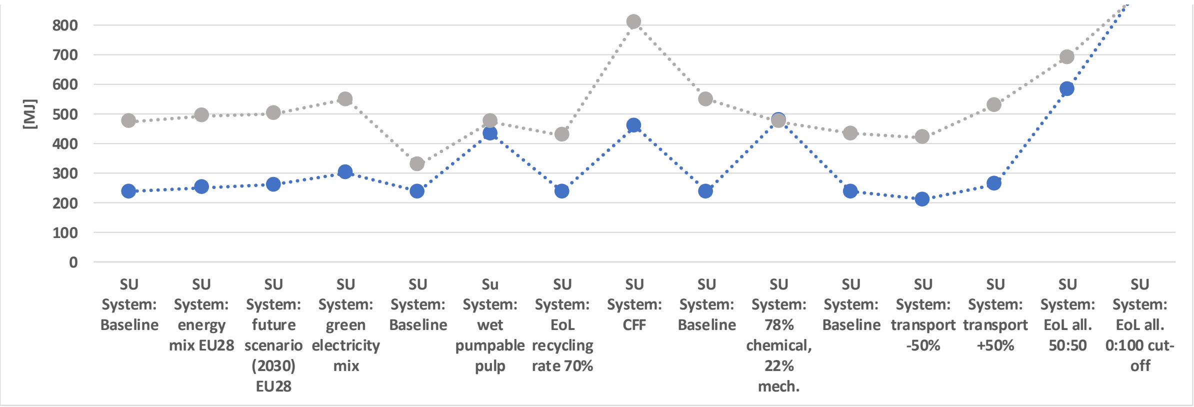
[60] See: (Eberhardt *et al.*, 2020)



- Figure 38), especially in the scenario with lower recycling rate (70%) compared to the Baseline scenario (around 84%). By considering a lower recycling rate, the single-use system shows indeed benefits when compared to the multiple-use system – these findings highlight that by incrementing the incineration rate at EoL, there is a beneficial effect on the results in the single-use system. This is due to high efficiency of paper and paperboard incineration process in the EU: incineration process has around 72% lower emissions than the recycling process considered in this study (per kg of input material) in the Climate Change, total category, for example.

- Although studies in literature have based their models and assumptions on secondary data for the life cycle of multiple-use plastic crates (as in this study), a potential step forward would be collecting primary data at industry level. This might be relevant in future works.

- The implementation of water assessment via Water use impact category in the Environmental Footprint (EF) methodology is subject to some limitations, as explained in Sphera documentation (last documentation, year 2018)[61]. As sources of uncertainties still remain in the application of the "available water remaining" (AWaRe) methodology in the EF Water use impact category in GaBi software, results in this impact category of this study could be therefore used as potential uncertain. This can be seen as a limitation in this study. These results are shown in this study for the sake of completeness. Further analysis is strongly envisaged in future studies.

This comparative LCA has been conducted in accordance with ISO standards 14040 and 14044, however an assessment of the most relevant EF categories using as a reference "Impact categories cumulatively contributing at least 80% of the total environmental impact (excluding toxicity related impact categories)" has been performed according to the Product Environmental Footprint Category Rules Guidance (version 6.3):

- **SU system:** the most relevant impact categories are Climate Change, total, Eutrophication, freshwater, Eutrophication, terrestrial, Particulate matter, Photochemical ozone formation, human health and Resource use, fossils. These categories have a cumulative contribution of 80.1% of the total impact, based on the normalized and weighted results, and excluding the toxicity related impacts,
- **MU system**: the most relevant impact categories are Climate Change, total, Particulate matter and Resource use, fossils. These categories have a cumulative contribution of 80.3% of the total impact, based on the normalized and weighted results, and excluding the toxicity related impacts.

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[61] Source: https://gabi.sphera.com/fileadmin/Documents/Introduction_to_Water_Assessment_V2.2_03.pdf

In conclusion, total impacts as well as the comparison between the single and the multiple-use systems are strongly dependent on underlying assumptions with regard to the EoL allocation method. In general, LCA results of comparative analysis are influenced by uncertain data on the waste management (e.g. wastepaper recycling) and the avoided virgin materials production, whose consideration can affect the findings of a LCA (Ekvall *et al.*, 2020).

5. CRITICAL REVIEW

Comparative Life Cycle Assessment (LCA) – Packaging solutions for the food

CRITICAL REVIEW STATEMENT

Reviewers: Tiina Pajula (VTT), Daniele Pernigotti (AEQUILIBRIA S.R.L.- SB), Michael Sturges (RISE)

Review Background

FEFCO has contracted Ramboll Italy Srl to study potential environmental impacts generated in B2B transport packaging solutions for the food segment - a recyclable corrugated solution and a reusable plastic crate - using standardised LCA methodology in accordance with LCA standards of ISO 14040 and ISO 14044. A critical review panel was assigned to critically review the study.

The critical review ensures that

a. the methods used to carry out the LCA study are consistent with ISO 14040-44 on Life Cycle Assessment
b. the methods used to carry out the LCA study are scientifically and technically valid
c. the data used are appropriate and reasonable in relation to the goal of the study
d. the interpretations reflect the limitations identified and the goal of the study
e. the study report is transparent and consistent

Review Process

The panel chair Tiina Pajula participated two meetings in concurrence with the early phase of the study providing immediate feedback to the goal and scope and the preliminary inventory. The first review by the whole panel was performed based on the first draft report provided by Ramboll on the 5th of November 2021 followed by the 2nd round of comments based on the report revision provided by Ramboll on the 17th of February 2022. The review process included explanatory meetings by Ramboll and feedback meetings by the Review Panel. In addition to the Ramboll experts and the Review Panel a few representatives from the FEFCO project steering committee were present. The Review Panel convened internally between the meetings. A 3rd round of comments was provided by email. Ramboll Italy Srl made the recommended changes and responded to the written comments by the reviewers correspondingly[1]. This review statement is based on the final LCA study report dated April, 2022[2].

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[1] Pajula, T., Pernigotti, D., Sturges, M. Ramboll packaging LCA, Critical Review panel comments and responses, 8.3.2022 (xlsx)

[2] Ramboll Italy Srl, COMPARATIVE LIFE CYCLE ASSESSMENT (LCA), PACKAGING SOLUTIONS FOR THE FOOD SEGMENT, April 2022

Review Statement

The undersigned reviewers confirm that the reviewed study “Comparative Life Cycle Assessment (LCA) – Packaging solutions for the food” has been conducted according to and in compliance with the ISO standards 14040 and 14044 and has relevant data sources. The reviewers would like to highlight the following:

- Choice of baseline method - avoided burdens approach - is highly influential on the results achieved and conclusions drawn, and therefore the inclusion of sensitivity analysis using different approaches is highly welcomed
- Choice of data for avoided burdens can be highly influential for results achieved and conclusions drawn - it is particularly difficult to estimate the avoided burdens for paper recycling versus virgin production due to the interconnectedness of the production systems for pulp and paper and the multiple reuses of fibres. The best available data has been used, and sensitivity analysis has been applied, which is appreciated
- The influence of the number of reuses of the plastic crate is significant as indicated in the analysis of total climate change impact. It would be good to see the influence of this parameter on other impact categories too, but it is understood that this is a resource intensive calculation that was out of the scope of the current study
- Overall, the study is detailed and comprehensive. It adds valuable insights to the discussion regarding the use of single trip and reusable packaging for fresh produce, and clearly demonstrates that the preferability of solution is dependent on the supply chain parameters considered and the impact categories considered.

We confirm we have been independent in our roles as reviewers, and we have no conflicts of interest regarding this review.

4.4.2022

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Principal scientist
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Michael Sturges
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RISE

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APPENDIX 1: WASTEPAPER RECYCLING TO WET PULP (LIFE CYCLE INVENTORY)

This appendix reports the LCI of Wastepaper recycling to wet pulp. This data is provided by CEPI and FEFCO, and it has been compiled as part of an ongoing project to determine the life cycle inventories for producing pulp from recovered fibers for various applications. A data provided is a pre-publication dataset. It has been compiled by RISE during 2021 by adapting data present in the FEFCO LCI database and considering information presented in the "Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board" (Suhr *et al.*, 2015). The data has been checked by a major producer of recycled corrugated case materials, considering operational experience. The reference is 1 ton of recovered pulp (wet pumpable pulp).

Table 29: LCI of wastepaper to pulp recycling (ref. 1 ton wet pumpable pulp) – "dm" indicates dry matter

Input	Value (unit)
Wastepaper input	1100 kg
Natural gas	480,70 MJ
Electrical energy	37 kWh
Heavy fuel oil	0,15 MJ
Light fuel oil	0,96 MJ
Diesel	0,08 MJ
Coal	58,85 MJ
Lignite	11,20 MJ
Biofuel (bark, scrap wood, tall oil)	2,36 MJ
Hydrogen peroxide	0,0127 kg (dm)
Starch (corn and wheat)	29,7 kg (dm)
Starch (modified)	0,30 kg (dm)
Water	3,5 m^3
Output	**Value (unit)**
Dust to air	8,57E-04 kg
CO2 fossil to air	60,036 kg
CO2 biogenic to air	6,763 kg
CO to air	0,017 kg
NOX (as NO2) to air	0,077 kg
SOX (as SO2) to air	0,015 kg
Wastewater	3,5 m^3
TSS to freshwater	0,22 kg
COD to freshwater	0,44 kg

AOX to freshwater	3,00E-04 kg
BOD5 to freshwater	0,12 kg
Total P to freshwater	3,25E-03 kg
Total N to freshwater	0,03 kg
TOC to freshwater	0,21 kg
Organic sludges - 35% dry content	28 kg
Rejects, paper (50% dry content)	23 kg
Rejects, other (50% dry content)	46 kg

APPENDIX 2: TRANSPORTATION ROUTES

Distances and respective references adopted in the model are shown in Table 30. Further explanation for the calculations including specific values and sources is presented in this appendix. Distances are rounded to the nearest fifth or tenth so that false accuracy is not feigned.

Table 30: Distances (km) used in the model for modeling the transportation[62]

Transport routes	Single-use corrugated box (CB system) (km)	Multiple-use plastic crate (RPC system) (km)	Source
manufacturer - food producer	55	370	Own calculations (weighted average in EU)
food producer - distribution center	840	840	Own calculations (weighted average in EU)
distribution - retailer	50	50	Assumed[63]
retailer - distribution center	n.a.	50	Assumed[64]
distribution - service center (washing and sanitizing)	n.a.	165	Own calculations (weighted average in EU)
service center - food producer	n.a.	380	Own calculations (weighted average in EU – domestic distance)
Transport routes (EoL)	**Single-use corrugated box (km)**	**Multiple-use plastic crate (km)**	**Source**
EoL recycling (CB: after each use; RPC: after the last route at end of lifespan)	150	840	Own calculations for CB system (weighted average in EU)[65] and assumed for RPC system[66]
EoL incineration (CB: after each use; RPC: after the last route at end of lifespan)	50	50	Assumed[67]

General information needed for most calculations are displayed in

Table 31, with the following assumptions:

- A weighted accumulation of the top five fruit and vegetables producing countries (rather six countries - France, Italy, Greece, The Netherlands, Poland, Spain - based on statistical data in the EE[68]) is used for the calculation;
- The 'Between countries share' is calculated according to the amount of food produced in the country in relation to all six chosen countries.

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[62] Distances are rounded.

[63] All assumed distances are standard distances in LCI.

[64] All assumed distances are standard distances in LCI.

[65] This assumption is made by considering data retrieved from Fraunhofer Institute for Building Physics IBP (2018). The authors evaluated a transport distance (867 km) for the EoL recycling route of RCPs. In this study, a similar distance (840 km) is taken into account, which is assumed as close as the assumption for "food producer – distribution".

[66] This assumption (150 km) is retrieved from literature Fraunhofer Institute for Building Physics IBP (2018).

[67] All assumed distances are standard distances in LCI.

[68] France, Italy, Greece, The Netherland, Poland, Spain (source: https://www.fruitlogistica.com/fruit-logistica/downloads-alle-sprachen/auf-einen-blick/european_statistics_handbook_2021.pdf)

- The domestic shares are calculated depending on the exported shares.

Table 31: General information (percent)

	France	Italy	Greece	Netherlands	Poland	Spain
Between countries share	13.3 %	25.7 %	4.5 %	7.8 %	13.8 %	35.0 %
Export share[69]	26.9 %	25.2 %	22.0 %	50.0 %	14.0 %	61.1 %
Domestic share	73.1 %	74.8 %	78.0 %	50.0 %	86.0 %	38.9 %

Manufacturer – food producer

The following steps were taken to calculate the distances between the manufacturer and the food producer for a multiple use plastic crate (RPC system):

- Main actor of plastic crates reverse logistics is considered;
- Manufacture's main site is considered;
- Data for Spain and Belgium is based on FEFCO questionnaire;
- It is estimated for Italy that the production is mainly concentrated in the Italian regions of Apulia, Calabria, Sicily, Campania and Emilia-Romagna, which account for almost 60% production[70];
- It is estimated for France that the production is mainly concentrated in Provence as it is growing over half of the nation's produce[71].

Table 32: Distance calculations (km) between manufacturer and food producer for multiple use plastic crate

	Spain 1	Spain 2	Belgium	Italy	France	Germany
Manufacturer of plastic crate (company)	Euro Pool system	IFCO	Euro Pool system	IFCO	IFCO	Mehrweg Stiftung Initiative
Company based in	Madrid	Picassent	Sint-Katelijne-Waver	Marcianise	Saint-Priest	Berlin
Most relevant production sites	Almeria, Murcia	Almeria, Murcia		Sicily / Apulia / Calabria	Provence	
Manufacturer > food producer (paths)	Madrid – Almeria (550 km) / Madrid – Murcia (398 km)	Picassent – Almeria (425 km) / Picassent – Murcia (216 km)	Average distance Belgium	Marcianise - Sicily (600km) / Marcianise - Apulia (300km) / Marcianise - Calabria (339km) / Marcianise - Emilia Romagna (561km)	Saint-Priest - Provence	Average distance Germany

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[69] European Statistics Handbook – FRUIT LOGISTICA 2021

[70] https://greenboxsl.com/en/news/italy-a-major-european-fruit-and-vegetable-producer/

[71] www.seeprovence.com

	Spain 1	Spain 2	Belgium	Italy	France	Germany
Average km	397		150	450	275	600
Average 374 km rounded to 370 km						

For the distance between the manufacturer and the food producer for a single use corrugated box (CB system), the below listed steps were followed:

- Research for the agricultural regions in each country was carried out, identifying the two to five main agriculture regions;
- Additionally, two to five food processing companies were randomly chosen for the above-mentioned countries[72];
- For each agricultural region, several bigger and smaller cities, spread evenly over the region, were selected and rounded distances to the next manufacturer were measured[73];
- An exception from this approach was made in the Netherlands. Specific agricultural regions could not be identified, because the entire country is used for agriculture. Therefore, five cities spread evenly throughout the country were chose to identify minimum and maximum transportation distances;
- In France and Italy, the agricultural regions are large with many FEFCO plants, therefore many more cities and distances were measured compared to the other four countries,
- The average distances of each country were then calculated, weighted depending on the 'Between countries share' of food production and added up.

Table 33: Distance calculations (km) between manufacturer and food producer for single use corrugated box

France		Italy		Greece		Netherlands		Poland		Spain	
Region	km	Region	km	Region	km	Region	km	Region	km	Region	km
Paris Basin	57[74]	Emilian-Romagna	43[75]	Tessalia[76]	140	Groningen	40	Lódz	45	Castile-Léon	55
Central France	49[77]	Sicily[78]	86	Makedonia	269	Amsterdam	41	Lublin	81	Castile-La Mancha	28
Rueil-Malmaison	4	Lombardia[79]	37	Thrace	539	Rotterdam	55	Kraków	85	Andalusia	12
Roissy En Brie	24	Palagianello	67	Xanthi	497	Enschede	77	Gdynia	148	Valencia	12
Rambouillet	46	Castel Maggiore	46	Sevastian a Skydra's	325	Eindhoven	5	Gorzów Wielkopolski	114	Catalonia	13

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[72] https://www.europages.co.uk/companies/food-processing.html

[73] Members Map | Fefco

[74] Paris: 2 km; Orléans: 40 km; Reims: 10 km; Troyes: 110 km; Chartres: 60 km; Auxerre: 120 km; Rouen: 8 km; Dieppe: 75 km; Le Havre: 85 km

[75] Rimini: 50 km; Ferrara: 45 km; Bologna: 55 km; Modena: 35 km; Parma: 13 km; Reggio Emilia: 35 km; Piacenza: 58 km; Borgo Val di Taro: 60 km; Ravenna: 35 km

[76] Larissa: 143 km; Volos: 177 km; Karditsa: 100 km; Kalabaka: 140 km

[77] Bourges: 30 km; Moulins: 97 km; Clermont-Ferrand: 65 km; Saint-Étienne: 40 km; Limoges: 10 km

[78] Trapani: 313 km; Messina: 112 km; Agrigento: 163 km; Pachino: 100 km

[79] Cremona: 68 km; Brescia: 35 km; Pavia: 23 km; Sondrio: 65 km; Livigno: 92 km; Milano: 1 km; Como: 6 km; Varese: 32 km; Lecco: 13 km

France		Italy		Greece		Netherlands		Poland		Spain	
		Nocera Inferiore	31					Paczewo	63	Madrid	6
								Toamszow Lubelski	98	Lugo	78
								Swidnica	81	Zaragoza	2
										Barcelona	5
										Sevilla	10
Average (km)											
36		52		273		44		89		22	
Average distance weight depending on 'Between countries share' (km)											
4.78		13.37		12.34		3.42		12.24		7.70	
SUM: 53.75 km rounded to 55 km											

Food producer – distribution center

The distances from the food producer to the distribution can be divided into export and domestic distances. The following calculation steps calculate these individually and are added up in the end.

- Accumulation of Europe's top six food and vegetable producing countries, and their top five export countries[80];
- For all of these countries, a city is chosen approximatively in the middle of the country; the distance between these two locations is used for the calculation in Table 34;
- The average export distance is calculated depending on the countries export share.

Table 34: Export distance calculations (km) between food producer and distribution

	Bourges (France)	Rome (Italy)	Larissa (Greece)	Utrecht (Netherlands)	Lódz (Poland)	Madrid (Spain)
Erfurt (Germany)	1009	1318	1989	551	969	2105
Rome (Italy)	1269		1054	1605		1962
Brussels (Belgium)	551					
Madrid (Spain)	1187	1962				1743
Utrecht (Netherlands)	713					
Bourges (France)		1269		713		1187
Liezen (Austria)		960				
Brasov (Romania)			948		1213	
Stara Zagora (Bulgaria)			575			
Lódz (Poland)		1666	1740	1079		
York (UK)				665	1727	2046

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[80] https://www.fruitlogistica.com/fruit-logistica/downloads-alle-sprachen/auf-einen-blick/european_statistics_handbook_2021.pdf

Minsk (Belarus)					674	
Cherkasy (Ukraine)					1108	
Average export distance	945.8	1435	1261.2	922.6	1138.2	1808.6
Export distance depending on export share	254.5	361.7	278.0	461.3	159.5	1104.5

- A distance for domestically transported fruits and vegetables: a city is selected in the middle of the Country and one at the outer border, assuming that this represents an average travel distance in Table 35;
- The average domestic distance is calculated depending on the countries domestic share.

Table 35: Domestic distance calculations (km) between food producer and distribution

	Bourges (France)	Rome (Italy)	Larissa (Greece)	Utrecht (Netherlands)	Lódz (Poland)	Madrid (Spain)
Milan (Italy)		571				
Gibraltar (Spain)						215
Roermond (Netherlands)				137		
Montpellier (France)	514					
Szczecin (Poland)					461	
Domestic distance depending on domestic share	375.7	427.1	276.0	68.5	396.4	83.7

Finally, the total distance between the food producer and distribution is calculated in Table 36.

Table 36: Total distance calculations (km) between food producer and distribution

	France	Italy	Greece	Netherlands	Poland	Spain
Export distance according to export share	254.5	361.7	278.0	461.3	159.5	1104.5
Domestic distance according to domestic share	375.7	427.1	276.0	68.5	396.4	83.7
Distance	630.2	788.8	553.9	529.8	555.9	1188.2
Total distance depending on 'Between countries share': 844.7 rounded to 840 km						

Distribution – Service center

The distance calculations between the distribution and service center are shown in Table 37 and further explained below:

- Distances to the closest recycling center were measured; the location of the recycling centers was given by Euro Pool System[81];
- Finding a city that is around mid-distance to the Euro Pool recycling center in that given country, if more recycling centers, then two with the median distance were chosen;
- The distances were weighted according to the country size citizens.

Table 37: Distance calculations (km) between distribution and service center

	France	Italy	Greece	Netherlands	Poland	Spain
	4 centers	7 centers	2 centers			
Distance	208.5	114.5	136.25	63	298	99.25
Country size citizens (million)	67	60	11	17	38	45
Share (percent)	28.15	25.21	4.62	7.1	15.96	18.9
Weighted total distance: 165 km						

Service center – food producer

The distance calculations between the service center and food producer are equal to the domestic distance calculations between food producers and distribution centers. Additionally, the domestic distance according to domestic shares are calculated according to 'Between the countries share' and added up.

Table 38: Distance calculations (km) between service center and food producer

	Bourges (France)	Rome (Italy)	Larissa (Greece)	Utrecht (Netherlands)	Lódz (Poland)	Madrid (Spain)
Milan (Italy)		571				
Gibraltar (Spain)						215
Roermond (Netherlands)				137		
Montpellier (France)	514					
Szczecin (Poland)					461	
Domestic distance depending on domestic share	375.7	427.1	276.0	68.5	396.4	83.7
Total domestic distance depending on 'Between country shares': 380.3 km rounded to 380 km						

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[81] https://www.europoolsystem.com/about-us/depot-information

By taking into account distance routes presented in Table 30, the following table presents these distance routes referred to a single box/crate.

Table 39: Distances (km) calculated per functional unit

	Single-use system (CB)			Multiple-use system (RPC)		
	distances (km)	n-times	distances (km) per f.u.	distances (km)	n-times	distances (km) per f.u.
Transport routes						
manufacturer - food producer	55	1	55	370	1/24	15,42
food producer - distribution center	840	1	840	840	1	840
distribution - retailer	50	1	50	50	1	50
retailer - distribution center	n.a.	1	n.a.	50	1	50
distribution - service center (washing and sanitizing)	n.a.	1	n.a.	165	1	165
service center - food producer	n.a.	1	n.a.	380	1	380
Transport routes (EoL)						
EoL recycling (CB: after each use; RPC: after the last route at end of lifespan)	150	1	150	840	1/24	35,00
EoL incineration (CB: after each use; RPC: after the last route at end of lifespan)	50	1	50	50	1/24	2,08
Overall distances of one box / crate (km)			1.145,0			1.537,5

APPENDIX 3: ENVIRONMENTAL IMPACTS IN THE BASELINE SCENARIO

Single-use system (CB): Impact categories	Raw material production and manufacturing	Transport	EoL incineration	EoL recycling	Avoided emissions (material)	Avoided emissions (energy)	Aggregated total
EF 2.0 Acidification [Mole of H+ eq.]	2,975E-01	7,419E-03	5,018E-03	2,345E-02	-1,818E-01	-8,779E-03	1,428E-01
EF 2.0 Climate Change - total [kg CO2 eq.]	5,915E+01	3,542E+00	4,724E-01	6,997E+00	-2,752E+01	-7,941E+00	3,470E+01
EF 2.0 Climate Change, biogenic [kg CO2 eq.]	2,844E-01	1,060E-02	1,780E-03	1,009E-02	-5,456E-01	-8,762E-03	-2,475E-01
EF 2.0 Climate Change, fossil [kg CO2 eq.]	5,871E+01	3,503E+00	4,701E-01	6,905E+00	-2,690E+01	-7,931E+00	3,476E+01
EF 2.0 Climate Change, land use and land use change [kg CO2 eq.]	1,500E-01	2,894E-02	5,376E-04	8,161E-02	-7,618E-02	-8,113E-04	1,841E-01
EF 2.0 Ecotoxicity, freshwater [CTUe]	5,558E+00	5,521E-01	2,822E-02	1,460E+01	-1,694E+01	-1,806E-01	3,617E+00
EF 2.0 Eutrophication, freshwater [kg P eq.]	1,627E-03	1,052E-05	7,044E-07	9,653E-04	-2,086E-02	-1,824E-06	-1,826E-02
EF 2.0 Eutrophication, marine [kg N eq.]	1,446E-01	3,123E-03	1,833E-03	1,095E-02	-4,900E-02	-2,722E-03	1,088E-01
EF 2.0 Eutrophication, terrestrial [Mole of N eq.]	1,265E+00	3,532E-02	2,280E-02	9,334E-02	-4,128E-01	-2,955E-02	9,740E-01
EF 2.0 Human toxicity, cancer [CTUh]	1,705E-07	2,387E-08	1,258E-09	1,019E-07	-6,319E-07	-4,578E-09	-3,390E-07
EF 2.0 Human toxicity, non-cancer [CTUh]	4,211E-06	3,097E-07	3,038E-08	6,065E-07	-5,514E-06	-2,261E-07	-5,826E-07
EF 2.0 Ionising radiation, human health [kBq U235 eq.]	5,212E+00	1,255E-02	4,478E-02	4,934E-01	-1,085E+01	-1,934E+00	-7,026E+00
EF 2.0 Ozone depletion [kg CFC-11 eq.]	4,896E-10	6,978E-16	3,432E-15	1,423E-07	-2,299E-06	-4,470E-14	-2,156E-06
EF 2.0 Particulate matter [Disease incidences]	4,800E-06	4,523E-08	2,784E-08	1,593E-07	-1,915E-06	-8,011E-08	3,037E-06
EF 2.0 Photochemical ozone formation, human health [kg NMVOC eq.]	4,152E-01	6,617E-03	4,824E-03	1,375E-02	-1,138E-01	-7,848E-03	3,188E-01
EF 2.0 Resource use, fossils [MJ]	8,040E+02	4,716E+01	6,048E+00	7,284E+01	-5,424E+02	-1,493E+02	2,384E+02
EF 2.0 Resource use, mineral and metals [kg Sb eq.]	1,418E-05	3,128E-07	5,496E-08	2,835E-05	-1,562E-04	-6,878E-07	-1,140E-04
EF 2.0 Water use [m^3 world equiv.]	1,800E+01	3,296E-02	2,198E+00	6,964E+00	-4,008E+01	-3,170E-01	-1,320E+01

Multiple-use system (RPC): Impact categories	**Raw material production and manufacturing**	**Transport**	**Washing centre (multiple-use)**	**EoL incineration**	**EoL recycling**	**Avoided emissions (material)**	**Avoided emissions (energy)**	**Aggregated total**
EF 2.0 Acidification [Mole of H+ eq.]	4,460E-02	1,839E-02	5,520E-02	1,340E-03	3,880E-03	-1,290E-02	-1,455E-02	9,596E-02
EF 2.0 Climate Change - total [kg CO2 eq.]	1,700E+01	8,489E+00	2,424E+01	1,310E+01	2,590E+00	-4,400E+00	-1,308E+01	4,794E+01
EF 2.0 Climate Change, biogenic [kg CO2 eq.]	5,770E-02	2,543E-02	3,864E-02	4,760E-04	8,590E-03	-1,060E-03	-1,431E-02	1,155E-01
EF 2.0 Climate Change, fossil [kg CO2 eq.]	1,690E+01	8,391E+00	2,222E+01	1,310E+01	2,580E+00	-4,400E+00	-1,304E+01	4,576E+01
EF 2.0 Climate Change, land use and land use change [kg CO2 eq.]	5,760E-03	6,949E-02	1,901E+00	1,490E-04	2,400E-03	-8,550E-06	-1,349E-03	1,977E+00
EF 2.0 Ecotoxicity, freshwater [CTUe]	7,120E+00	1,323E+00	9,048E+00	7,950E-03	1,950E+00	-2,160E+00	-3,011E-01	1,699E+01
EF 2.0 Eutrophication, freshwater [kg P eq.]	5,900E-04	2,520E-05	7,536E-04	1,600E-07	1,220E-04	-1,370E-04	-3,038E-06	1,351E-03
EF 2.0 Eutrophication, marine [kg N eq.]	1,050E-02	7,807E-03	3,312E-02	2,880E-04	1,170E-03	-2,940E-03	-4,497E-03	4,545E-02
EF 2.0 Eutrophication, terrestrial [Mole of N eq.]	1,110E-01	8,817E-02	2,568E-01	6,280E-03	1,200E-02	-3,180E-02	-4,878E-02	3,937E-01
EF 2.0 Human toxicity, cancer [CTUh]	8,390E-08	5,723E-08	1,078E-07	3,910E-10	8,810E-08	-1,650E-08	-7,568E-09	3,133E-07
EF 2.0 Human toxicity, non-cancer [CTUh]	5,900E-07	7,435E-07	6,840E-07	6,040E-09	1,530E-07	-1,420E-07	-3,714E-07	1,663E-06
EF 2.0 Ionising radiation, human health [kBq U235 eq.]	2,110E+00	2,990E-02	1,574E+00	1,450E-02	3,360E-01	-1,490E-01	-3,236E+00	6,793E-01
EF 2.0 Ozone depletion [kg CFC-11 eq.]	4,520E-08	1,665E-15	9,432E-08	9,860E-16	3,250E-08	-4,950E-10	-7,474E-14	1,715E-07
EF 2.0 Particulate matter [Disease incidences]	5,074E-07	1,115E-07	4,189E-07	7,914E-09	4,177E-08	-1,544E-07	-1,327E-07	8,003E-07
EF 2.0 Photochemical ozone formation, human health [kg NMVOC eq.]	4,671E-02	1,644E-02	4,709E-02	8,439E-04	3,340E-03	-1,471E-02	-1,299E-02	8,672E-02
EF 2.0 Resource use, fossils [MJ]	5,831E+02	1,131E+02	1,862E+02	1,732E+00	2,616E+01	-1,880E+02	-2,461E+02	4,762E+02
EF 2.0 Resource use, mineral and metals [kg Sb eq.]	5,109E-06	7,504E-07	3,163E-05	1,571E-08	5,270E-06	-1,454E-07	-1,141E-06	4,148E-05
EF 2.0 Water use [m^3 world equiv.]	1,061E+01	7,868E-02	2,674E+00	1,210E+00	4,239E-01	-3,637E+00	-5,325E-01	1,083E+01

APPENDIX 4: CONTRIBUTION TO THE TOTAL IMPACTS (PEF METHOD)

According to the Product Environmental Footprint Category Rules Guidance (version 6.3) the contribution to the total impacts should be presented using as reference “Impact categories cumulatively contributing at least 80% of the total environmental impact (excluding toxicity related impact categories)”.
By applying this procedure, the results show for:

- **SU system**: the most relevant impact categories are Climate Change, total, Eutrophication, freshwater, Eutrophication, terrestrial, Particulate matter, Photochemical ozone formation, human health and Resource use, fossils. These categories have a cumulative contribution of 80.1% of the total impact, based on the normalized and weighted results, and excluding the toxicity related impacts,
- **MU system**: the most relevant impact categories are Climate Change, total, Particulate matter and Resource use, fossils. These categories have a cumulative contribution of 80.3% of the total impact, based on the normalized and weighted results, and excluding the toxicity related impacts.

Single-use system - Impact category	Contribution to the total impact (%), excluding toxicity impact categories
EF 2.0 Acidification [Mole of H+ eq.]	5,2%
EF 2.0 Climate Change - total [kg CO2 eq.]	30,8%
EF 2.0 Eutrophication, freshwater [kg P eq.]	6,5%
EF 2.0 Eutrophication, marine [kg N eq.]	3,7%
EF 2.0 Eutrophication, terrestrial [Mole of N eq.]	6,7%
EF 2.0 Ionising radiation, human health [kBq U235 eq.]	2,7%
EF 2.0 Ozone depletion [kg CFC-11 eq.]	0,2%
EF 2.0 Particulate matter [Disease incidences]	14,0%
EF 2.0 Photochemical ozone formation, human health [kg NMVOC eq.]	12,3%
EF 2.0 Resource use, fossils [MJ]	9,9%
EF 2.0 Resource use, mineral and metals [kg Sb eq.]	4,9%
EF 2.0 Water use [m³ world equiv.]	3,2%

Multiple-use system - Impact category	Contribution to the total impact (%), excluding toxicity impact categories
EF 2.0 Acidification [Mole of H+ eq.]	4,3%
EF 2.0 Climate Change - total [kg CO2 eq.]	51,7%
EF 2.0 Eutrophication, freshwater [kg P eq.]	0,6%
EF 2.0 Eutrophication, marine [kg N eq.]	1,9%
EF 2.0 Eutrophication, terrestrial [Mole of N eq.]	3,3%
EF 2.0 Ionising radiation, human health [kBq U235 eq.]	0,3%
EF 2.0 Ozone depletion [kg CFC-11 eq.]	0,02%
EF 2.0 Particulate matter [Disease incidences]	4,5%
EF 2.0 Photochemical ozone formation, human health [kg NMVOC eq.]	4,1%
EF 2.0 Resource use, fossils [MJ]	24,1%
EF 2.0 Resource use, mineral and metals [kg Sb eq.]	2,1%
EF 2.0 Water use [m³ world equiv.]	3,2%

APPENDIX 5: SENSITIVITY ANALYSIS, RESULTS

					EoL allocation							
	Baseline scenario		CFF (A=0,2)		0:100 approach (CUT OFF)		50:50 approach		Avoided emissions (78% chemical, 22% mechanical)		Avoided emissions (wet pumpable pulp)	
	Single-use	Multiple-use	Single-use	Multiple-use	Single-use	Multiple-use	Single-use	Multiple-use	Single-use	Multiple-use	Single-use	Multiple-use
EF Acidification [Mole of H+ eq.]	0,14	0,10	0,17	0,12	0,33	0,12	0,24	0,11	0,20	0,10	0,15	0,10
EF Climate Change - total [kg CO2 eq.]	34,70	47,94	42,20	61,86	70,16	65,42	52,43	56,68	45,85	47,94	46,35	47,94
EF Climate Change, biogenic [kg CO2 eq.]	-0,25	0,12	-0,08	0,11	0,31	0,13	0,03	0,12	0,01	0,12	-0,23	0,12
EF Climate Change, fossil [kg CO2 eq.]	34,76	45,76	42,15	59,65	69,59	63,20	52,18	54,48	45,64	45,76	46,39	45,76
EF Climate Change, land use and land use change [kg CO2 eq.]	0,18	1,98	0,13	1,98	0,26	1,98	0,22	1,98	0,20	1,98	0,18	1,98
EF Ecotoxicity, freshwater [CTUe]	3,62	16,99	-4,68	17,78	20,74	19,45	12,18	18,22	8,29	16,99	3,71	16,99
EF Eutrophication, freshwater [kg P eq.]	-1,83E-02	1,35E-03	-1,22E-02	1,33E-03	2,60E-03	1,49E-03	-7,83E-03	1,42E-03	-8,29E-03	1,35E-03	-1,83E-02	1,35E-03
EF Eutrophication, marine [kg N eq.]	0,11	0,05	0,11	0,05	0,16	0,05	0,13	0,05	0,12	0,05	0,11	0,05
EF Eutrophication, terrestrial [Mole of N eq.]	0,97	0,39	0,98	0,45	1,42	0,47	1,20	0,43	1,06	0,39	1,01	0,39
EF Human toxicity, cancer [CTUh]	-3,39E-07	3,13E-07	-2,26E-07	2,98E-07	2,98E-07	3,37E-07	-2,07E-08	3,25E-07	-1,43E-07	3,13E-07	-3,34E-07	3,13E-07
EF Human toxicity, non-cancer [CTUh]	-5,83E-07	1,66E-06	7,17E-07	2,03E-06	5,16E-06	2,18E-06	2,29E-06	1,92E-06	1,27E-06	1,66E-06	-2,17E-07	1,66E-06
EF Ionising radiation, human health [kBq U235 eq.]	-7,03	0,68	-2,22	3,57	5,76	4,06	-0,63	2,37	-1,70	0,68	-7,02	0,68
EF Ozone depletion [kg CFC-11 eq.]	-2,16E-06	1,72E-07	-1,52E-06	1,48E-07	1,43E-07	1,72E-07	-1,01E-06	1,72E-07	-1,53E-06	1,72E-07	-2,16E-06	1,72E-07
EF Particulate matter [Disease incidences]	3,04E-06	8,00E-07	3,37E-06	9,96E-07	5,03E-06	1,09E-06	4,03E-06	9,44E-07	2,79E-06	8,00E-07	3,11E-06	8,00E-07
EF Photochemical ozone formation, human health [kg NMVOC eq.]	0,32	0,09	0,33	0,11	0,44	0,11	0,38	0,10	0,34	0,09	0,33	0,09
EF Resource use, fossils [MJ]	238,37	476,23	459,48	811,16	930,05	910,30	584,21	693,27	480,72	476,23	435,02	476,23
EF Resource use, mineral and metals [kg Sb eq.]	-1,14E-04	4,15E-05	-8,85E-05	3,99E-05	4,29E-05	4,28E-05	-3,56E-05	4,21E-05	-6,53E-05	4,15E-05	-1,14E-04	4,15E-05
EF Water use [m^3 world equiv.]	-13,20	10,83	-8,97	13,37	27,19	15,00	7,00	12,92	-12,24	10,83	-13,27	10,83

	Energy mix						EoL treatment				Manufacturing
	EU28		Future scenario EU-28 (2030)		Green electricity grid mix		wastepaper recycling (secondary data)		recycling 70% both systems		recycled content (rec40%)
	Single-use	Multiple-use	Single-use	Multiple-use	Single-use	Multiple-use	Single-use	Multiple-use	Single-use	Multiple-use	Multiple-use
EF Acidification [Mole of H+ eq.]	0,14	0,09	0,14	0,10	0,14	0,10	0,15	0,10	0,17	0,09	0,09
EF Climate Change - total [kg CO2 eq.]	35,00	48,25	35,65	49,02	37,45	51,14	45,52	47,94	34,06	43,61	45,60
EF Climate Change, biogenic [kg CO2 eq.]	-0,27	0,09	-0,26	0,10	-0,31	0,04	-0,31	0,12	-0,16	0,12	0,19
EF Climate Change, fossil [kg CO2 eq.]	35,09	46,19	35,73	46,95	37,59	49,14	45,54	45,76	34,03	41,50	43,43
EF Climate Change, land use and land use change [kg CO2 eq.]	0,18	1,97	0,18	1,97	0,17	1,96	0,29	1,98	0,18	1,98	1,98
EF Ecotoxicity, freshwater [CTUe]	3,61	16,96	3,63	16,99	3,63	16,99	-8,36	16,99	3,96	16,90	18,25
EF Eutrophication, freshwater [kg P eq.]	-1,83E-02	1,34E-03	-1,83E-02	1,34E-03	-1,83E-02	1,32E-03	-2,21E-02	1,35E-03	-1,47E-02	1,34E-03	1,85E-03
EF Eutrophication, marine [kg N eq.]	0,11	0,05	0,11	0,05	0,11	0,05	0,10	0,05	0,12	0,05	0,04
EF Eutrophication, terrestrial [Mole of N eq.]	0,97	0,39	0,98	0,40	0,98	0,40	0,91	0,39	1,03	0,39	0,38
EF Human toxicity, cancer [CTUh]	-3,39E-07	3,13E-07	-3,39E-07	3,14E-07	0,00	0,00	-3,79E-07	3,13E-07	-2,45E-07	3,63E-07	4,07E-07
EF Human toxicity, non-cancer [CTUh]	-6,14E-07	1,62E-06	-6,13E-07	1,63E-06	0,00	0,00	-1,07E-06	1,66E-06	1,92E-07	1,76E-06	1,71E-06
EF Ionising radiation, human health [kBq U235 eq.]	-6,71	1,06	-6,10	1,77	-5,49	2,50	-4,39	0,68	-6,31	1,62	0,87
EF Ozone depletion [kg CFC-11 eq.]	-2,16E-06	1,71E-07	-2,16E-06	1,71E-07	-2,16E-06	1,71E-07	-2,23E-06	1,72E-07	-1,77E-06	1,93E-07	3,02E-07
EF Particulate matter [Disease incidences]	3,04E-06	7,97E-07	3,05E-06	8,02E-07	3,06E-06	8,27E-07	2,98E-06	8,00E-07	3,33E-06	7,54E-07	7,39E-07
EF Photochemical ozone formation, human health [kg NMVOC eq.]	0,32	0,09	0,32	0,09	0,32	0,09	4,29	0,09	0,34	0,08	0,08
EF Resource use, fossils [MJ]	252,83	494,03	261,22	503,35	301,61	551,09	481,25	476,23	238,12	428,45	329,99
EF Resource use, mineral and metals [kg Sb eq.]	-1,15E-04	4,10E-05	-1,15E-04	4,07E-05	-1,16E-04	3,88E-05	-7,31E-05	4,15E-05	-9,15E-05	4,52E-05	5,24E-05
EF Water use [m^3 world equiv.]	-13,41	10,59	-13,32	10,67	-13,21	10,83	-22,62	10,83	-5,86	8,21	8,18

	Breakage rate		Washing		Transport distances					
	breakage rate (BR_0.5%)	breakage rate (BR_5%)	optimized detergents	min demand	Transport -50% (both systems)		Transport +50% (both systems)		Less challenging transport for MU (-25%)	
	Multiple-use	Multiple-use	Multiple-use	Multiple-use	Single-use	Multiple-use	Single-use	Multiple-use	Single-use	Multiple-use
EF Acidification [Mole of H+ eq.]	0,10	0,09	0,09	0,09	0,14	0,09	0,15	0,10	0,14	0,09
EF Climate Change - total [kg CO2 eq.]	43,58	53,28	46,71	44,51	32,52	43,75	36,68	52,06	34,70	45,81
EF Climate Change, biogenic [kg CO2 eq.]	0,12	0,11	0,11	0,11	-0,25	0,10	-0,24	0,13	-0,25	0,11
EF Climate Change, fossil [kg CO2 eq.]	41,49	51,19	46,47	43,56	32,93	41,64	36,72	49,92	34,76	43,74
EF Climate Change, land use and land use change [kg CO2 eq.]	1,98	1,98	0,13	0,84	0,17	1,94	0,20	2,01	0,18	1,96
EF Ecotoxicity, freshwater [CTUe]	15,38	18,97	10,00	13,43	3,32	16,34	3,93	17,62	3,62	16,65
EF Eutrophication, freshwater [kg P eq.]	1,34E-03	1,37E-03	1,22E-03	9,26E-04	-1,83E-02	1,34E-03	-1,83E-02	1,36E-03	-1,83E-02	1,35E-03
EF Eutrophication, marine [kg N eq.]	0,05	0,04	0,03	0,04	0,11	0,04	0,11	0,05	0,11	0,04
EF Eutrophication, terrestrial [Mole of N eq.]	0,40	0,38	0,37	0,36	0,95	0,35	1,00	0,43	0,97	0,37
EF Human toxicity, cancer [CTUh]	3,13E-07	3,13E-07	2,87E-07	2,77E-07	-3,51E-07	2,85E-07	-3,26E-07	3,41E-07	-3,39E-07	2,99E-07
EF Human toxicity, non-cancer [CTUh]	1,71E-06	1,60E-06	2,00E-06	1,79E-06	-7,72E-07	1,30E-06	-4,10E-07	2,03E-06	-5,83E-07	1,48E-06
EF Ionising radiation, human health [kBq U235 eq.]	1,78	-0,70	0,42	0,23	-7,03	0,67	-7,02	0,70	-7,03	0,67
EF Ozone depletion [kg CFC-11 eq.]	1,71E-07	1,73E-07	7,36E-07	1,14E-07	-2,16E-06	1,71E-07	-2,16E-06	1,71E-07	-2,16E-06	1,71E-07
EF Particulate matter [Disease incidences]	8,22E-07	7,73E-07	6,79E-07	6,96E-07	3,01E-06	7,47E-07	3,06E-06	8,53E-07	3,04E-06	7,74E-07
EF Photochemical ozone formation, human health [kg NMVOC eq.]	0,09	0,08	0,08	0,08	0,31	0,08	0,32	0,09	0,32	0,08
EF Resource use, fossils [MJ]	549,65	384,46	434,77	436,04	212,00	420,77	264,65	531,69	238,37	448,50
EF Resource use, mineral and metals [kg Sb eq.]	4,18E-05	4,11E-05	2,98E-05	2,25E-05	-1,14E-04	4,11E-05	-1,14E-04	4,19E-05	-1,14E-04	4,13E-05
EF Water use [m³ world equiv.]	9,91	11,98	10,43	8,17	-13,22	10,79	-13,18	10,87	-13,20	10,81