Life Cycle Assessment (LCA) of different packaging solutions for white and brown goods

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Summary

This Life Cycle Assessment (LCA) compares the environmental performance of providing protective packaging for the delivery of white and brown goods with four different packaging solutions. Expanded Polypropylene (EPP), Expanded Polystyrene (EPS), honeycomb paperboard, and molded pulp, are evaluated for the delivery of two products: TV and washing machine.

Several uncertain factors were found to significantly influence the results of the study, including the assumed damage rate during transportation, the mass of the package, and modeling choices, such as whether damaged products during transportation are considered. The relative superiority of one alternative over another depends on how these factors are considered, as well as on the type of product, and the environmental impact category being assessed. The results revealed that the impacts resulting from the damaged products that the packaging solutions fail to protect are the most substantial, accounting for up to 59% of the total impacts on average for washing machines and 72% for TVs. This is followed by the impact of packaging materials, which contribute 24% of the total impact for TVs and 36% for washing machines, and transportation, which accounts for 4% of the total impact for TVs and 5% for washing machines.

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1 Introduction

From 2009 to 2020, the EU experienced a 20% increase in the overall volume of packaging waste generated. The Packaging and Packaging Waste Directive (PPWD – Directive 94/62/EC) outlines strategies to reduce packaging waste production while encouraging the reuse, recycling, and other methods of managing packaging waste. Specifically, for large household appliances, there is a targeted goal of ensuring that 90% of the products are made available in reusable transport packaging by January 2030 (European Parliament, 2023).

Consumer goods like fridges, washing machines, and TVs typically require protective materials for their packaging that ensure safe transportation from the manufacturer to the consumer. Traditionally, Expanded Polystyrene (EPS) has been the go-to material for this purpose. However, due to growing environmental concerns associated with EPS such as energy-intensive production and chemical emissions during the manufacturing process, there are increasing efforts to implement circular collection and advanced recycling processes to repurpose EPS waste, along with innovations in production to reduce its environmental footprint. Meanwhile, manufacturers of protective packaging are transitioning to biobased alternatives such as cardboard or molded pulp. Nonetheless, the shift to these alternative materials does not always ensure environmental benefits. Variations in the quality of protection may increase the amount of material needed and can potentially cause damage or loss of the packaged items, resulting in both economic losses and additional environmental burdens, which can be substantial.

EUMEPS has approached TNO to study the environmental implications of shifting from EPS protective packaging to alternative materials for delivering TVs and washing machines. This research uses a Life Cycle Assessment (LCA) to quantify potential environmental impacts and trade-offs associated with this transition, providing an overall evaluation of each alternative's environmental sustainability. The findings will offer valuable insights to decision-makers, helping them balance environmental considerations, product protection, and economic factors.

The guidelines outlined in ISO 14040 and ISO 14044 (International Organization for Standardization, 2006a, 2006b) were followed to conduct the LCA. The following chapters present in detail the application of the four steps of LCA to this case study: goal and scope definition, calculation of the life cycle inventories (LCI), assessment of the life cycle impacts (LCIA), and interpretation of the results.

2 Goal and Scope Definition

2.1 The goal of the study

2.1.1 The goal

The goal of this study is to evaluate the potential life cycle environmental benefits and drawbacks of different packaging solutions for the delivery of two types of consumer goods: TVs and washing machines. Four packaging solutions are evaluated, namely Expanded Polystyrene (EPS), Expanded Polypropylene (EPP), honeycomb paperboard, and molded pulp.

2.1.2 Intended use

The study results will reveal the environmental impact profiles of each packaging solution, aiding in the identification of their potential benefits and drawbacks. Additionally, the results will highlight the life-cycle stages and processes that are primarily contributing to these environmental impacts.

2.1.3 Reasons for carrying out the study

EUMEPS has approached TNO to conduct this study to assist decision-makers in understanding the implications of transitioning from EPS protective packaging to alternative materials. This study aims to provide a deeper understanding of the potential consequences associated with this shift and to understand the overall environmental sustainability of these alternatives.

2.1.4 Intended audience

This research will be valuable to industrial decision-makers and technical experts, helping them make informed choices in areas such as product development. Additionally, policymakers could utilize the findings to formulate policies based on the environmental implications of different packaging alternatives, taking into account a sustainability perspective.

2.2 The scope of the study

2.2.1 Functional unit

The function of the assessed product systems is defined as providing protective packaging for the delivery of products from the manufacturer to the client in good functioning order. The functional unit is, therefore, defined as follows:

- **For TV:** Providing protective packaging for the delivery of one 50-inch flat-screen TV from the manufacturer to the client by truck in Europe.
- **For washing machine:** Providing protective packaging for the delivery of one 80 kg washing machine from the manufacturer to the client by truck in Europe.

Each reusable package (i.e., EPP) is expected to be reused five times over its lifetime, resulting in a reusability rate of 5. This means the reusable package goes through five reuse cycles, with a total of six use cycles, including the initial use. On the other hand, single-use packages (i.e., EPS, paperboard, and molded pulp) are sent for mechanical recycling after each service cycle, completing 6 life cycles until final disposal. Impact calculations are first made for a total of six service cycles: one initial use plus five direct reuses or instances of mechanical recycling. The impact per functional unit is then calculated as 1/6 of the total impact required for all six service cycles. The comparison is based on a scenario in which the reuse return rate for reusable packages and the recycling collection rate for single-use packages are assumed to be equal. This is not meant to reflect current practices, but rather to serve as an exploratory scenario in which the specified recycle and reuse targets are met. This ensures a fair comparison between the two packaging types, regardless of how accurately these rates reflect real-world conditions. The calculations of the fractions of material and transportation required in each of the six service cycles are further explained in section 0.

2.2.2 Alternative product systems

Four packaging alternatives are considered in this study, each used to provide protection for the delivery of a 50-inch TV, categorized as a brown good, and an 80 kg washing machine, classified as a white good. Four packaging materials were considered for delivery of a TV: EPS, EPP, honeycomb paperboard, and molded pulp. For the delivery of a washing machine, EPS, EPP, and honeycomb paperboard were considered. Molded pulp was excluded for the washing machine as it does not meet the required specifications for the product, according to the client. The use of secondary packaging materials, such as LDPE or additional paper protection, was considered equal in all scenarios and therefore excluded from the study.

2.2.3 System boundaries

The choice of system boundaries is consistent with the goal of the study. It encompasses the phases of materials extraction and manufacturing, transportation (including the distribution and return of the package in the case of reusable packaging), and end-of-life. Europe was chosen as the geographical location for the foreground system. The system boundary, which is similar for all alternatives assessed, is shown in Figure 2.1.

We include the damaged packaged product (TV, washing machine) within the system boundaries to ensure the quality of the packaging material in protecting the product is considered. This means that any product damage resulting from packaging failure is taken into account in the calculation of environmental burdens. This damage is assumed to be total (non-partial), necessitating the full replacement of both the packaging and the product. This approach aligns with recommendations put forth by the European Commission’s Joint Research Centre in the context of food-packaging (Sinkko et al., 2024) and gives consideration to subsequent critiques (Zero Waste Europe, 2023) discussing the adequacy of modeling choices to represent reusable and single-use packaging alternatives in LCA models. The production and EoL treatment of undamaged products were excluded from the system boundaries, as they are equivalent across all scenarios. The protective inner packaging materials and capital goods were also excluded due to their minimal impact and irrelevance to this study.

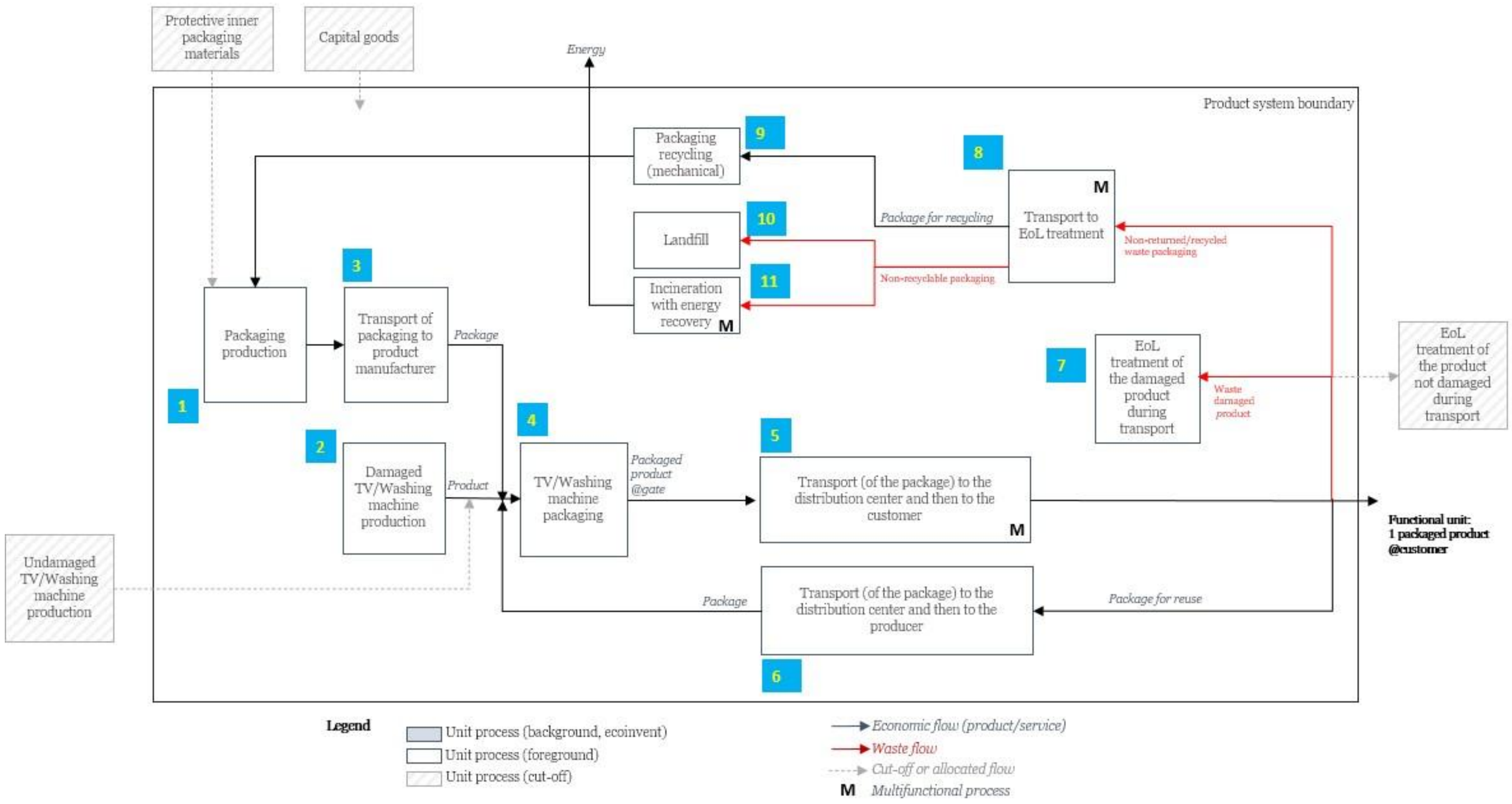


Figure 2.1: The system boundaries of the LCA study

2.2.4 LCIA methodology and types of impacts

The LCA software SimaPro 10.0.0.28 was utilized for this study. The LCIA method Environmental Footprint (EF) 3.1 (adapted) V1.01 (European Commission. Joint Research Centre., 2023) was employed, following the guidelines of the Product Environmental Footprint (PEF) guide and adhering to the Product Environmental Footprint Category Rules (PEFCR) established by the European Commission Joint Research Centre (JRC) (European Commission, 2018).

2.2.5 Data requirements

The ecoinvent 3.10 (ecoinvent, 2024) and Industry data 2.0 (SimaPro, 2023) databases provided the secondary data used in the inventory tables. Regarding the quality of the primary data in the LCA study provided by the client, some data points, such as the mass of the products and packaging, exhibited higher accuracy and reliability. This was because they were derived from EPS manufacturers' data and existing packaging solutions already in use in the market. Additionally, the quality of mechanical recycling was estimated based on industry data, ensuring a reasonable level of credibility. Other primary data, however, exhibited higher levels of uncertainty. For example, the damage rate was determined through internal testing, which involved a considerable degree of uncertainty. Similarly, the reusability rate of reusable packages and the return rate were both based on assumed scenarios rather than direct empirical measurements, introducing an additional layer of uncertainty to the overall assessment. The sources and justification for necessary assumptions for data are listed in Table 3.1 and the LCI tables in Appendix A.

2.2.6 Limitations

The results of this study are valid only for the defined goal and scope. To obtain these results, several modelling choices and assumptions were required. It is important to note that these decisions may constrain the validity of the results and conclusions of the study to the narrow scopes of scenarios represented by the assumptions. This is particularly relevant for the assumed required mass of different packaging materials, their damage rates during transportation, and the return and reusability rates for reusable packaging. Thus, the results and conclusions are subject to change under different sets of assumptions or additional data that may become available after the conclusion of this study.

3 Life Cycle Inventory (LCI)

The LCI data collection and calculations were aligned and established based on the goal and scope of the study, as described in the previous sections. Table A.1 to Table A.72 in Appendix A provides the LCI tables for each foreground process in the assessed product systems. Here is a brief overview of the boxes (unit processes) within the system boundaries:

- **Box 1**: The production of the package (based on market data, including the extraction and transportation of raw materials).
- **Box 2**: The production of the product, applicable only to damaged products. As explained in Section 2.2.3, the production of undamaged products are excluded, as they are identical across all scenarios.
- **Box 3**: Transport of the package from the package manufacturer to the product manufacturer.
- **Box 4**: Placing the product inside the package. This process is manual and does not require energy or material inputs.
- **Box 5**: Transport of the packaged product to the distribution center and then to the customer, fulfilling the functional unit, i.e., the delivery of one packaged product to the customer.
- **Box 6**: For reusable packages, this box represents the transportation of the empty package after use back to the product manufacturer (Box 4). If the reusable package is no longer reusable, it proceeds to Box 8 for EoL treatment.
- **Box 7**: The EoL treatment of products damaged during transport.
- **Box 8**: Transport of the package to the waste treatment center for EoL treatment. This occurs when the package is single-use or no longer reusable and has been collected for waste treatment.
- **Box 9**: Mechanical recycling process, applied when the EoL path of the package is mechanical recycling.
- **Box 10**: Landfill process, applied when the EoL path of the package is landfill.
- **Box 11**: Incineration with energy recovery process, applied when the EoL path of the package is incineration.

Assumptions, data and parameters

Table 3.1 provides an overview of the assumptions used in the LCA study, along with their sources. Explanations of the calculations for each data point are included in the full LCI, presented in Appendix A. Table 3.2 summarizes the material fractions utilized in each service cycle, while Table 3.3 presents the EoL fractions for each service cycle. Table 3.4 outlines the quantities and types of transportation required in each service cycle. The mass balances for all scenarios are provided in Appendix B.

Table 3.1: The main assumptions and data sources of the LCA study

Relevant process in Figure 2.1	**Input parameters**			**Value**	**Unit**	**Source**
	Parameter	**of**	**for**			
1	Mass	EPS	TV	0.33	kg	Primary data from the client
		EPS	Washing machine	0.877	kg	
		EPP	TV	0.45	kg	
		EPP	Washing machine	1.8	kg	
		Paperboard	TV	0.56	kg	
		Paperboard	Washing machine	3.5	kg	
		Molded pulp	TV	1.22	kg	
2	Mass	TV		15	kg	Primary data from the client. The defined mass in the original ecoinvent inventory is 30 kg, so the mass is scaled down.
		Washing machine		80	kg	Primary data from the client. The defined mass in the original ecoinvent inventory is 75 kg, so the mass is scaled up.
3	Transport	Packaging	Transport of the package to the product manufacturer	20	km	Assumed to be 20 km, by 3.5-7.5 t truck EUR0 3
5	Packaged product		Between the product manufacturer and the	1200	km	>32 t truck EUR0 4 according to the PEF (section 7.14.3), (European Commission, 2018)

			distribution center			
			Between the distribution center and the customer	125	km	250 km roundtrip by 3.5-7.5 t truck EURO 3 according to the PEF (section 7.14.3), (European Commission, 2018)
6	Reusability rate	EPP		5		Primary data from the client. It refers to the number of times the package can be reused.
	Reuse return rate	Reusable package (EPP)		70	%	Primary data from the client. It represents the percentage of customers who return the package for reuse by the product manufacturer
	Packaged product		Between the customer and the distribution center	125	km	250 km roundtrip by 3.5-7.5 t truck EURO 3 according to the PEF (section 7.14.3), (European Commission, 2018)
			Between the distribution center and the product manufacturer	1200	km	>32 t truck EURO 4 according to the PEF (section 7.14.3), (European Commission, 2018)
7	Damage rate	EPS		0.8	%	Primary data from the client
		EPP		0.8	%	
		Paperboard		1.25	%	
		Molded pulp		1.25	%	
8	Recycling collection rate	All packages		70	%	The recycling collection rate of the package transported to the waste treatment center is assumed to be equal to the reuse return rate for the reusable package, as both reflect post-use customer behavior with the package.
	Transport	Non-returned	Transport to EoL treatment	10	km	Assumed to be 10 km, by 3.5-7.5 t truck EURO 3

		waste packaging				
9	EoL path fractions of the packages after the 6th service cycle (In the previous cycles: reuse for EPP, mechanical recycling for EPS, paperboard, and molded pulp)	Mechanical recycling fraction	EPS and EPP	0.38		38% recycled (EUMEPS, 2021), all mechanical recycled
			Paperboard and molded pulp	0.815		81.5% recycled (Eurostat, 2024), all mechanical recycling
10	EoL path fractions of the packages after the 6th service cycle (In the previous cycles: reuse for EPP, mechanical recycling for EPS, paperboard, and molded pulp)	Landfill fraction	EPS and EPP	0.24		(EUMEPS, 2021)
			Paperboard and molded pulp	0.093		(Eurostat, 2024)
11	EoL path fractions of the packages after the 6th service cycle (In the previous cycles: reuse for EPP, mechanical recycling for EPS,	Incineration and energy recovery fraction	EPS and EPP	0.38		(EUMEPS, 2021)
			Paperboard and molded pulp	0.092		(Eurostat, 2024)

	paperboard, and molded pulp)					
	LHV	EPS		32.2	MJ/kg	(Dutch Environmental Database (NMD), 2022)
		EPP		44	MJ/kg	(ARPRO, 2018)
		Paperboard		15.92	MJ/kg	(Dutch Environmental Database (NMD), 2022)
		Molded pulp		15.92	MJ/kg	(Dutch Environmental Database (NMD), 2022)
	Efficiency	Electricity efficiency of Waste-to-Energy plant	Incineration and energy recovery	0.18		(Dutch Environmental Database (NMD), 2022)
		Heat efficiency of Waste-to-Energy plant		0.31		(Dutch Environmental Database (NMD), 2022)
12	Recycling return rate	Single-use packages (EPS, paperboard, molded pulp)		70	%	It represents the percentage of customers who return the package for intermediate recycling by the product manufacturer. The value was considered to be equal to the reuse return rate explained above for the process 6
	The quality factor	Mechanical recycling	EPS	0.995		Primary data from the client, check Table 3.2 for the fractions of virgin and recycled materials
			EPP	0.995		
			Paperboard	0.9		
			Molded pulp	0.9		

Table 3.2: Fractions of materials used in each service cycle

Service cycle	Fraction	Single-use			Reusable
		EPS	Molded pulp	Paperboard	EPP
1st	Virgin	1	1	1	1
	Recycled	-	-	-	-
	Reused	-	-	-	-
2nd	Virgin	0.3035	0.37	0.37	0.3
	Recycled	0.6965	0.63	0.63	-
	Reused	-	-	-	0.7
3rd	Virgin	0.3035	0.37	0.37	0.3
	Recycled	0.6965	0.63	0.63	-
	Reused	-	-	-	0.7
4th	Virgin	0.3035	0.37	0.37	0.3
	Recycled	0.6965	0.63	0.63	-
	Reused	-	-	-	0.7
5th	Virgin	0.3035	0.37	0.37	0.3
	Recycled	0.6965	0.63	0.63	-
	Reused	-	-	-	0.7
6th	Virgin	0.3035	0.37	0.37	0.3
	Recycled	0.6965	0.63	0.63	-
	Reused	-	-	-	0.7
Total material fraction in 6 service cycles excluding the damage rate	**Virgin**	**2.52**	**2.85**	**2.85**	**2.50**
	Recycled	**3.48**	**3.15**	**3.15**	**0**
	Reused	**0**	**0**	**0**	**3.50**
Total material fraction in 6 service cycles including the damage rate	**Virgin**	**2.54**	**2.89**	**2.89**	**2.52**
	Recycled	**3.51**	**3.19**	**3.19**	**0**
	Reused	**0**	**0**	**0**	**3.53**
Total material fraction per FU excluding the damage rate	**Virgin**	**0.42**	**0.48**	**0.48**	**0.42**
	Recycled	**0.59**	**0.53**	**0.53**	**0**
	Reused	**0**	**0**	**0**	**0.59**
Total material fraction per FU including the damage rate	**Virgin**	**0.42**	**0.48**	**0.48**	**0.42**
	Recycled	**0.59**	**0.53**	**0.53**	**0**
	Reused	**0**	**0**	**0**	**0.59**

Table 3.3: EoL fractions in each service cycle

Service cycle	EoL fraction	Single-use			Reusable
		EPS	Molded pulp	Paperboard	EPP
1st	Mechanical	0.81	0.94	0.94	0.11
	Landfill	0.07	0.03	0.03	0.07
	Incineration	0.11	0.03	0.03	0.11
	Reuse	0	0	0	0.70
2nd	Mechanical	0.81	0.94	0.94	0.11
	Landfill	0.07	0.03	0.03	0.07
	Incineration	0.11	0.03	0.03	0.11
	Reuse	0	0	0	0.70
3rd	Mechanical	0.81	0.94	0.94	0.11
	Landfill	0.07	0.03	0.03	0.07
	Incineration	0.11	0.03	0.03	0.11
	Reuse	0	0	0	0.70
4th	Mechanical	0.81	0.94	0.94	0.11
	Landfill	0.07	0.03	0.03	0.07
	Incineration	0.11	0.03	0.03	0.11
	Reuse	0	0	0	0.70
5th	Mechanical	0.81	0.94	0.94	0.11
	Landfill	0.07	0.03	0.03	0.07
	Incineration	0.11	0.03	0.03	0.11
	Reuse	0	0	0	0.70
6th	Mechanical	0.38	0.82	0.82	0.38
	Landfill	0.24	0.09	0.09	0.24
	Incineration	0.38	0.09	0.09	0.38
	Reuse	0	0	0	0
Total EoL fractions in 6 service cycles	Mechanical	4.45	5.54	5.54	0.95
	Landfill	0.60	0.23	0.23	0.60
	Incineration	0.95	0.23	0.23	0.95
	Reuse	0	0	0	3.50
Total material fraction per FU	Mechanical	0.74	0.92	0.92	0.16
	Landfill	0.10	0.04	0.04	0.10
	Incineration	0.16	0.04	0.04	0.16
	Reuse	0	0	0	0.58

Table 3.4: Quantity and types of transportation required in each service cycle

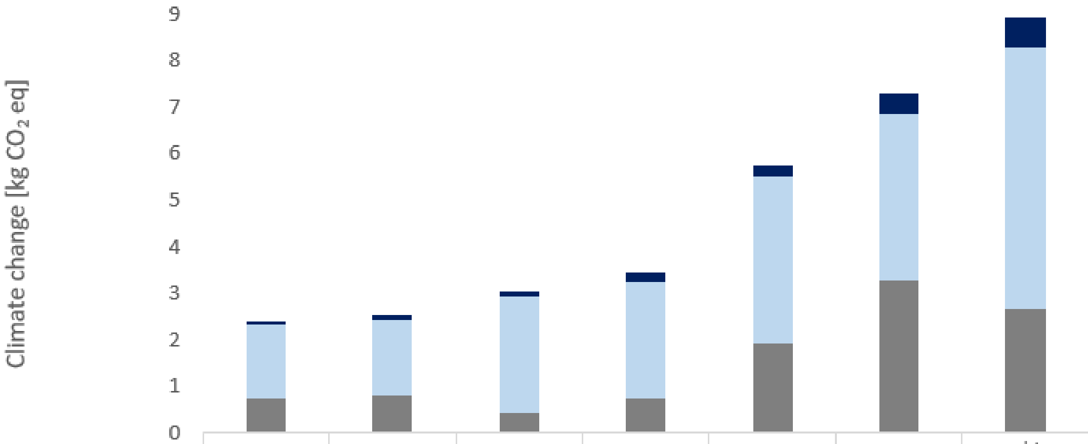
Service cycle	Transport process box	Single-use			Reusable
		EPS	Molded pulp	Paperboard	EPP
1st	3	1			1
	5	1			1
	6	0			0.7
	8	0.3			0.3
2nd	3	1			0
	5	1			1
	6	0			0.7
	8	0.3			0.3
3rd	3	1			0
	5	1			1
	6	0			0.7
	8	0.3			0.3
4th	3	1			0
	5	1			1
	6	0			0.7
	8	0.3			0.3
5th	3	1			0
	5	1			1
	6	0			0.7
	8	0.3			0.3
6th	3	1			0
	5	1			1
	6	0			0
	8	1			1
Total in 6 service cycles (excluding damage)	3	**6**	**6**	**6**	**1**
	5	**6**	**6**	**6**	**6**
	6	**0**	**0**	**0**	**3.5**
	8	**2.5**	**2.5**	**2.5**	**2.5**
Total in 6 service cycles (including damage)	3	**6.05**	**6.08**	**6.08**	**1.01**
	5	**6.05**	**6.08**	**6.08**	**6.05**
	6	**0**	**0**	**0**	**3.53**
	8	**2.52**	**2.53**	**2.53**	**2.52**
Total per FU (including damage)	3	**1.01**	**1.01**	**1.01**	**0.17**
	5	**1.01**	**1.01**	**1.01**	**1.01**
	6	**0.00**	**0.00**	**0.00**	**0.59**
	8	**0.42**	**0.42**	**0.42**	**0.42**

3.1 Multifunctionality

According to ISO 14044 standard (International Organization for Standardization, 2006b), allocation was avoided for multifunctional processes whenever possible. In such cases, substitution was applied, as with incineration with energy recovery, by crediting heat and energy recovery (box 11). Two additional multifunctional processes were identified, as indicated in figure 2.1, boxes 5 and 8. In these cases, a package for reuse and a package for recycling, respectively, come out as byproducts. Both these byproducts flow into a closed-loop which stays within the product system, thus no allocation, system expansion or substitution strategy was required.

4 Life Cycle Impact Assessment (LCIA)

Figure 4.1 compares the total climate change impacts of the assessed packaging solutions across their entire life cycles, based on the functional unit defined in section 2.2.1. The impact scores for all environmental impact categories are also reported separately for the packaging material (Table C1), damaged product (Table C2), transportation (Table C3), and total impacts (Table C4), in Appendix C.



	TV delivery with EPS package	TV delivery with EPP package	TV delivery with paperboard package	TV delivery with molded pulp package	washing machine delivery with EPS package	washing machine delivery with EPP package	washing machine delivery with paperboard package
Transport	0.06	0.10	0.11	0.20	0.21	0.42	0.64
Damaged product	1.60	1.60	2.50	2.50	3.62	3.62	5.65
Packaging material	0.71	0.81	0.42	0.75	1.90	3.26	2.64
Sum	2.38	2.51	3.03	3.45	5.73	7.29	8.94

Figure 4.1: Comparison of the overall climate change impacts of different alternatives

When examining the overall climate change impacts of the delivered packaged TV product, it can be seen that the delivery of TV with the EPS package shows the best performance (2.38 kg CO_2 eq), followed by the delivery with the EPP package (2.51 kg CO_2 eq), delivery with the paperboard package (3.03 kg CO_2 eq), and then delivery with the molded pulp package (3.45 kg CO_2 eq). Similarly for washing machine, delivery with the EPS package has the lowest climate change impacts (5.73 kg CO_2 eq), followed by delivery with the EPP package (7.29 kg CO_2 eq), and delivery with the paperboard package (8.94 kg CO_2 eq).

Focusing solely on the impacts of the packaging material for TV, delivery with the paperboard package demonstrates the best performance at 0.42 kg CO_2 eq, followed by delivery with the EPS package at 0.71 kg CO_2 eq, molded pulp at 0.75 kg CO_2 eq, and then delivery with the EPP package at 0.81 kg CO_2 eq. However, for washing machine packaging, delivery with the EPS package performs the best at 1.90 kg CO_2 eq, followed by delivery with the paperboard package at 2.64 kg CO_2 eq, and delivery with the EPP package at 3.26 kg CO_2 eq. The difference between the climate change impacts of delivery with the EPS and EPP packages for washing machines is notable, which can be linked to the significantly higher mass of EPP packaging (1.80 kg) compared to EPS packaging (0.88 kg).

The choice of packaging material is, however, causally linked to the impacts of the damaged products. The climate change impacts of the expected damaged products, given the assumptions explained in section 3, are 1.60 kg CO2 eq for the delivery of the TVs packaged in EPS and EPP, and 2.50 kg CO2 eq for those packaged in paperboard and molded pulp. The difference in climate change impacts is attributed to the lower damage rates of deliveries with EPS and EPP packages (0.8%) compared to those with paperboard and molded pulp (1.25%). Similarly, for washing machines, deliveries with the EPS and EPP packages have lower climate change impacts at 3.62 kg CO2 eq, compared to 5.65 kg CO2 eq for delivery with the paperboard package. However, it is important to note that these differences in product damage also lead to the need for additional products and transport, which affects other related impacts.

In terms of transportation impacts for TV, delivery with the EPS package has the lowest climate change impact (0.06 kg CO_2 eq), with delivery with the EPP package at 0.10 kg CO_2 eq, delivery with the paperboard package at 0.11 kg CO_2 eq, and delivery with the molded pulp package at 0.20 kg CO_2 eq. For transportation impacts of washing machine, delivery with the EPS package shows the lowest impact (0.21 kg CO_2 eq), followed by delivery with the EPP package (0.42 kg CO_2 eq) and delivery with the paperboard package (0.64 kg CO_2 eq). This consistent trend across both products is driven by the lighter mass of EPS packaging, which results in lower transportation emissions. Additionally, the higher transportation impact of delivery with the EPP package is partly due to the extra transport needed for returning used packaging.

Figure 4.2 illustrates the percentage contributions of packaging material, damaged product, and transportation to the overall climate change impacts of each option. For all packaging alternatives, the transportation impacts are significantly lower compared to the packaging material impacts and the damage to products that occurs during transportation, depending on the type of packaging. The transportation impacts are 4% for TV and 5% for washing machine, while the packaging material impacts account for around 24% of the total impact for TV and 36% for washing machine. Damage to products during transportation represents an impact of 72% for TV and 59% for washing machines. These values highlight the importance of taking the damage during transportation into account. It should be noted that the transportation impacts consider only the mass of the packaging and the damaged product, excluding the transportation of undamaged products, as specified in the system boundaries (Section 2.2.3).

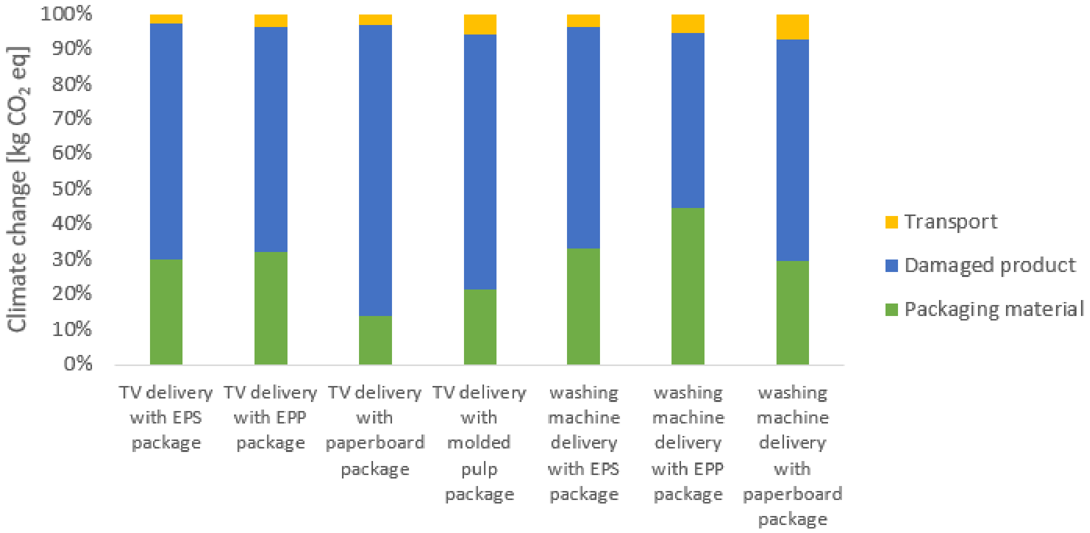


Figure 4.2: Contributions of packaging material, damaged product, and transport to overall climate change impacts of different alternatives.

Figure 4.3 and Figure 4.4 compare the total impact of deliveries in different packaging alternatives across their entire life cycles in all environmental impact categories studied for TV and washing machines, respectively. Similar to the climate change impact category (Figure 4.1), deliveries in the molded pulp and then paperboard packages show the highest impacts in all categories. It can also be observed that delivery with the EPP package shows a higher impact than delivery with the EPS package in all impact categories, except for water use. It should be noted that these comparisons account for the total impact, including the effects of the packaging material, damaged products, and transportation.

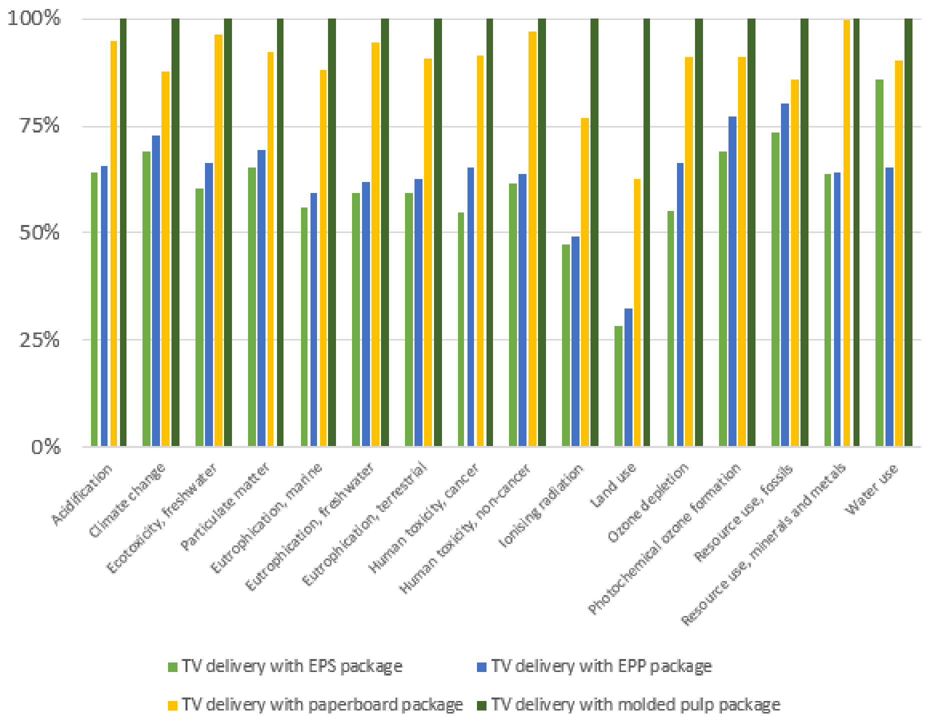


Figure 4.3: Comparison of the total impact of different packaging alternatives for TV in all studied environmental impact categories

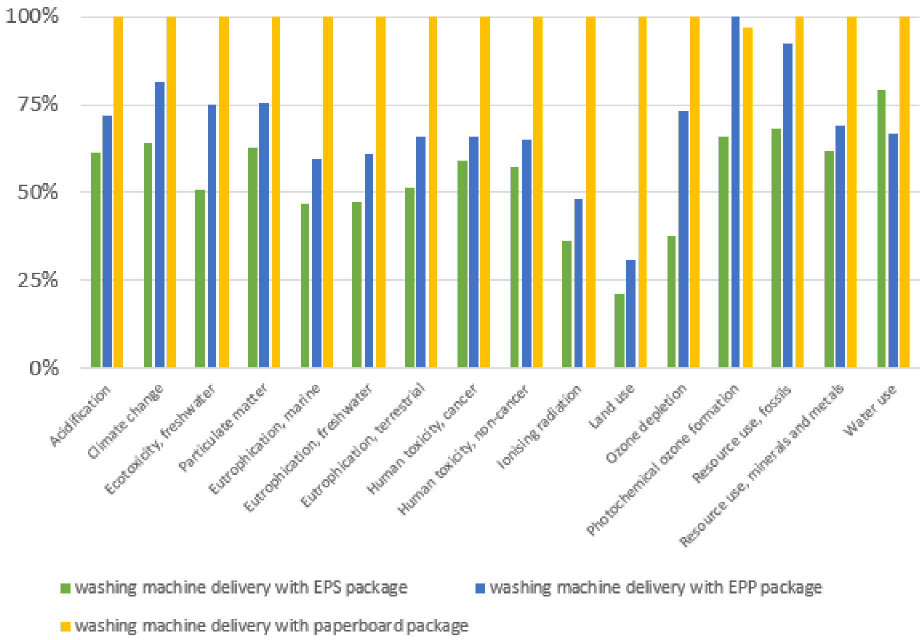


Figure 4.4: Comparison of the total impact of different packaging alternatives for washing machine in all studied environmental impact categories

To understand the environmental profile of different packaging materials, Figure 4.5 and Figure 4.6 compare the impact of packaging material for different alternatives across their entire life cycles in all studied environmental impact categories for TV and washing machine, respectively. It is clear that the superiority of delivering with different packaging material alternatives varies across environmental impact categories, depending on the specific category being assessed. To explain these differences, it is necessary to examine the energy and material inputs and outputs across various processes throughout the entire life cycle of the packaging materials. For instance, the land use impact category shows a higher impact for deliveries with the molded pulp and paperboard packages, as these packaging materials require more plant-based resources.

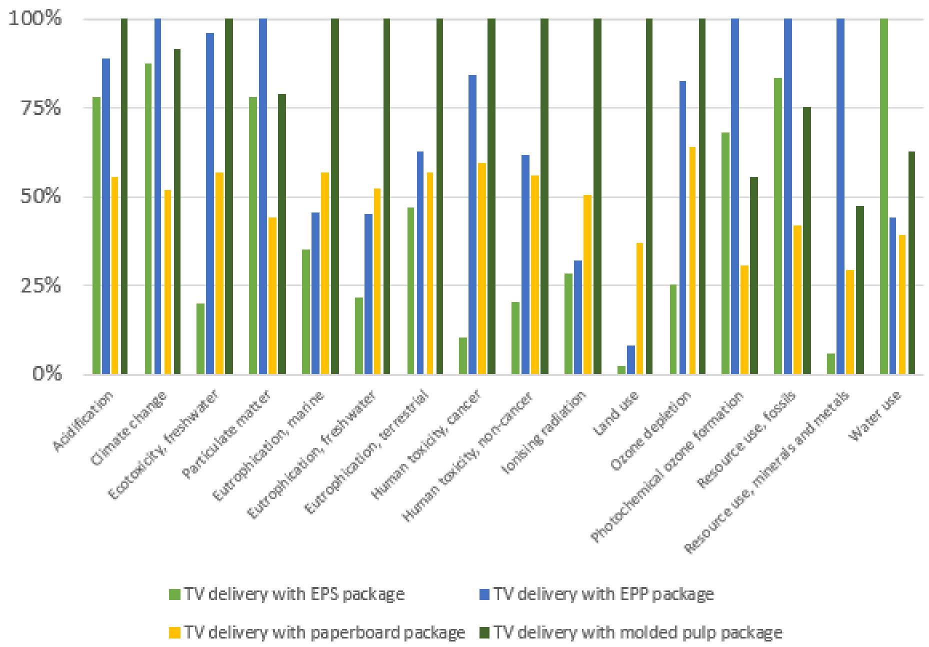


Figure 4.5: Comparison of the impact of packaging material for different alternatives for TV in all studied environmental impact categories

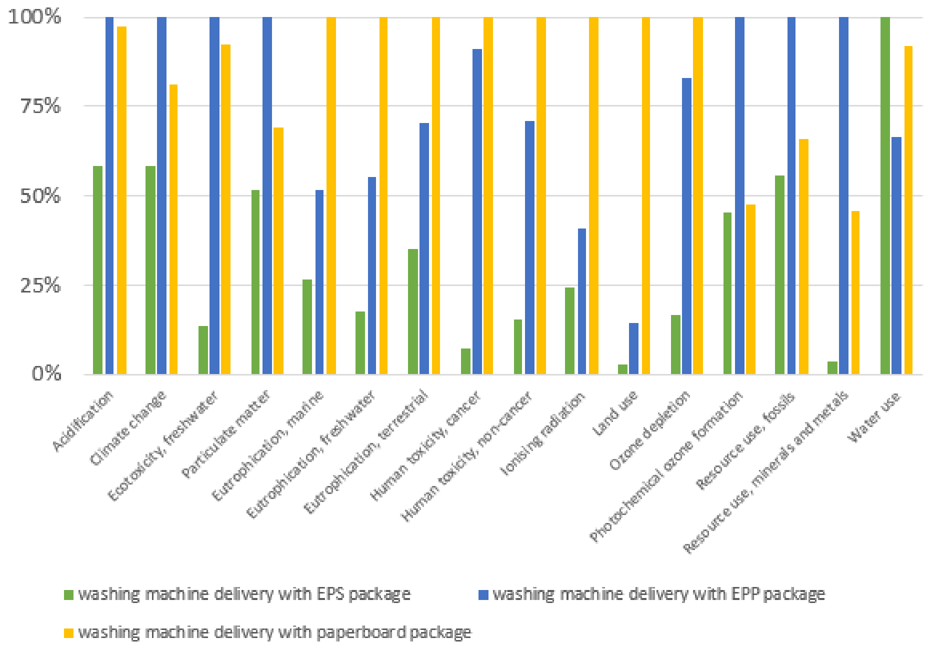


Figure 4.6: Comparison of the impact of packaging material for different alternatives for washing machine in all studied environmental impact categories

Figure 4.7 and Figure 4.8 compare the normalized values of the impact of packaging materials, based on the EF 3.1 normalization factors, for different alternatives across their entire life cycles in all studied environmental impact categories for TV and washing machine, respectively. It can be observed that resource use (minerals and metals) shows the highest impact among the studied life cycle impact categories for TVs, while human toxicity (cancer) shows the highest impact among the studied life cycle impact categories for washing machines.

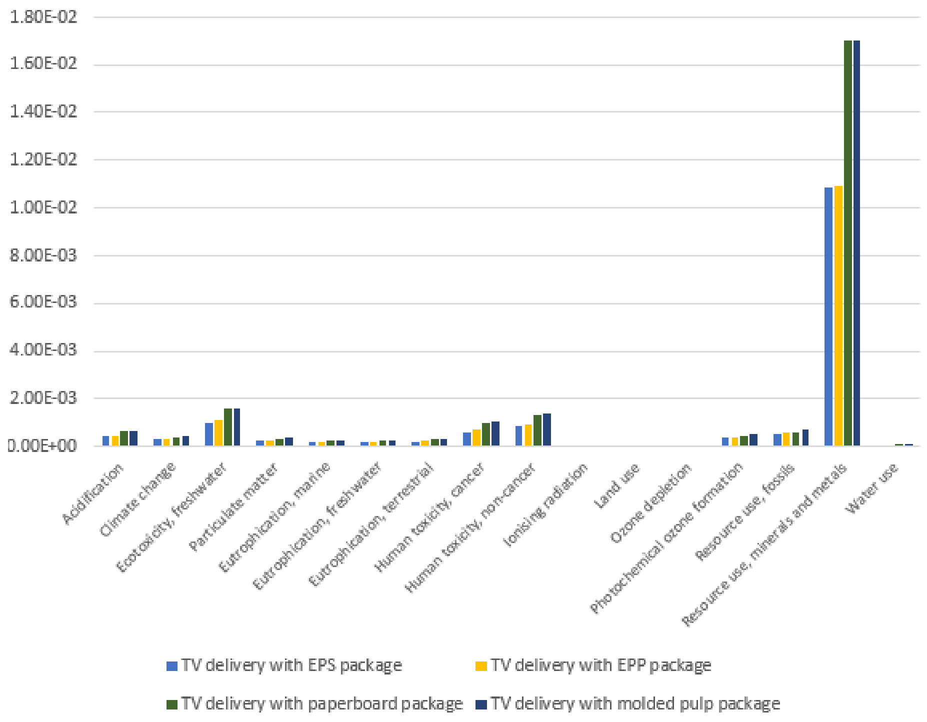


Figure 4.7: Comparison of the impact of packaging materials for different alternatives for TV in all studied environmental impact categories (normalized values)

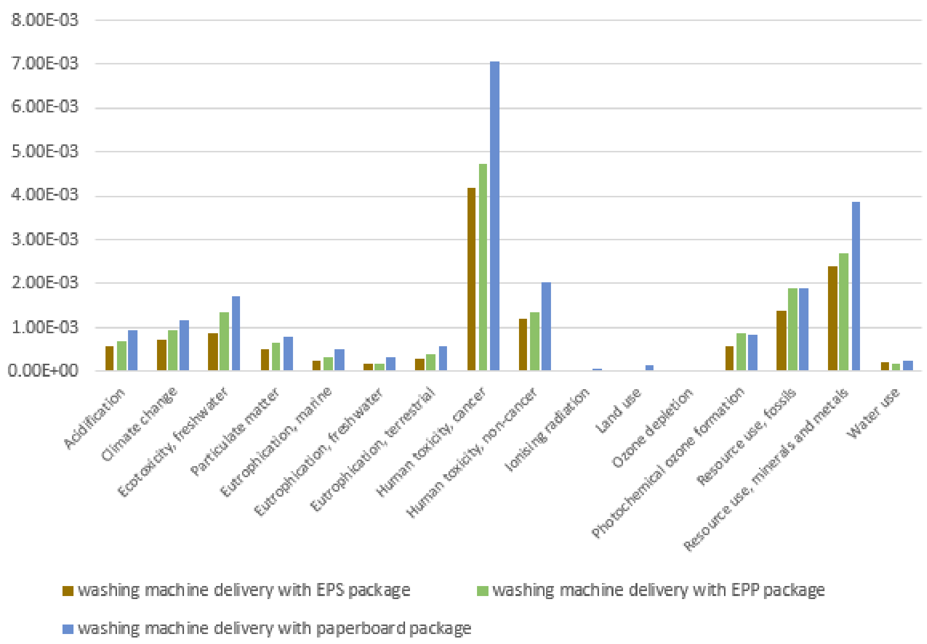


Figure 4.8: Comparison of the impact of packaging materials for different alternatives for washing machine in all studied environmental impact categories (normalized values)

5 Interpretation

5.1 Discussion of uncertainties

The results of this study are highly dependent on its underlying assumptions and the limitations described in section 2.2.6, many of which are associated with uncertainties. Below is an overview of the key parameters and sources of uncertainty in this study:

- **Mass of Packaging:** The masses of the packaging alternatives were based on data provided by the client. These values, however, are subject to change, and any variation could significantly influence the results.

- **Mass of Products:** Product masses were also based on the primary data from the client, which differ from those in secondary databases. Adjustments (scaling up or down) were made to align with the database values. Variations in product mass could significantly affect the results, especially since damaged products have the largest contribution to the overall environmental impacts.

- **Damage during transport**: Data on transport damage was associated with uncertainty as it lacked experimental validation for the specific product-package combinations studied. Since damage during transport constitutes the largest share of environmental impacts, any inaccuracies in this data could substantially affect the findings.

- **Transport distances and means**: Transport distances and means were based on various inputs:
  - Reference data, such as distances between manufacturers, distributors, and customers (based on PEF guidelines).
  - Study-specific assumptions, such as the transport of packaging to the product manufacturer and transport to EoL treatment center.
  - Secondary databases, like market data for raw materials in the ecoinvent database.

While transport impacts were less influential compared to packaging materials and damaged products, assumptions in this area could also affect the results.

- **Reusability Rate**: For reusable packaging, a reusability rate of five times was assumed based on client inputs. To enable a fair comparison between single-use and reusable packaging, six service cycles (one initial use plus five reuses or intermediate mechanical recycling) were considered. Variations in reusability rates or intermediate recycling numbers could alter the results.

- **Reuse return and recycling collection rates**: A 70% rate was considered for both reuse return and recycling collection rates. These values, which are ultimately determined by consumer behavior, are hypothetical and are not meant to reflect current practices. Getting actual data for these rates would require behavioral studies and surveys, which were outside the scope of this study. Different rates could significantly impact the comparative results of the alternatives and the conclusions of this report.

- **EoL waste treatment modeling**: The modeling of EoL scenarios was limited. For example, recycling processes were approximated based on energy consumption, and damaged product disposal was modeled using electronic device data. A more precise assessment would require primary data tailored to the specific packaging materials and products studied, which could notably affect the results.

- **Excluded processes**: As outlined in section 2.2.3, certain flows, such as protective inner packaging materials, were excluded from the analysis. Including these items could influence the results to a certain extent as well.

Among these influential factors, three were selected for sensitivity analysis to evaluate how the study results depend on these potentially significant parameters: the damage rate, the reuse, return and recycling collection rates, and the mass of the package. These results are presented in the following sections.

5.2 Sensitivity analysis

5.2.1 Damage rate

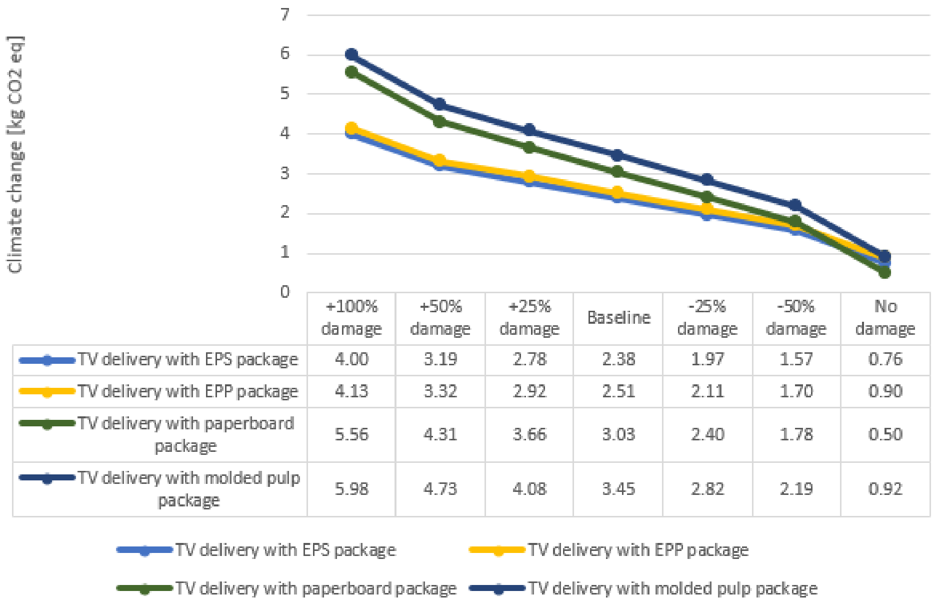
Noting the uncertainty regarding the damage rate, a sensitivity analysis was conducted to evaluate its significance by examining damage rates of ±25%, ±50%, and ±100% relative to the baseline values provided by the client. The -100% scenario represents a scenario with no damage rate at all. All packaging alternatives were evaluated, as listed in Table 5.1.

Table 5.1: Sensitivity analysis on the damage rate

Scenario	Damage rate (%)			
	EPS	EPP	Paperboard	Molded pulp
+100% damage	1.6	1.6	2.5	2.5
+50% damage	1.2	1.2	1.88	1.88
+25% damage	1	1	1.56	1.56
Baseline	**0.8**	**0.8**	**1.25**	**1.25**
-25% damage	0.6	0.6	0.94	0.94
-50% damage	0.4	0.4	0.63	0.63
No damage	0	0	0	0

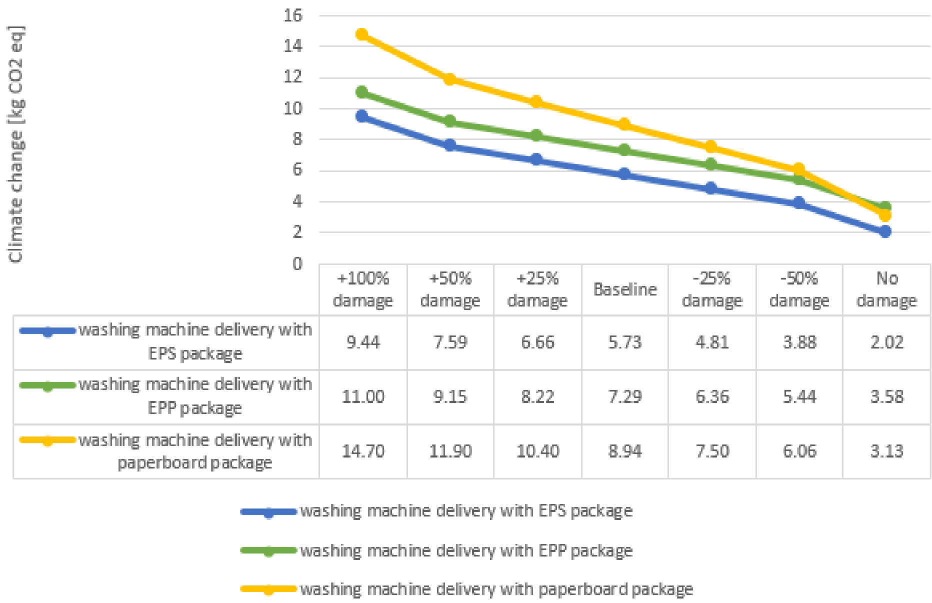
Figure 5.1 and Figure 5.2 illustrate the impact of damage rates on the total climate change impact scores of the assessed packaging solutions for TV and washing machine, respectively. The results demonstrate a significant influence of the damage rate on the overall climate change impact of each alternative. A ±50% variation in the damage rate leads to an average ±34% change in the climate change impact for deliveries with different packaging alternatives. Nonetheless, the relative performance of the alternatives, in terms of their impact rankings, remains unchanged across these scenarios.
In the case of no damage (excluding the influence of product damage and considering only the impacts of the packaging material and transportation), the results show that the delivery with the paperboard package has the lowest climate change impact among all alternatives for the TV. For washing machines, delivery with paperboard packaging has a lower climate

impact than EPP but remains higher than EPS packaging. These results demonstrate how the inclusion or exclusion of damages during transportation can influence the comparative superiority of packaging alternatives.



	+100% damage	+50% damage	+25% damage	Baseline	-25% damage	-50% damage	No damage
TV delivery with EPS package	4.00	3.19	2.78	2.38	1.97	1.57	0.76
TV delivery with EPP package	4.13	3.32	2.92	2.51	2.11	1.70	0.90
TV delivery with paperboard package	5.56	4.31	3.66	3.03	2.40	1.78	0.50
TV delivery with molded pulp package	5.98	4.73	4.08	3.45	2.82	2.19	0.92

Figure 5.1: Influence of the damage rate on the overall climate change impact of different alternatives for TV



	+100% damage	+50% damage	+25% damage	Baseline	-25% damage	-50% damage	No damage
washing machine delivery with EPS package	9.44	7.59	6.66	5.73	4.81	3.88	2.02
washing machine delivery with EPP package	11.00	9.15	8.22	7.29	6.36	5.44	3.58
washing machine delivery with paperboard package	14.70	11.90	10.40	8.94	7.50	6.06	3.13

Figure 5.2: Influence of the damage rate on the overall climate change impact of different alternatives for washing machine

Since the damage rate has a significant impact on the results, we further compared the two best alternatives based on the previous findings (the EPS and EPP packages) by conducting a break-even analysis. This analysis determined the change in the damage rate required for one package to outperform the other.
Figure 5.3 and /

Figure 5.4 show the results of the break-even analyses for the impact of damage rates of the EPS and EPP packages on the overall climate change impact, for TV and washing machine, respectively.

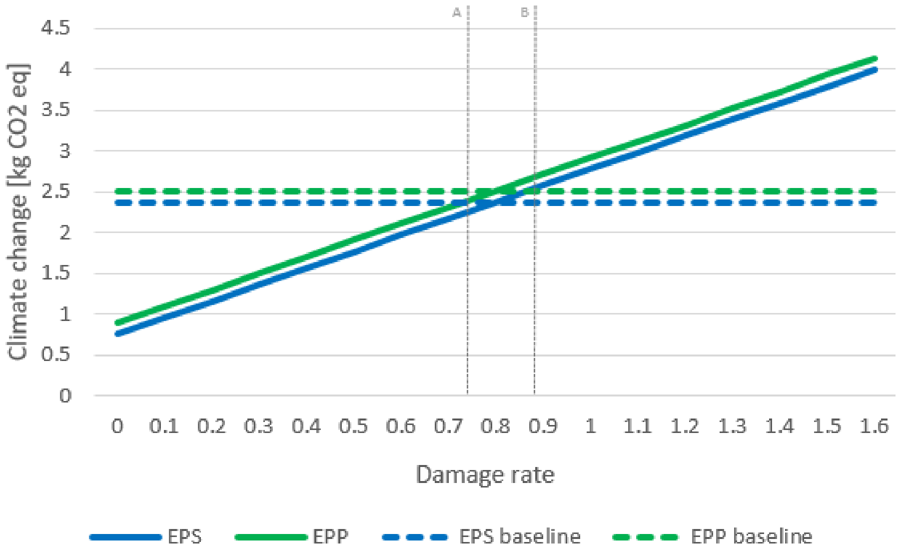


Figure 5.3: Break-even analysis of the impact of damage rates of the EPS and EPP packages for TV on the overall climate change impact

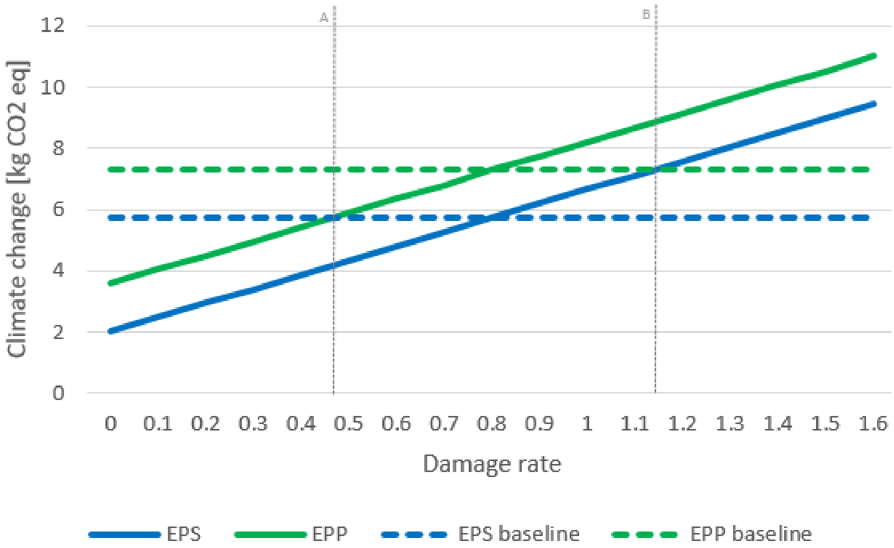


Figure 5.4: Break-even analysis of the impact of damage rates of the EPS and EPP packages for washing machine on the overall climate change impact.

As shown in the graphs, the results indicate that even a small difference in the damage rate of each packaging alternative can significantly influence its overall climate change impact relative to the others. For example, in the case of the TV, a change as minor as 0.06 or 0.07 in the damage rate (i.e., if the EPP package damage rate decreases from 0.8 to 0.74, as indicated by line A in Figure 5.3, or if the EPS package damage rate increases from 0.8 to

0.87, as indicated by line B in Figure 5.3) results in the EPP package having a lower climate change impact than the EPS package.

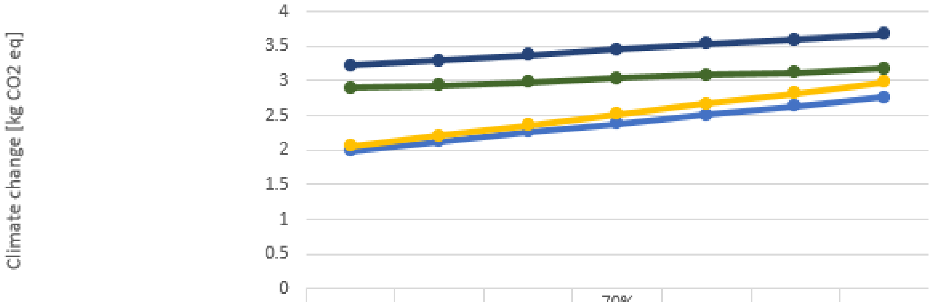
Similarly, for the washing machine, a change of just 0.34 in the damage rate (i.e., if the EPP package damage rate decreases from 0.8 to 0.46, as indicated by line A in figure 5.4, or if the EPS package damage rate increases from 0.8 to 1.14, as indicated by line B in Figure 5.4, leads to the EPP package having a lower climate change impact than the EPS package. This is a crucial point, as the damage rate for each alternative can range from 0 to 100. A shift of less than 0.1 for TV or less than 0.4 for washing machines can significantly alter the ranking of different alternatives. Given this sensitivity, it is essential to carefully consider the precision of the data before drawing conclusions when comparing the overall climate change impact of various packaging options.

5.2.2 Reuse return and recycling collection rates

The reuse return and recycling collection rates were also influential factors in this study, playing an important role in the evaluation of reusable packaging (EPP) and how its performance compares with single-use packaging alternatives. Reuse return and recycling collection rates of 70% were considered the baseline for this study. In order to evaluate the influence of this factor on the results, six additional scenarios were examined by varying both influential return rates simultaneously, from 40% to 100%.

Figure 5.5 and Figure 5.6 illustrate the impact of recycling and reuse return rates on the overall climate change impacts of different alternatives for TV and washing machine, respectively. The results indicate that, as expected, the reuse return and recycling collection rates inversely affect the climate change impact: higher rates reduce the climate change impact, while lower rates increase it. For TVs, a ±30% variation in the reuse return and recycling collection rates leads to an average ±17% change in the climate change impact for deliveries using the EPS package and an average ±22% change for those using the EPP package. This emphasizes how strongly the results depend on these rates.

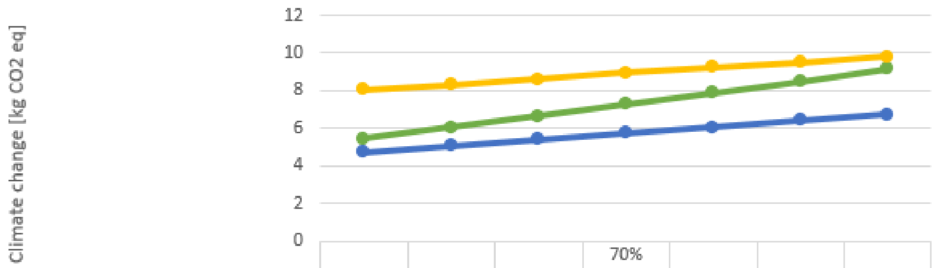
It should be noted that the reuse return rate and recycling collection rate were assumed to be equal in this study. Actual variations in these rates, based on consumer behavior studies, could significantly affect the comparative results of these alternatives. Additionally, in this sensitivity analysis, all other influential parameters were held constant. If additional parameters were included or if the existing parameters deviated from their baseline values, the reuse return and recycling collection rates could have an even greater influence on the overall climate change impact of the packaging alternatives.



	100%	90%	80%	70% (Baseline)	60%	50%	40%
TV delivery with EPS package	1.99	2.12	2.26	2.38	2.50	2.63	2.76
TV delivery with EPP package	2.05	2.20	2.35	2.51	2.66	2.81	2.98
TV delivery with paperboard package	2.89	2.93	2.98	3.03	3.08	3.12	3.17
TV delivery with molded pulp package	3.22	3.29	3.37	3.45	3.53	3.59	3.67

TV delivery with EPS package
TV delivery with EPP package
TV delivery with paperboard package
TV delivery with molded pulp package

Figure 5.5: The influence of the recycling and reuse return rates on the overall climate change impact of different alternatives for TV



	100%	90%	80%	70% (Baseline)	60%	50%	40%
washing machine delivery with EPS package	4.71	5.05	5.41	5.73	6.06	6.42	6.74
washing machine delivery with EPP package	5.43	6.04	6.63	7.29	7.89	8.49	9.17
washing machine delivery with paperboard package	8.04	8.32	8.61	8.94	9.23	9.51	9.81

washing machine delivery with EPS package
washing machine delivery with EPP package
washing machine delivery with paperboard package

Figure 5.6: The influence of the recycling and reuse return rates on the overall climate change impact of different alternatives for washing machine

5.2.3 Mass of package

To evaluate the influence of packaging mass, a scenario was examined in which an average mass was assigned consistently across plastic packaging options (EPS and EPP), as well as paperboard and molded pulp (for TVs only, since no molded pulp scenario was considered for washing machines). The values for both the baseline study and this alternative scenario are listed in Table 5.2.

Table 5.2: Baseline and alternative scenario values for the mass of package for different alternatives

	TV delivery with EPS package	TV delivery with EPP package	TV delivery with paperboard package	TV delivery with molded pulp package	washing machine delivery with EPS package	washing machine delivery with EPP package
Baseline, mass of package [kg]	0.33	0.45	0.56	1.22	0.88	1.80
Alternative scenario, mass of package [kg]	0.39	0.39	0.89	0.89	1.34	1.34

The results of this assessment, shown in Figure 5.7, show that when equivalent packaging mass is considered for plastic alternatives, delivery with the EPP package results in a lower climate change impact compared to delivery with the EPS package for both TVs and washing machines. Similarly, the delivery with the moulded pulp package shows a lower climate change impact compared to delivery with the paperboard package for TV. These findings underscore the significant role that packaging mass plays in the study outcomes and illustrate how the impact shifts when the same mass is applied across different packaging options.

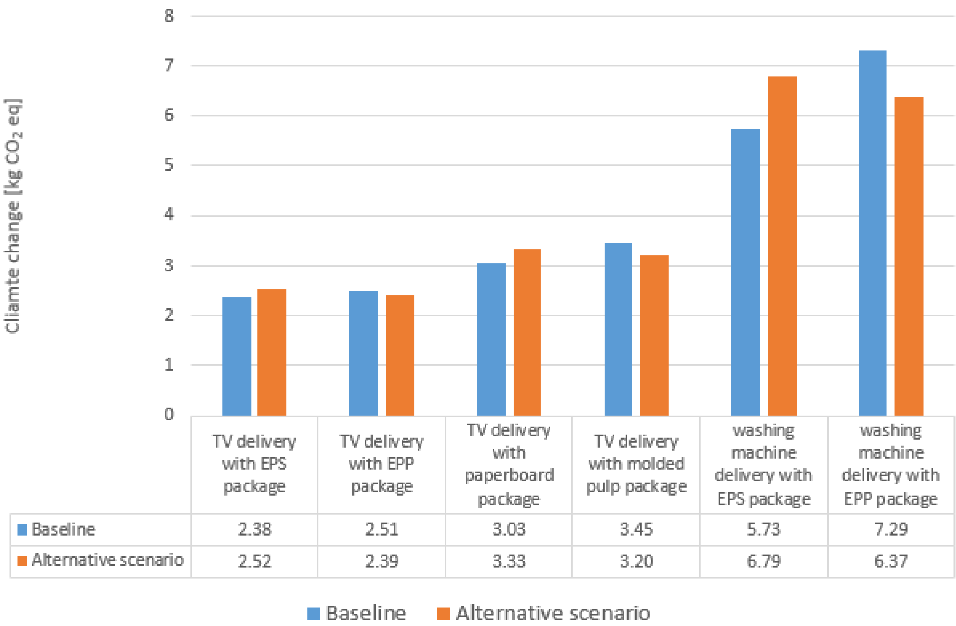


Figure 5.7: Comparison of the climate change impact of the alternative scenario for the mass of packaging with the baseline scenario

6 Conclusions and Recommendations

The main conclusions of this study can be summed up as follows:

- **Comparison of the studied packaging alternatives:** This study analyzed four different packaging materials for the defined functional unit, i.e. providing protective packaging to deliver products from the manufacturer to the client in good working order. It was observed that several highly uncertain factors significantly influenced the analysis, including the damage rate, the mass of the package, and modeling choices such as whether damaged products during transportation are taken into account. The relative superiority of one alternative over another depends on assumptions made on the expected values and ranges of variability of these factors, as well as the type of product protected, and, in some cases, the environmental impact category assessed. The findings highlight the imperative need for more empirical data to address these influential factors and associated uncertainties in order to draw more robust conclusions.

- **Impacts of damaged products:** The impact of damaged products constitutes the largest portion of the overall impacts, accounting for an average of 59% of total impacts for delivering washing machines and 72% for delivering TVs. When considering the overall impact, delivery with the EPS package shows the lowest environmental impact, followed by deliveries with the EPP package, paperboard package, and molded pulp package. Nonetheless, if we exclude the impact of damaged products, delivery with the paperboard package emerges as the alternative with the lowest climate change impact for TV. However, for washing machines, delivery with the paperboard package still results in higher impacts compared to delivery with the EPS packages. The damage rate was found to be highly influential: a ±50% variation in the damage rate leads to an average ±34% change in the climate change impact for deliveries with different packaging alternatives. The results of a break-even analysis comparing EPS and EPP packaging reveal that even small differences (less than 0.1 for TVs or less than 0.4 for washing machines, with damage rates for each alternative ranging from 0 to 100) can shift the superiority of one option over the other. This underscores the inability to draw definitive conclusions about the ranking of packaging alternatives and highlights the critical need for empirical data on damage rates across various product-packaging combinations to enable more accurate and effective environmental assessments.

- **Impacts of packaging materials and their mass:** When considering only the packaging material, it contributes, on average, 24% of the total impact for TVs and 36% for washing machines. However, the choice of packaging also affects the impacts associated with damaged products and transportation. Future studies could explore optimizing these trade-offs to support the development of more sustainable solutions. The mass of the packaging is another key factor influencing the results. The studied EPP package has a significantly higher mass than the EPS one (more than double in the case of the washing machine). This leads to higher impacts both from the EPP packaging itself and from transportation. In a scenario evaluating equivalent packaging masses for plastic alternatives, delivery with the EPP package results in a lower climate change impact compared to delivery with the EPS package for both TVs and washing machines.

- **Impacts of transportation:** Transportation impacts were lower compared to those of the damaged product and packaging material, accounting for 4% of the total impacts for TVs and 5% for washing machines. Nonetheless, it is important to note that the transportation impacts in this analysis consider only the mass of the packaging and the damaged products, excluding the transportation of undamaged products, as this is identical across alternatives. Including those impacts would increase the transportation share of the total impacts. Future studies could explore the adoption of environmentally efficient transportation methods to further reduce transport-related impacts.

- **Reuse return and recycling collection rates:** The sensitivity analysis of the recycling and reuse return rates showed that while these rates inversely affect the climate change impact for all alternatives, the decrease in reusable packaging (EPP) is more notable. It should be noted that if additional parameters were included, existing parameters varied, or reuse return and recycling collection rates were considered differently, these parameters could have more significant effects on the overall climate change impact of the packaging alternatives.

- **Limitations**: The results and conclusions of this study are contingent upon the goal and scope of the study as well as a narrow set of assumptions required. Of particular relevance are the assumed required mass of different packaging materials, their damage rates during transportation, and the return and reusability rates for reusable packaging. Thus the results and conclusions are subject to change under different sets of assumptions or additional data that may become available after the conclusion of this study.

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Signature

TNO ⟩ Energy & Materials Transition ⟩ Utrecht, 31 March 2026

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Appendix A
Life Cycle Inventory (LCI) for each unit process and all scenarios

Table A.1: The LCI of the production of the EPS package for TV (Box 1) per FU

	Flow	Value	Unit	Remark
Input	Polystyrene, expandable {GLO}| market for polystyrene, expandable | Cut-off, U	0.14	kg	Virgin fraction from Table 3.2 × mass of package
	Polymer foaming {RER}| polymer foaming | Cut-off, U	0.14	kg	Virgin fraction from Table 3.2 × mass of package
	Recycled EPS for TV	0.19	kg	Recycled fraction from Table 3.2 × mass of package
Output	EPS package for TV	0.33	kg	

Table A.2: The LCI of the production of the EPP package for TV (Box 1) per FU

	Flow	Value	Unit	Remark
Input	Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	0.19	kg	Virgin fraction from Table 3.2 × mass of package
	Polymer foaming {RER}| polymer foaming | Cut-off, U	0.19	kg	Virgin fraction from Table 3.2 × mass of package
	Reused EPP for TV	0.26	kg	Reused fraction from Table 3.2 × mass of package
Output	EPP package for TV	0.45	kg	

Table A.3: The LCI of the production of the paperboard package for TV (Box 1) per FU

	Flow	Value	Unit	Remark
Input	Corrugated board box {RER}| market for corrugated board box | Cut-off, U	0.27	kg	Virgin fraction from Table 3.2 × mass of package
	Recycled paperboard for TV	0.30	kg	Recycled fraction from Table 3.2 × mass of package
Output	Paperboard package for TV	0.57	kg	

Table A.4: The LCI of the production of the molded pulp package for TV (Box 1) per FU

	Flow	Value	Unit	Remark
Input	Containerboard, linerboard {RER}| market for containerboard, linerboard | Cut-off, U	0.59	kg	Virgin fraction from Table 3.2 × mass of package | The selection is based on (Sangjin Jeong, LG Electronics, 2023)
	Recycled molded pulp for TV	0.65	kg	Recycled fraction from Table 3.2 × mass of package
Output	Molded pulp package for TV	1.24	kg	

Table A.5: The LCI of the production of the EPS package for washing machine (Box 1) per FU

	Flow	Value	Unit	Remark
Input	Polystyrene, expandable {GLO}| market for polystyrene, expandable | Cut-off, U	0.37	kg	Virgin fraction from Table 3.2 × mass of package
	Polymer foaming {RER}| polymer foaming | Cut-off, U	0.37	kg	Virgin fraction from Table 3.2 × mass of package

	Recycled EPS for washing machine	0.51	kg	Recycled fraction from Table 3.2 × mass of package
Output	EPS package for washing machine	0.88	kg	

Table A.6: The LCI of the production of the EPP package for washing machine (Box 1) per FU

	Flow	Value	Unit	Remark
Input	Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	0.76	kg	Virgin fraction from Table 3.2 × mass of package
	Polymer foaming {RER}| polymer foaming | Cut-off, U	0.76	kg	Virgin fraction from Table 3.2 × mass of package
	Reused EPP for washing machine	1.06	kg	Reused fraction from Table 3.2 × mass of package
Output	EPP package for washing machine	1.81	kg	

Table A.7: The LCI of the production of the paperboard package for washing machine (Box 1) per FU

	Flow	Value	Unit	Remark
Input	Corrugated board box {RER}| market for corrugated board box | Cut-off, U	1.68	kg	Virgin fraction from Table 3.2 × mass of package
	Recycled paperboard for washing machine	1.86	kg	Recycled fraction from Table 3.2 × mass of package
Output	Paperboard package for washing machine	3.54	kg	

Table A.8: The LCI of the production of the damaged TV (Box 2) for EPS package per FU

	Flow	Value	Unit	Remark
Input	Television {GLO}| market for television | Cut-off, U	0.004	p	The original ecoinvent inventory represents a 30 kg TV, so mass of TV [kg]/30 [kg] is considered.
Output	TV for EPS package	0.12	kg	mass of TV × (damage rate/100)

Table A.9: The LCI of the production of the damaged TV (Box 2) for EPP package per FU

	Flow	Value	Unit	Remark
Input	Television {GLO}| market for television | Cut-off, U	0.004	p	The inventory represents a 30 kg TV, so mass of TV [kg]/30 [kg] is considered.
Output	TV for EPP package	0.12	kg	mass of TV × (damage rate/100)

Table A.10: The LCI of the production of the damaged TV (Box 2) for Paperboard package per FU

	Flow	Value	Unit	Remark
Input	Television {GLO}| market for television | Cut-off, U	0.006	p	The inventory represents a 30 kg TV, so mass of TV [kg]/30 [kg] is considered.
Output	TV for paperboard package	0.19	kg	mass of TV × (damage rate/100)

Table A.11: The LCI of the production of the damaged TV (Box 2) for molded pulp package per FU

	Flow	Value	Unit	Remark
Input	Television {GLO}| market for television | Cut-off, U	0.006	p	The inventory represents a 30 kg TV, so mass of TV [kg]/30 [kg] is considered.
Output	TV for molded pulp package	0.19	kg	mass of TV × (damage rate/100)

Table A.12: The LCI of the production of the damaged washing machine (Box 2) for EPS package per FU

	Flow	Value	Unit	Remark
Input	Washing machine {GLO}| market for washing machine | Cut-off, U	0.009	p	The inventory represents a 75 kg washing machine, so mass of washing machine [kg]/75 [kg] is considered.
Output	Washing machine for EPS package	0.64	kg	mass of washing machine × (damage rate/100)

Table A.13: The LCI of the production of the damaged washing machine (Box 2) for EPP package per FU

	Flow	Value	Unit	Remark
Input	Washing machine {GLO}| market for washing machine | Cut-off, U	0.009	p	The inventory represents a 75 kg washing machine, so mass of washing machine [kg]/75 [kg] is considered.
Output	Washing machine for EPP package	0.64	kg	mass of washing machine × (damage rate/100)

Table A.14: The LCI of the production of the damaged washing machine (Box 2) for paperboard package per FU

	Flow	Value	Unit	Remark
Input	Washing machine {GLO}| market for washing machine | Cut-off, U	0.013	p	The inventory represents a 75 kg washing machine, so mass of washing machine [kg]/75 [kg] is considered.
Output	Washing machine for paperboard package	1	kg	mass of washing machine × (damage rate/100)

Table A.15: The LCI of the transportation of the EPS package to the TV manufacturer (Box 3) per FU

	Flow	Value	Unit	Remark
Input	EPS package for TV	0.33	kg	Output of Box 1
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	3.33	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation of the package to the product manufacturer. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (20km/2) is considered.
Output	Transported EPS package to the TV manufacturer	0.33	kg	

Table A.16: The LCI of the transportation of the EPP package to the TV manufacturer (Box 3) per FU

	Flow	Value	Unit	Remark
Input	EPP package for TV	0.19	kg	Output of Box 1
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	0.32	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg]
Output	Transported EPP package to the TV manufacturer	0.19	kg	

Table A.17: The LCI of the transportation of the paperboard package to the TV manufacturer (Box 3) per FU

	Flow	Value	Unit	Remark
Input	Paperboard package for TV	0.57	kg	Output of Box 1
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	5.67	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation of the package to the product manufacturer. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (20km/2) is considered.
Output	Transported paperboard package to the TV manufacturer	0.57	kg	

Table A.18: The LCI of the transportation of the molded pulp package to the TV manufacturer (Box 3) per FU

	Flow	Value	Unit	Remark
Input	Molded pulp package for TV	1.24	kg	Output of Box 1
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	12.35	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg]
Output	Transported molded pulp package to the TV manufacturer	1.24	kg	

Table A.19: The LCI of the transportation of the EPS package to the washing machine manufacturer (Box 3) per FU

	Flow	Value	Unit	Remark
Input	EPS package for washing machine	0.88	kg	Output of Box 1
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	8.84	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg]
Output	Transported EPS package to the washing machine manufacturer	0.88	kg	

Table A.20: The LCI of the transportation of the EPP package to the washing machine manufacturer (Box 3) per FU

	Flow	Value	Unit	Remark
Input	EPP package for washing machine	0.76	kg	Output of Box 1
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	1.26	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg]
Output	Transported EPP package to the washing machine manufacturer	0.76	kg	

Table A.21: The LCI of the transportation of the paperboard package to the washing machine manufacturer (Box 3) per FU

	Flow	Value	Unit	Remark
Input	Paperboard package for washing machine	3.54	kg	Output of Box 1
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	35.44	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg]
Output	Transported paperboard package to the washing machine manufacturer	3.54	kg	

Table A.22: The LCI of the packaging damaged TV by EPS package (Box 4)

	Flow	Value	Unit	Remark
Input	Damaged TV by EPS package	0.12	kg	Output of Box 2
	EPS package for TV	0.33	kg	Output of Box 1
Output	EPS-packaged TV	0.45	kg	

Table A.23: The LCI of the packaging damaged TV by EPP package (Box 4)

	Flow	Value	Unit	Remark
Input	Damaged TV by EPP package	0.12	kg	Output of Box 2
	EPP package for TV	0.45	kg	Output of Box 1
Output	EPP-packaged TV	0.57	kg	

Table A.24: The LCI of the packaging damaged TV by paperboard package (Box 4)

	Flow	Value	Unit	Remark
Input	Damaged TV by paperboard package	0.19	kg	Output of Box 2
	paperboard package for TV	0.57	kg	Output of Box 1
Output	paperboard-packaged TV	0.75	kg	

Table A.25: The LCI of the packaging damaged TV by molded pulp package (Box 4)

	Flow	Value	Unit	Remark
Input	Damaged TV by molded pulp package	0.19	kg	Output of Box 2
	Molded pulp package for TV	1.24	kg	Output of Box 1
Output	Molded pulp-packaged TV	1.42	kg	

Table A.26: The LCI of the packaging damaged washing machine by EPS package (Box 4)

	Flow	Value	Unit	Remark
Input	Damaged washing machine by EPS package	0.64	kg	Output of Box 2
	EPS package for washing machine	0.88	kg	Output of Box 1
Output	EPS-packaged washing machine	1.52	kg	

Table A.27: The LCI of the packaging damaged TV by EPP package (Box 4)

	Flow	Value	Unit	Remark
Input	Damaged washing machine by EPP package	0.64	kg	Output of Box 2
	EPP package for washing machine	1.81	kg	Output of Box 1
Output	EPP-packaged washing machine	2.45	kg	

Table A.28: The LCI of the packaging damaged TV by paperboard package (Box 4)

	Flow	Value	Unit	Remark
Input	Damaged washing machine by paperboard package	1.00	kg	Output of Box 2
	paperboard package for washing machine	3.54	kg	Output of Box 1
Output	paperboard-packaged washing machine	4.54	kg	

Table A.29: The LCI of the transportation of the EPS-packaged TV to the distribution center and subsequently to the customer (Box 5) per FU

	Flow	Value	Unit	Remark
Input	EPS-packaged TV	0.45	kg	Output of Box 4
	Transport, freight, lorry >32 metric ton, EURO4 {RER}| market for transport, freight, lorry >32 metric ton, EURO4 | Cut-off, U	2.72E+02	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation between the product manufacturer and the distribution center. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (1200 km/2) is considered.
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	5.66E+01	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation between the distribution center and the customer. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (250 km/2) is considered.
Output	Used EPS package for TV for EoL treatment	0.33	kg	To Box 8
	Damaged TV during transport for EoL treatment	0.12	kg	To Box 7

Table A.30: The LCI of the transportation of the EPP-packaged TV to the distribution center and subsequently to the customer (Box 5) per FU

	Flow	Value	Unit	Remark
Input	EPP-packaged TV	0.57	kg	Output of Box 4
	Transport, freight, lorry >32 metric ton, EURO4 {RER}| market for transport, freight, lorry >32 metric ton, EURO4 | Cut-off, U	3.44E+02	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation between the product manufacturer and the distribution center. The inventory includes an empty return, so half the distance (1200 km/2) is considered.
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	7.17E+01	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation between the distribution center and the customer. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (250 km/2) is considered.
Output	Used EPP package for TV for reuse	0.26	kg	To Box 6
	Used EPP package for TV for EoL treatment	0.19	kg	To Box 8
	Damaged TV during transport	0.12	kg	To Box 7

Table A.31: The LCI of the transportation of the paperboard-packaged TV to the distribution center and subsequently to the customer (Box 5) per FU

	Flow	Value	Unit	Remark
Input	Paperboard-packaged TV	0.75	kg	Output of Box 4
	Transport, freight, lorry >32 metric ton, EURO4 {RER}| market for transport, freight, lorry >32 metric ton, EURO4 | Cut-off, U	4.53E+02	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation between the product manufacturer and the distribution center. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (1200 km/2) is considered.
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	9.43E+01	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation between the distribution center and the customer. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (250 km/2) is considered.
Output	Used paperboard package for TV for EoL treatment	0.57	kg	To Box 8
	Damaged TV during transport for EoL treatment	0.19	kg	To Box 7

Table A.32: The LCI of the transportation of the molded pulp-packaged TV to the distribution center and subsequently to the customer (Box 5) per FU

	Flow	Value	Unit	Remark
Input	Molded pulp-packaged TV	1.42	kg	Output of Box 4
	Transport, freight, lorry >32 metric ton, EURO4 {RER}| market for transport, freight, lorry >32 metric ton, EURO4 | Cut-off, U	8.54E+02	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation between the product manufacturer and the distribution center. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (1200/2 km) is considered.
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	1.78E+02	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation between the distribution center and the customer. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (250 km/2) is considered.
Output	Used molded pulp package for TV for EoL treatment	1.24	kg	To Box 8
	Damaged TV during transport for EoL treatment	0.19	kg	To Box 7

Table A.33: The LCI of the transportation of the EPS-packaged washing machine to the distribution center and subsequently to the customer (Box 5) per FU

	Flow	Value	Unit	Remark
Input	EPS-packaged washing machine	1.52	kg	Output of Box 4
	Transport, freight, lorry >32 metric ton, EURO4 {RER}| market for transport, freight, lorry >32 metric ton, EURO4 | Cut-off, U	9.14E+02	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation between the product manufacturer and the distribution center. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (1200/2 km) is considered.
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	1.91E+02	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation between the distribution center and the customer. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (250 km/2) is considered.
Output	Used EPS package for washing machine for EoL treatment	0.88	kg	To Box 8
	Damaged washing machine during transport for EoL treatment	0.64	kg	To Box 7

Table A.34: The LCI of the transportation of the EPP-packaged washing machine to the distribution center and subsequently to the customer (Box 5) per FU

	Flow	Value	Unit	Remark
Input	EPP-packaged washing machine	2.45	kg	Output of Box 4
	Transport, freight, lorry >32 metric ton, EURO4 {RER}| market for transport, freight, lorry >32 metric ton, EURO4 | Cut-off, U	1.47E+03	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation between the product manufacturer and the distribution center. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (1200 km/2) is considered.
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	3.07E+02	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation between the distribution center and the customer. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (250 km/2) is considered.
Output	Used EPP package for washing machine for reuse	1.06	kg	To Box 6
	Used EPP package for washing machine for EoL treatment	0.76	kg	To Box 8
	Damaged washing machine during transport	0.64	kg	To Box 7

Table A.35: The LCI of the transportation of the paperboard-packaged washing machine to the distribution center and subsequently to the customer (Box 5) per FU

	Flow	Value	Unit	Remark
Input	Paperboard-packaged washing machine	4.54	kg	Output of Box 4
	Transport, freight, lorry >32 metric ton, EURO4 {RER}| market for transport, freight, lorry >32 metric ton, EURO4 | Cut-off, U	2.73E+03	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation between the product manufacturer and the distribution center. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (1200 km/2) is considered.
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	5.68E+02	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation between the distribution center and the customer. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (250 km/2) is considered.
Output	Used paperboard package for washing machine for EoL treatment	3.54	kg	To Box 8
	Damaged washing machine during transport for EoL treatment	1	kg	To Box 7

Table A.36: The LCI of the return transportation of the EPP package used for TV to the distribution center and subsequently to the product manufacturer (Box 6) per FU

	Flow	Value	Unit	Remark
Input	EPP package for TV for reuse	0.26	kg	Reused EPP for TV from Box 5
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	19.29	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation between the customer and the distribution center. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (250 km/2) is considered.
	Transport, freight, lorry >32 metric ton, EURO4 {RER}| market for transport, freight, lorry >32 metric ton, EURO4 | Cut-off, U	92.61	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation between the distribution center and the product manufacturer. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (1200 km/2) is considered.
Output	Returned EPP package used for TV to the product manufacturer	0.26	kg	

Table A.37: The LCI of the return transportation of the EPP package used for washing machine to the distribution center and subsequently to the product manufacturer (Box 6) per FU

	Flow	Value	Unit	Remark
Input	EPP package for washing machine for reuse	1.06	kg	Reused EPP for TV from Box 5
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	77.18	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation between the customer and the distribution center. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (250 km/2) is considered.
	Transport, freight, lorry >32 metric ton, EURO4 {RER}| market for transport, freight, lorry >32 metric ton, EURO4 | Cut-off, U	370.44	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation between the distribution center and the product manufacturer. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (1200 km/2) is considered.
Output	Returned EPP package used for washing machine to the product manufacturer	1.06	kg	

Table A.38: The LCI of the EoL treatment of the damaged TV which was in EPS package (Box 7) per FU

	Flow	Value	Unit	Remark
Input	Damaged TV by EPS package	0.12	kg	Damaged product from Box 5

	Used industrial electronic device {GLO}| treatment of used industrial electronic device, mechanical treatment | Cut-off, U	0.12	kg	According to the appendix of (Otterbach and Fröhling, 2024)
Output	EoL processed damaged TV by EPS package	0.12	kg	

Table A.39: The LCI of the EoL treatment of the damaged TV which was in EPP package (Box 7) per FU

	Flow	Value	Unit	Remark
Input	Damaged TV by EPP package	0.12	kg	Damaged product from Box 5
	Used industrial electronic device {GLO}| treatment of used industrial electronic device, mechanical treatment | Cut-off, U	0.12	kg	According to the appendix of (Otterbach and Fröhling, 2024)
Output	EoL processed damaged TV by EPP package	0.12	kg	

Table A.40: The LCI of the EoL treatment of the damaged TV which was in paperboard package (Box 7) per FU

	Flow	Value	Unit	Remark
Input	Damaged TV by paperboard package	0.19	kg	Damaged product from Box 5
	Used industrial electronic device {GLO}| treatment of used industrial electronic device, mechanical treatment | Cut-off, U	0.19	kg	According to the appendix of (Otterbach and Fröhling, 2024)

Output	EoL processed damaged TV by paperboard package	0.19	kg	

Table A.41: The LCI of the EoL treatment of the damaged TV which was in molded pulp package (Box 7) per FU

	Flow	Value	Unit	Remark
Input	Damaged TV by molded pulp package	0.19	kg	Damaged product from Box 5
	Used industrial electronic device {GLO}| treatment of used industrial electronic device, mechanical treatment | Cut-off, U	0.19	kg	According to the appendix of (Otterbach and Fröhling, 2024)
Output	EoL processed damaged TV by molded pulp package	0.19	kg	

Table A.42: The LCI of the EoL treatment of the damaged washing machine which was in EPS package (Box 7) per FU

	Flow	Value	Unit	Remark
Input	Damaged washing machine by EPS package	0.64	kg	Damaged product from Box 5
	Used industrial electronic device {GLO}| treatment of used industrial electronic device, mechanical treatment | Cut-off, U	0.64	kg	According to the appendix of (Otterbach and Fröhling, 2024)
Output	EoL processed damaged washing machine by EPS package	0.64	kg	

Table A.43: The LCI of the EoL treatment of the damaged washing machine which was in EPP package (Box 7) per FU

	Flow	Value	Unit	Remark
Input	Damaged washing machine by EPP package	0.64	kg	Damaged product from Box 5
	Used industrial electronic device {GLO}| treatment of used industrial electronic device, mechanical treatment | Cut-off, U	0.64	kg	According to the appendix of (Otterbach and Fröhling, 2024)
Output	EoL processed damaged washing machine by EPP package	0.64	kg	

Table A.44: The LCI of the EoL treatment of the damaged washing machine which was in paperboard package (Box 7) per FU

	Flow	Value	Unit	Remark
Input	Damaged washing machine by paperboard package	1	kg	Damaged product from Box 5
	Used industrial electronic device {GLO}| treatment of used industrial electronic device, mechanical treatment | Cut-off, U	1	kg	According to the appendix of (Otterbach and Fröhling, 2024)
Output	EoL processed damaged washing machine by paperboard package	1	kg	

Table A.45: The LCI of the transportation of the EPS package used for TV to the EoL treatment center (Box 8) per FU

	Flow	Value	Unit	Remark
Input	Used EPS package for TV	0.33	kg	Damaged package from Box 5
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	0.69	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation of the package to the product manufacturer. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (10 km/2) is considered.
Output	Transported EPS package to the EoL treatment center	0.33	kg	

Table A.46: The LCI of the transportation of the EPP package used for TV to the EoL treatment center (Box 8) per FU

	Flow	Value	Unit	Remark
Input	Used EPP package for TV, not reusable	0.19	kg	Damaged package from Box 5
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	0.40	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation of the package to the EoL treatment center. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (10 km/2) is considered.
Output	Transported EPP package to the EoL treatment center	0.19	kg	

Table A.47: The LCI of the transportation of the paperboard package used for TV to the EoL treatment center (Box 8) per FU

	Flow	Value	Unit	Remark
Input	Used paperboard package for TV	0.57	kg	Damaged package from Box 5
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	1.18	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation of the package to the product manufacturer. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (10 km/2) is considered.
Output	Transported paperboard package to the EoL treatment center	0.57	kg	

Table A.48: The LCI of the transportation of the molded pulp package used for TV to the EoL treatment center (Box 8) per FU

.	Flow	Value	Unit	Remark
Input	Used molded pulp package for TV	0.76	kg	Damaged package from Box 5
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	1.58	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation of the package to the product manufacturer. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (10 km/2) is considered.

Output	Transported molded pulp package to the EoL treatment center	0.76	kg	

Table A.49: The LCI of the transportation of the EPS package used for washing machine to the EoL treatment center (Box 8) per FU

	Flow	Value	Unit	Remark
Input	Used EPS package for washing machine	0.88	kg	Damaged package from Box 5
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	1.84	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation of the package to the product manufacturer. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (10 km/2) is considered.
Output	Transported EPS package to the EoL treatment center	0.88	kg	

Table A.50: The LCI of the transportation of the EPP package used for washing machine to the EoL treatment center (Box 8) per FU

	Flow	Value	Unit	Remark
Input	Used EPP package for washing machine	1.81	kg	Damaged package from Box 5
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	3.78	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation of the package to the EoL treatment center. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (10 km/2) is considered.

Output	Transported EPP package to the EoL treatment center	1.81	kg	

Table A.51: The LCI of the transportation of the paperboard package used for washing machine to the EoL treatment center (Box 8) per FU

	Flow	Value	Unit	Remark
Input	Used paperboard package for washing machine	3.54	kg	Damaged package from Box 5
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	7.38	kgkm	Total transportation required from Table 3.4 × distance[kg] × mass[kg] | Transportation of the package to the product manufacturer. The original inventory for this process, taken from ecoinvent includes an empty return, so half the distance (10 km/2) is considered.
Output	Transported paperboard package to the EoL treatment center	3.54	kg	

Table A.52: The LCI of the mechanical recycling of the EPS package used for TV (Box 9) per FU

	Flow	Value	Unit	Remark
Input	Transported EPS package used for TV to the EoL treatment center going to mechanical recycling	0.25	kg	Output of Box 8 × (Virgin fraction × fraction of EoL mechanical recycling + recycled fraction), Check Table 3.2 for virgin and recycled fractions and

				Table 3.1 for EoL fraction of mechanical recycling
	Electricity, medium voltage {RER}| market group for electricity, medium voltage | Cut-off, U	0.17	kWh	TNO data for mechanical recycling based on extrusion, 0.676 kWh per kg of material
Output	Mechanically recycled EPS package used for TV	0.25	kg	

Table A.53: The LCI of the mechanical recycling of the EPP package used for TV (Box 9) per FU

	Flow	Value	Unit	Remark
Input	Transported EPP package used for TV to the EoL treatment center going to mechanical recycling	0.07	kg	Output of Box 8 × (Virgin fraction × fraction of EoL mechanical recycling + recycled fraction), Check Table 3.2 for virgin and recycled fractions and Table 3.1 for EoL fraction of mechanical recycling
	Electricity, medium voltage {RER}| market group for electricity, medium voltage | Cut-off, U	0.05	kWh	TNO data for mechanical recycling based on extrusion, 0.676 kWh per kg of material
Output	Mechanically recycled EPP package used for TV	0.07	kg	

Table A.54: The LCI of the mechanical recycling of the paperboard package used for TV (Box 9) per FU

	Flow	Value	Unit	Remark
Input	Transported paperboard package used for TV to the EoL treatment center going to mechanical recycling	0.52	kg	Output of Box 8 × (Virgin fraction × fraction of EoL mechanical recycling + recycled fraction), Check Table 3.2 for virgin and recycled fractions and Table 3.1 for EoL fraction of mechanical recycling
	Electricity, medium voltage {RER}| market group for electricity, medium voltage | Cut-off, U	0.35	kWh	In line with mechanical recycling for EPP and EPS, only electricity inputs in considered. Value based on (Furberg and Lyng, 2022)
Output	Mechanically recycled paperboard package used for TV	0.52	kg	

Table A.55: The LCI of the mechanical recycling of the molded pulp package used for TV (Box 9) per FU

	Flow	Value	Unit	Remark
Input	Transported molded pulp package used for TV to the EoL treatment center going to mechanical recycling	1.14	kg	Output of Box 8 × (Virgin fraction × fraction of EoL mechanical recycling + recycled fraction), Check Table 3.2 for virgin and recycled fractions and

				Table 3.1 for EoL fraction of mechanical recycling
	Electricity, medium voltage {RER}| market group for electricity, medium voltage | Cut-off, U	0.76	kWh	In line with mechanical recycling for EPP and EPS, only electricity inputs in considered. Value based on (Furberg and Lyng, 2022)
Output	Mechanically recycled molded pulp package used for TV	1.14	kg	

Table A.56: The LCI of the mechanical recycling of the EPS package used for washing machine (Box 9) per FU

	Flow	Value	Unit	Remark
Input	Transported EPS package used for washing machine to the EoL treatment center going to mechanical recycling	0.66	kg	Output of Box 8 × (Virgin fraction × fraction of EoL mechanical recycling + recycled fraction), Check Table 3.2 for virgin and recycled fractions and Table 3.1 for EoL fraction of mechanical recycling

	Electricity, medium voltage {RER}| market group for electricity, medium voltage | Cut-off, U	0.44	kWh	TNO data for mechanical recycling based on extrusion, 0.676 kWh per kg of material
Output	Mechanically recycled EPS package used for washing machine	0.66	kg	

Table A.57: The LCI of the mechanical recycling of the EPP package used for washing machine (Box 9) per FU

	Flow	Value	Unit	Remark
Input	Transported EPP package used for washing machine to the EoL treatment center going to mechanical recycling	0.29	kg	Output of Box 8 × (Virgin fraction × fraction of EoL mechanical recycling + recycled fraction), Check Table 3.2 for virgin and recycled fractions and Table 3.1 for EoL fraction of mechanical recycling
	Electricity, medium voltage {RER}| market group for electricity, medium voltage | Cut-off, U	0.19	kWh	TNO data for mechanical recycling based on extrusion, 0.676 kWh per kg of material
Output	Mechanically recycled EPP package used for washing machine	0.29	kg	

Table A.58: The LCI of the mechanical recycling of the paperboard package used for washing machine (Box 9) per FU

	Flow	Value	Unit	Remark
Input	Transported paperboard package used for washing machine to the EoL treatment center going to mechanical recycling	3.27	kg	Output of Box 8 × (Virgin fraction × fraction of EoL mechanical recycling + recycled fraction), Check Table 3.2 for virgin and recycled fractions and Table 3.1 for EoL fraction of mechanical recycling
	Electricity, medium voltage {RER}| market group for electricity, medium voltage | Cut-off, U	2.18	kWh	In line with mechanical recycling for EPP and EPS, only electricity inputs in considered. Value based on (Furberg and Lyng, 2022)
Output	Mechanically recycled paperboard package used for washing machine	3.27	kg	

Table A.59: The LCI of the landfill of the EPS package used for TV (Box 10) per FU

	Flow	Value	Unit	Remark
Input	Transported EPS package used for TV to the EoL treatment center going to mechanical recycling going to landfill	0.03	kg	Output of Box 8 × (Virgin fraction × fraction of EoL landfilling + recycled fraction), Check Table 3.2 for virgin and recycled fractions and

				Table 3.1 for EoL fraction of landfilling
	Waste polystyrene {RoW}| treatment of waste polystyrene, sanitary landfill | Cut-off, U	0.03	kg	Waste treatment
Output	Landfilled EPS package used for TV	0.03	kg	

Table A.60: The LCI of the landfill of the EPP package used for TV (Box 10) per FU

	Flow	Value	Unit	Remark
Input	Transported EPP package used for TV to the EoL treatment center going to landfill	0.05	kg	Output of Box 8 × (Virgin fraction × fraction of EoL landfilling + recycled fraction), Check Table 3.2 for virgin and recycled fractions and Table 3.1 for EoL fraction of landfilling
	Waste polystyrene {RoW}| treatment of waste polystyrene, sanitary landfill | Cut-off, U	0.05	kg	Waste treatment
Output	Landfilled EPP package used for TV	0.05	kg	

Table A.61: The LCI of the landfill of the paperboard package used for TV (Box 10) per FU

	Flow	Value	Unit	Remark
Input	Transported paperboard package used for TV to the EoL treatment center going to landfill	0.02	kg	Output of Box 8 × (Virgin fraction × fraction of EoL landfilling + recycled fraction), Check Table 3.2 for virgin and recycled fractions and Table 3.1 for EoL fraction of landfilling
	Waste paperboard {RoW}| treatment of waste paperboard, sanitary landfill | Cut-off, U	0.02	kg	Waste treatment
Output	Landfilled paperboard package used for TV	0.02	kg	

Table A.62: The LCI of the landfill of the molded pulp package used for TV (Box 10) per FU

	Flow	Value	Unit	Remark
Input	Transported molded pulp package used for TV to the EoL treatment center going to landfill	0.05	kg	Output of Box 8 × (Virgin fraction × fraction of EoL landfilling + recycled fraction), Check Table 3.2 for virgin and recycled fractions and

				Table 3.1 for EoL fraction of landfilling
	Waste paperboard {RoW}| treatment of waste paperboard, sanitary landfill | Cut-off, U	0.05	kg	Waste treatment
Output	Landfilled molded pulp package used for TV	0.05	kg	

Table A.63: The LCI of the landfill of the EPS package used for washing machine (Box 10) per FU

	Flow	Value	Unit	Remark
Input	Transported EPS package used for washing machine to the EoL treatment center going to landfill	0.09	kg	Output of Box 8 × (Virgin fraction × fraction of EoL landfilling + recycled fraction), Check Table 3.2 for virgin and recycled fractions and Table 3.1 for EoL fraction of landfilling
	Waste polystyrene {RoW}| treatment of waste polystyrene, sanitary landfill | Cut-off, U	0.09	kg	Waste treatment
Output	Landfilled EPS package used for washing machine	0.09	kg	

Table A.64: The LCI of the landfill of the EPP package used for washing machine (Box 10) per FU

	Flow	Value	Unit	Remark
Input	Transported EPP package used for washing machine to the EoL treatment center going to landfill	0.18	kg	Output of Box 8 × (Virgin fraction × fraction of EoL landfilling + recycled fraction), Check Table 3.2 for virgin and recycled fractions and Table 3.1 for EoL fraction of landfilling
	Waste polystyrene {RoW}| treatment of waste polystyrene, sanitary landfill | Cut-off, U	0.18	kg	Waste treatment
Output	Landfilled EPP package used for washing machine	0.18	kg	

Table A.65: The LCI of the landfill of the paperboard package used for washing machine (Box 10) per FU

	Flow	Value	Unit	Remark
Input	Transported paperboard package used for washing machine to the EoL treatment center going to landfill	0.14	kg	Output of Box 8 × (Virgin fraction × fraction of EoL landfilling + recycled fraction), Check Table 3.2 for virgin and recycled fractions and

				Table 3.1 for EoL fraction of landfilling
	Waste paperboard {RoW}| treatment of waste paperboard, sanitary landfill | Cut-off, U	0.14	kg	Waste treatment
Output	Landfilled paperboard package used for washing machine	0.14	kg	

Table A.66: The LCI of the incineration of the EPS package used for TV (Box 11) per FU

	Flow	Value	Unit	Remark
Input	Transported EPS package used for TV to the EoL treatment center going to incineration	0.05	kg	Output of Box 8 × (Virgin fraction × fraction of EoL incineration + recycled fraction), Check Table 3.2 for virgin and recycled fractions and Table 3.1 for EoL fraction of incineration
	Waste expanded polystyrene {GLO}| treatment of waste expanded polystyrene, municipal incineration | Cut-off, U	0.05	kg	Waste treatment

Output	Electricity, high voltage {NL}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Cut-off, U	0.31	MJ	According to (Dutch Environmental Database (NMD), 2022), mass*LHV*electricity efficiency
	Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW | Cut-off, U	0.53	MJ	According to (Dutch Environmental Database (NMD), 2022), mass*LHV*heat efficiency
	Incinerated EPS package used for TV	0.05	kg	

Table A.67: The LCI of the incineration of the EPP package used for TV (Box 11) per FU

	Flow	Value	Unit	Remark
Input	Transported EPP package used for TV to the EoL treatment center going to incineration	0.07	kg	Output of Box 8 × (Virgin fraction × fraction of EoL incineration + recycled fraction), Check Table 3.2 for virgin and recycled fractions and Table 3.1 for EoL fraction of incineration
	Waste polypropylene {GLO}| treatment of waste polypropylene, municipal incineration | Cut-off, U	0.07	kg	Waste treatment

Output	Electricity, high voltage {NL}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Cut-off, U	0.57	MJ	According to (Dutch Environmental Database (NMD), 2022), mass*LHV*electricity efficiency
	Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW | Cut-off, U	0.98	MJ	According to (Dutch Environmental Database (NMD), 2022), mass*LHV*heat efficiency
	Incinerated EPS package used for TV	0.07	kg	

Table A.68: The LCI of the incineration of the paperboard package used for TV (Box 11) per FU

	Flow	Value	Unit	Remark
Input	Transported paperboard package used for TV to the EoL treatment center going to incineration	0.02	kg	Output of Box 8 × (Virgin fraction × fraction of EoL incineration + recycled fraction), Check Table 3.2 for virgin and recycled fractions and Table 3.1 for EoL fraction of incineration
	Waste paperboard {GLO}| treatment of waste paperboard, municipal incineration | Cut-off, U	0.02	kg	Waste treatment

Output	Electricity, high voltage {NL}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, U	0.06	MJ	According to (Dutch Environmental Database (NMD), 2022), mass*LHV*electricity efficiency
	Heat, district or industrial, other than natural gas {NL}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, U	0.11	MJ	According to (Dutch Environmental Database (NMD), 2022), mass*LHV*heat efficiency
	Incinerated paperboard package used for TV	0.02	kg	

Table A.69: The LCI of the incineration of the molded pulp package used for TV (Box 11) per FU

	Flow	Value	Unit	Remark
Input	Transported molded pulp package used for TV to the EoL treatment center going to incineration	0.05	kg	Output of Box 8 × (Virgin fraction × fraction of EoL incineration + recycled fraction), Check Table 3.2 for virgin and recycled fractions and Table 3.1 for EoL fraction of incineration
	Waste paperboard {GLO}| treatment of waste paperboard, municipal incineration | Cut-off, U	0.05	kg	Waste treatment

Output	Electricity, high voltage {NL}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, U	0.14	MJ	According to (Dutch Environmental Database (NMD), 2022), mass*LHV*electricity efficiency
	Heat, district or industrial, other than natural gas {NL}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, U	0.23	MJ	According to (Dutch Environmental Database (NMD), 2022), mass*LHV*heat efficiency
	Incinerated paperboard package used for TV	0.05	kg	

Table A.70: The LCI of the incineration of the EPS package used for washing machine (Box 11) per FU

	Flow	Value	Unit	Remark
Input	Transported EPS package used for washing machine to the EoL treatment center going to incineration	0.14	kg	Output of Box 8 × (Virgin fraction × fraction of EoL incineration + recycled fraction), Check Table 3.2 for virgin and recycled fractions and Table 3.1 for EoL fraction of incineration
	Waste expanded polystyrene {GLO}| treatment of waste expanded polystyrene,	0.14	kg	Waste treatment

	municipal incineration | Cut-off, U			
Output	Electricity, high voltage {NL}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Cut-off, U	0.81	MJ	According to (Dutch Environmental Database (NMD), 2022), mass*LHV*electricity efficiency
	Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW | Cut-off, U	1.40	MJ	According to (Dutch Environmental Database (NMD), 2022), mass*LHV*heat efficiency
	Incinerated EPS package used for washing machine	0.14	kg	

Table A.71: The LCI of the incineration of the EPP package used for washing machine (Box 11) per FU

	Flow	Value	Unit	Remark
Input	Transported EPP package used for washing machine to the EoL treatment center going to incineration	0.29	kg	Output of Box 8 × (Virgin fraction × fraction of EoL incineration + recycled fraction), Check Table 3.2 for virgin and recycled fractions and Table 3.1 for EoL fraction of incineration
	Waste polypropylene {GLO}| treatment of waste	0.29	kg	Waste treatment

	polypropylene, municipal incineration | Cut-off, U			
Output	Electricity, high voltage {NL}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Cut-off, U	2.28	MJ	According to (Dutch Environmental Database (NMD), 2022), mass*LHV*electricity efficiency
	Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW | Cut-off, U	3.92	MJ	According to (Dutch Environmental Database (NMD), 2022), mass*LHV*heat efficiency
	Incinerated EPS package used for washing machine	0.29	kg	

Table A.72: The LCI of the incineration of the paperboard package used for washing machine (Box 11) per FU

	Flow	Value	Unit	Remark
Input	Transported paperboard package used for washing machine to the EoL treatment center going to incineration	0.14	kg	Output of Box 8 × (Virgin fraction × fraction of EoL incineration + recycled fraction), Check Table 3.2 for virgin and recycled fractions and

				Table 3.1 for EoL fraction of incineration
	Waste paperboard {GLO}| treatment of waste paperboard, municipal incineration | Cut-off, U	0.14	kg	Waste treatment
Output	Electricity, high voltage {NL}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, U	0.39	MJ	According to (Dutch Environmental Database (NMD), 2022), mass*LHV*electricity efficiency
	Heat, district or industrial, other than natural gas {NL}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, U	0.67	MJ	According to (Dutch Environmental Database (NMD), 2022), mass*LHV*heat efficiency
	Incinerated paperboard package used for washing machine	0.14	kg	

Appendix B
Mass balance for all scenarios

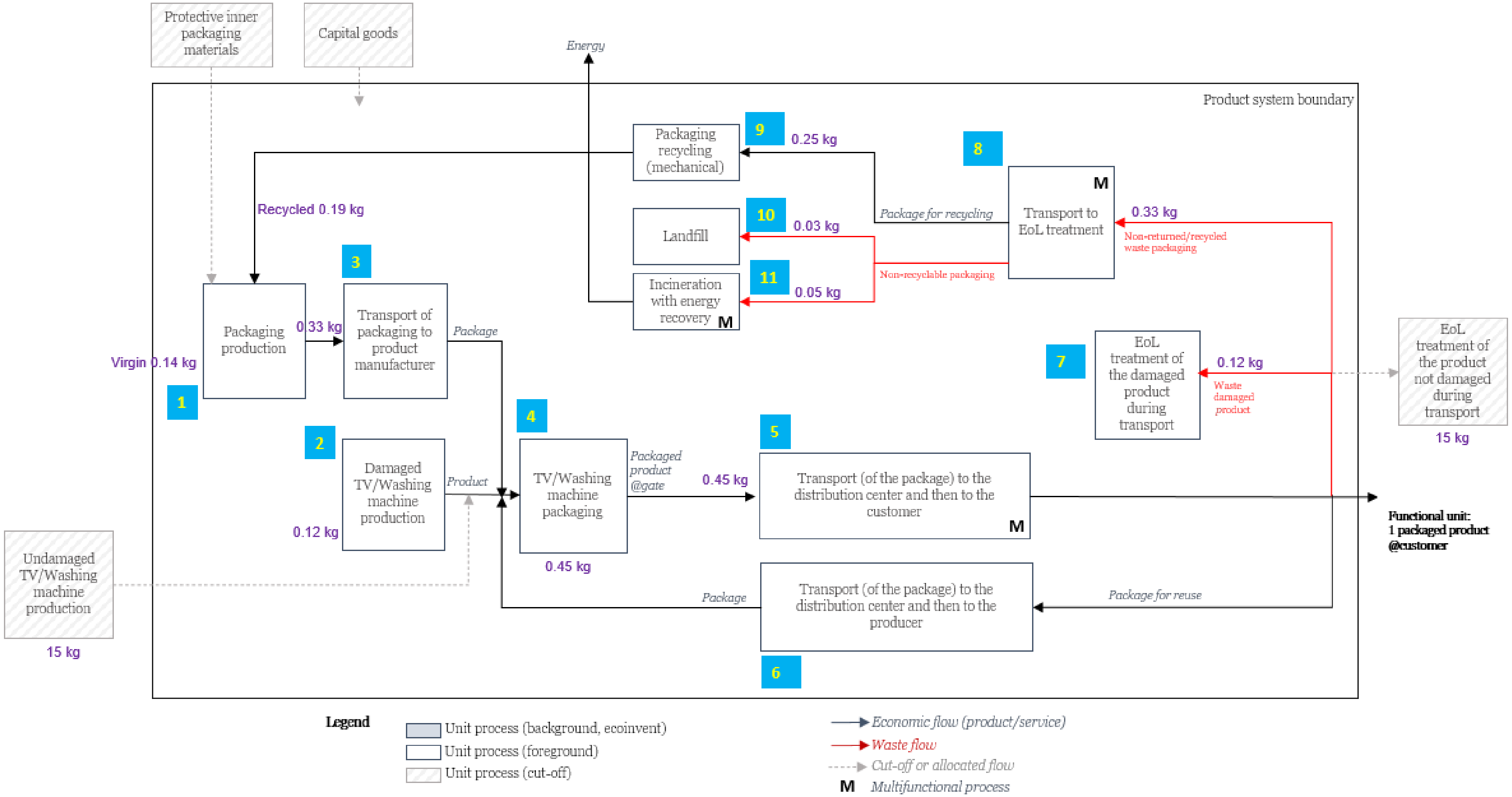

Figure B.1: Mass balance of the value chain consisting of the EPS package and TV

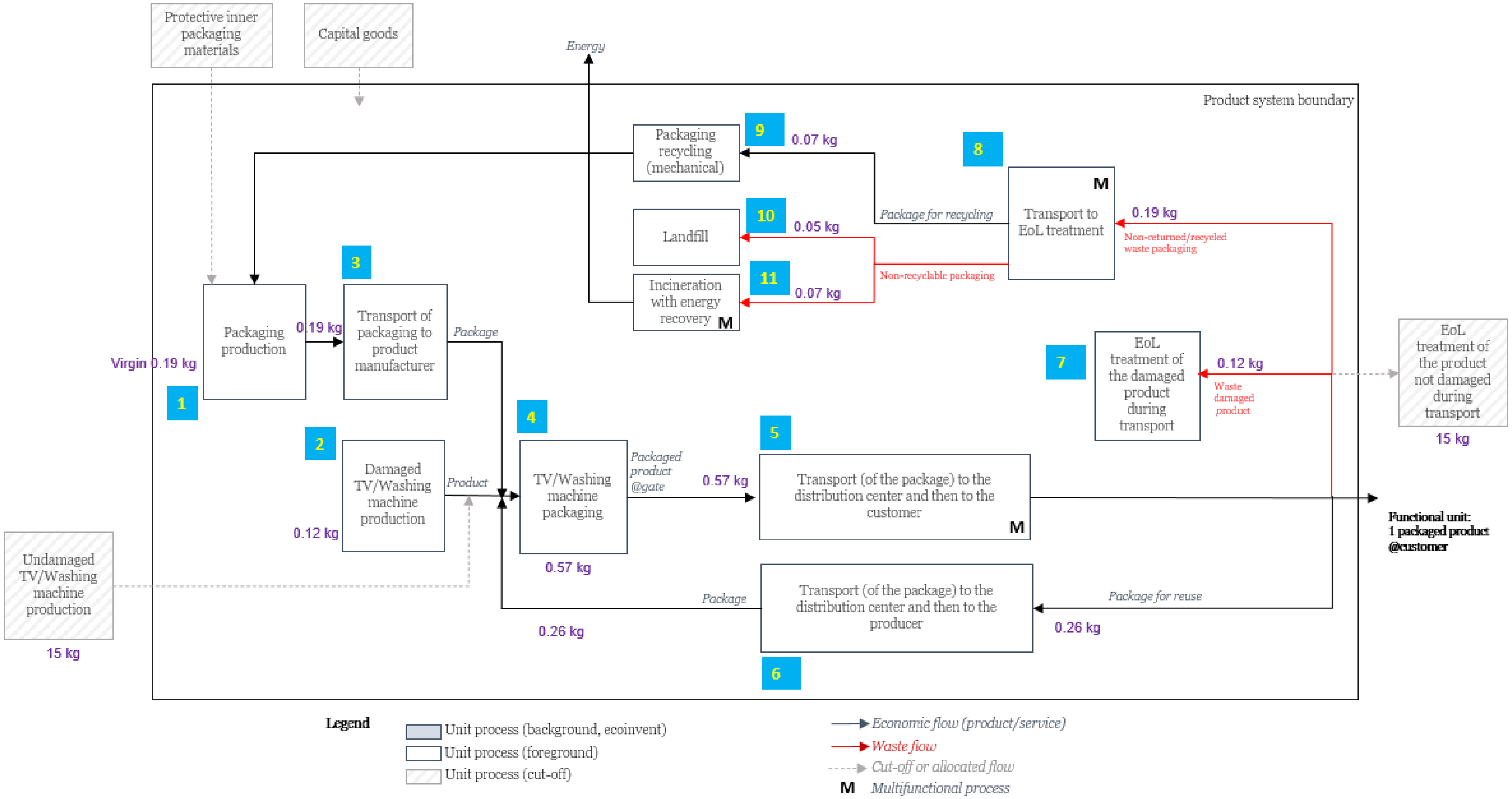

Figure B.2: Mass balance of the value chain consisting of the EPP package and TV

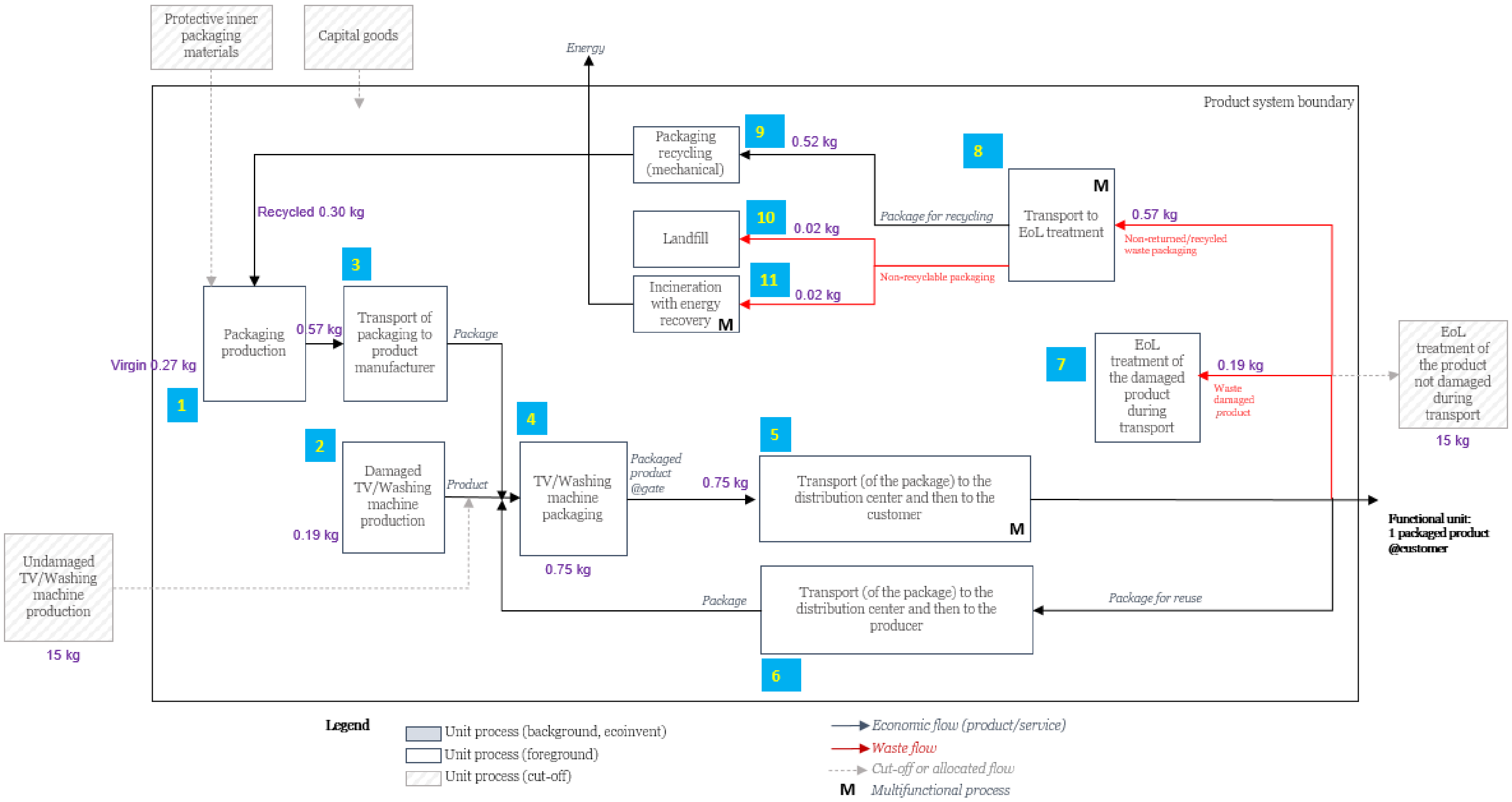

Figure B.3: Mass balance of the value chain consisting of the paperboard package and TV

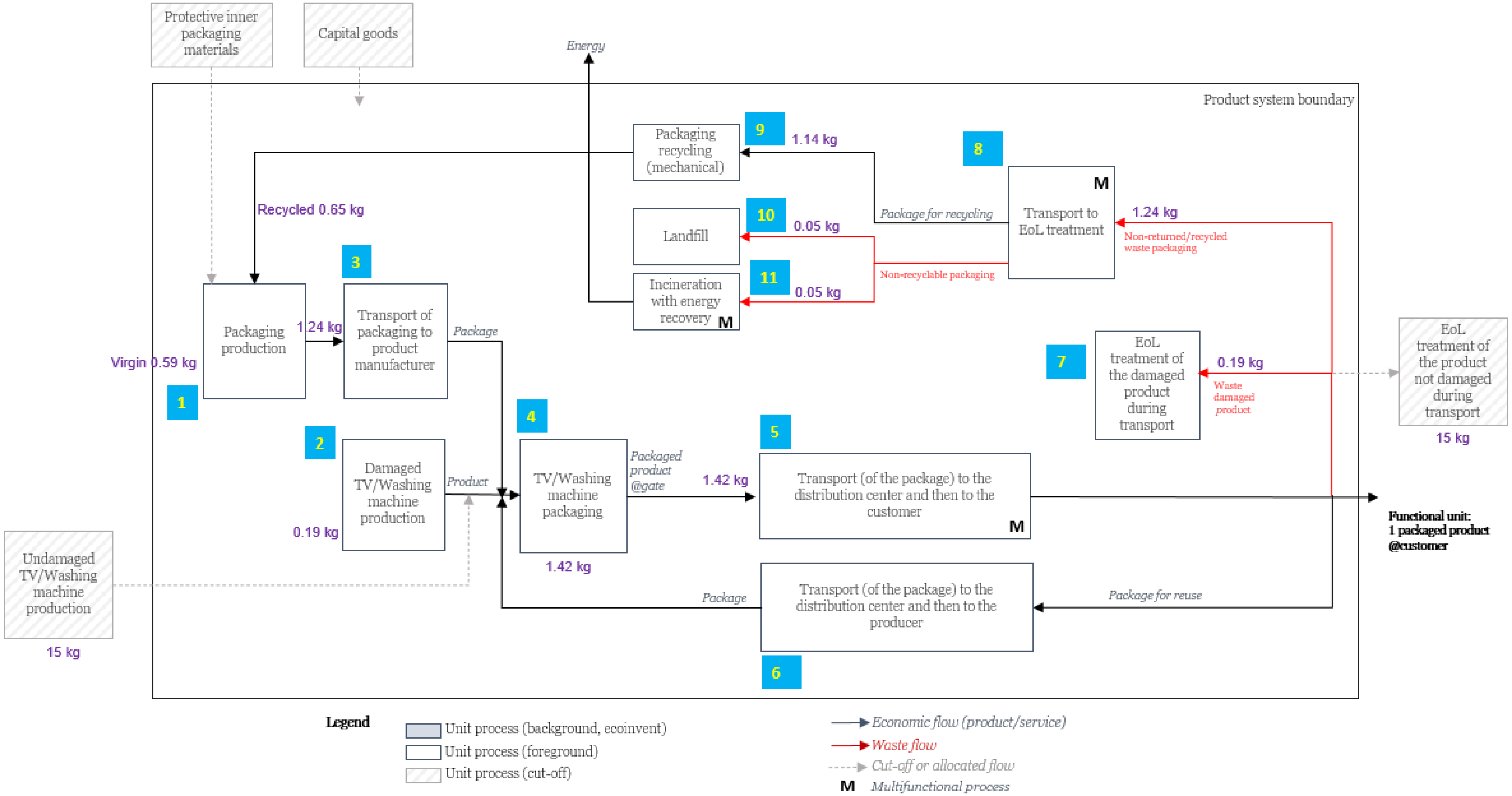

Figure B.4: Mass balance of the value chain consisting of the molded pulp package and TV

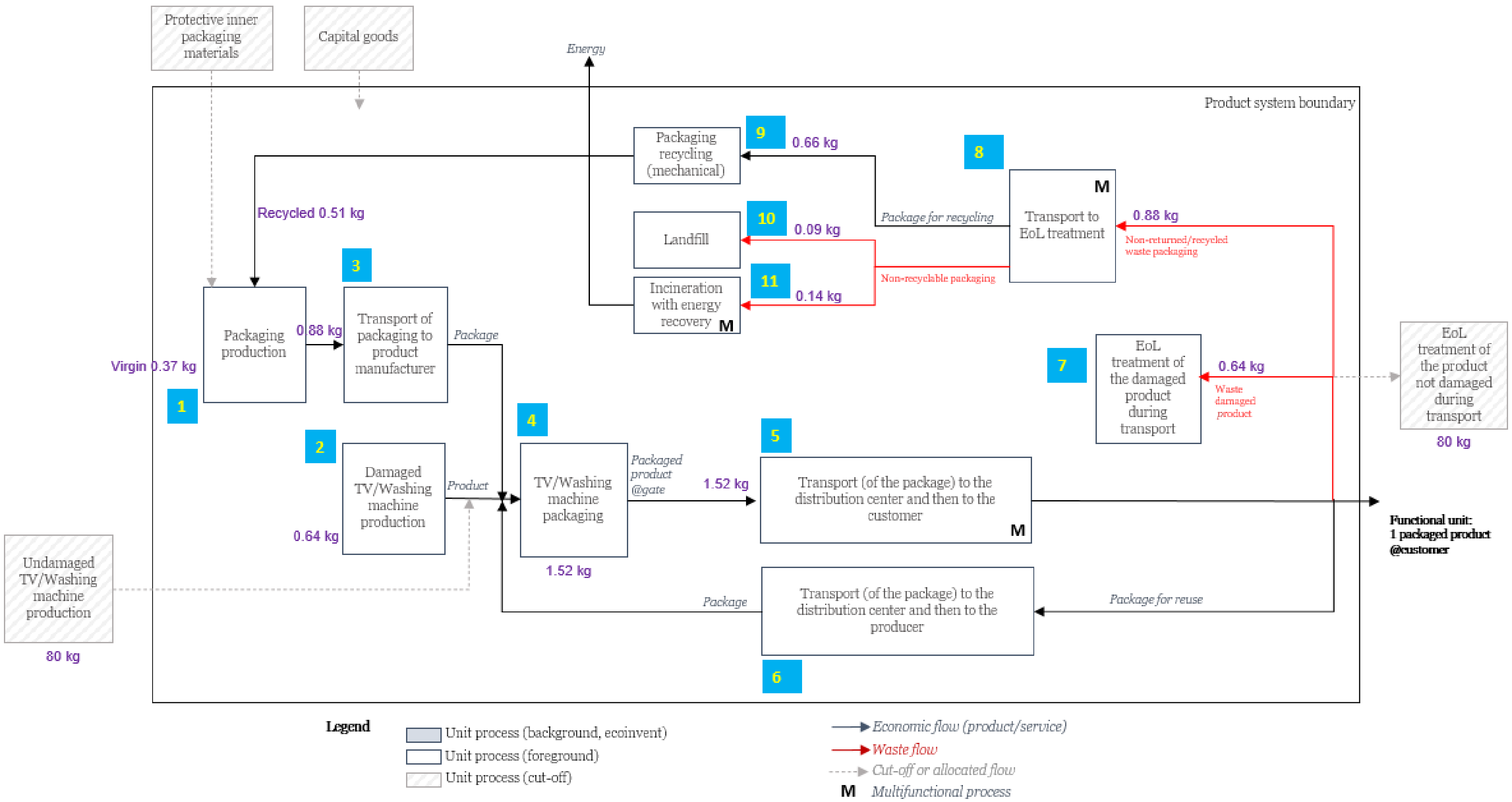

Figure B.5: Mass balance of the value chain consisting of the EPS package and washing machine

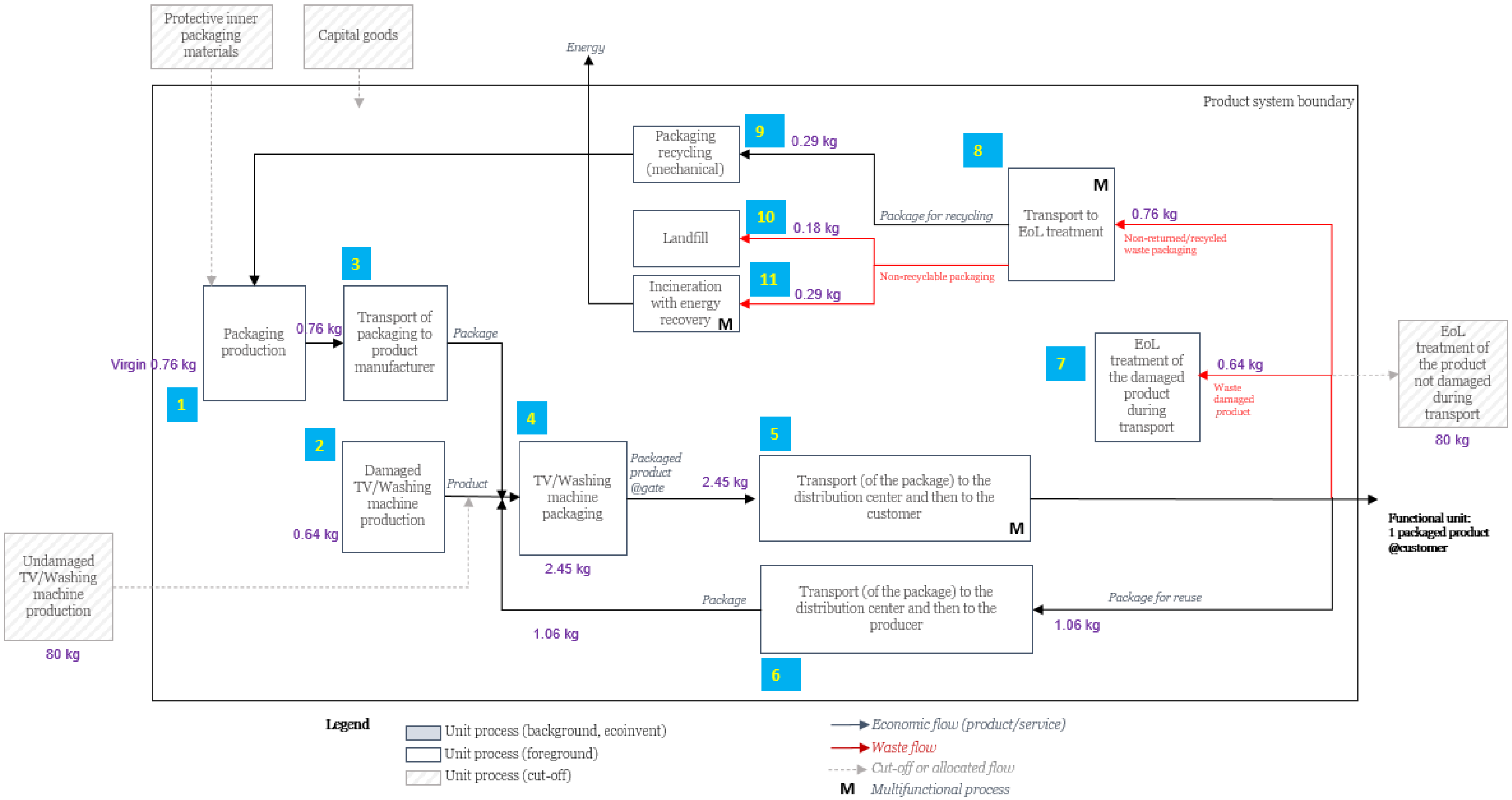

Figure B.6: Mass balance of the value chain consisting of the EPP package and washing machine

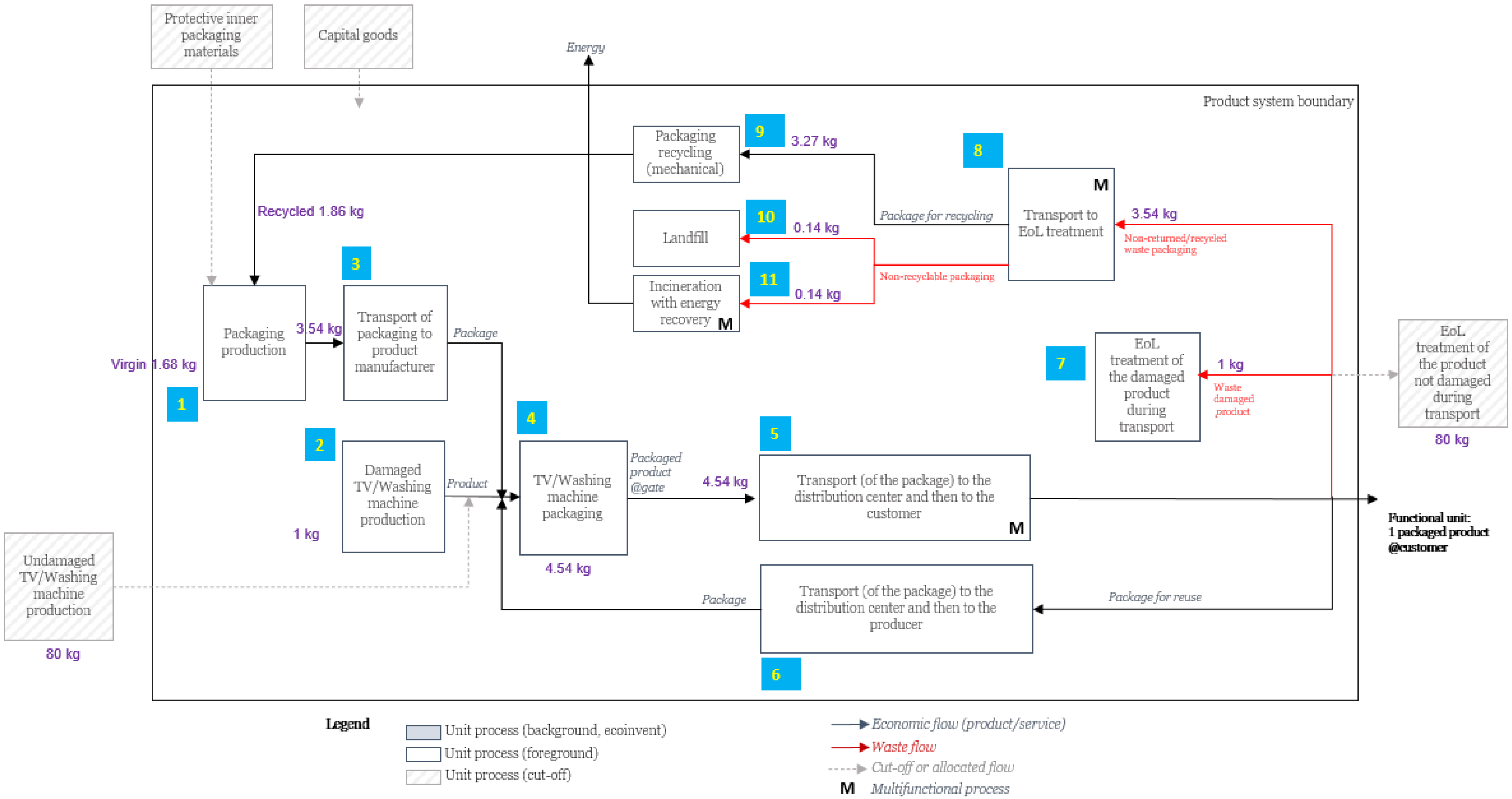

Figure B.7: Mass balance of the value chain consisting of the paperboard package and washing machine

Appendix C
Life Cycle Impact Assessment (LCIA) results

Table C.1: Cradle-to-grave environmental impacts of the packaging material for the different alternatives

Impact category	Unit	TV delivery with EPS package	TV delivery with EPP package	TV delivery with paperboard package	TV delivery with molded pulp package	washing machine delivery with EPS package	washing machine delivery with EPP package	washing machine delivery with paperboard package
Acidification	mol H+ eq	2.48E-03	2.83E-03	1.76E-03	3.18E-03	6.61E-03	1.13E-02	1.10E-02
Climate change	kg CO2 eq	7.13E-01	8.14E-01	4.23E-01	7.47E-01	1.90E+00	3.26E+00	2.64E+00
Ecotoxicity, freshwater	CTUe	1.41E+00	6.82E+00	4.04E+00	7.08E+00	3.76E+00	2.73E+01	2.52E+01
Particulate matter	disease inc.	2.51E-08	3.22E-08	1.43E-08	2.54E-08	6.69E-08	1.29E-07	8.91E-08
Eutrophication, marine	kg N eq	4.17E-04	5.41E-04	6.72E-04	1.19E-03	1.11E-03	2.16E-03	4.20E-03
Eutrophication, freshwater	kg P eq	1.03E-04	2.13E-04	2.46E-04	4.71E-04	2.75E-04	8.54E-04	1.54E-03
Eutrophication, terrestrial	mol N eq	4.07E-03	5.47E-03	4.97E-03	8.71E-03	1.09E-02	2.19E-02	3.11E-02
Human toxicity, cancer	CTUh	2.38E-10	1.91E-09	1.34E-09	2.26E-09	6.36E-10	7.63E-09	8.39E-09
Human toxicity, non-cancer	CTUh	1.83E-09	5.60E-09	5.05E-09	9.03E-09	4.88E-09	2.24E-08	3.16E-08
Ionising radiation	kBq U-235 eq	5.83E-02	6.57E-02	1.03E-01	2.04E-01	1.56E-01	2.63E-01	6.42E-01
Land use	Pt	6.84E-01	2.35E+00	1.04E+01	2.82E+01	1.82E+00	9.39E+00	6.49E+01
Ozone depletion	kg CFC11 eq	3.65E-09	1.19E-08	9.22E-09	1.44E-08	9.74E-09	4.77E-08	5.76E-08
Photochemical ozone formation	kg NMVOC eq	3.21E-03	4.72E-03	1.44E-03	2.62E-03	8.55E-03	1.89E-02	9.03E-03
Resource use, fossils	MJ	1.30E+01	1.56E+01	6.56E+00	1.17E+01	3.46E+01	6.22E+01	4.10E+01
Resource use, minerals and metals	kg Sb eq	2.68E-07	4.51E-06	1.33E-06	2.14E-06	7.14E-07	1.80E-05	8.29E-06
Water use	m3 depriv.	4.02E-01	1.78E-01	1.58E-01	2.53E-01	1.07E+00	7.12E-01	9.86E-01

Table C.2: Cradle-to-grave environmental impacts of the damaged products (depending on the type of packaging and the associated damage rate, the total quantity of the damaged products may vary)

Impact category	Unit	TV delivery with EPS package	TV delivery with EPP package	TV delivery with paperboard package	TV delivery with molded pulp package	washing machine delivery with EPS package	washing machine delivery with EPP package	washing machine delivery with paperboard package
Acidification	mol H+ eq	2.07E-02	2.07E-02	3.23E-02	3.23E-02	2.50E-02	2.50E-02	3.90E-02
Climate change	kg CO2 eq	1.60E+00	1.60E+00	2.50E+00	2.50E+00	3.62E+00	3.62E+00	5.65E+00
Ecotoxicity, freshwater	CTUe	5.49E+01	5.49E+01	8.57E+01	8.57E+01	4.63E+01	4.63E+01	7.23E+01
Particulate matter	disease inc.	1.33E-07	1.33E-07	2.08E-07	2.08E-07	3.08E-07	3.08E-07	4.81E-07
Eutrophication, marine	kg N eq	2.66E-03	2.66E-03	4.16E-03	4.16E-03	3.71E-03	3.71E-03	5.80E-03
Eutrophication, freshwater	kg P eq	2.41E-03	2.41E-03	3.76E-03	3.76E-03	1.77E-03	1.77E-03	2.77E-03
Eutrophication, terrestrial	mol N eq	3.06E-02	3.06E-02	4.78E-02	4.78E-02	3.76E-02	3.76E-02	5.88E-02
Human toxicity, cancer	CTUh	9.41E-09	9.41E-09	1.47E-08	1.47E-08	7.00E-08	7.00E-08	1.09E-07
Human toxicity, non-cancer	CTUh	1.08E-07	1.08E-07	1.68E-07	1.68E-07	1.45E-07	1.45E-07	2.27E-07
Ionising radiation	kBq U-235 eq	1.51E-01	1.51E-01	2.36E-01	2.36E-01	1.79E-01	1.79E-01	2.80E-01
Land use	Pt	1.29E+01	1.29E+01	2.01E+01	2.01E+01	1.65E+01	1.65E+01	2.57E+01
Ozone depletion	kg CFC11 eq	3.94E-08	3.94E-08	6.16E-08	6.16E-08	3.05E-08	3.05E-08	4.76E-08
Photochemical ozone formation	kg NMVOC eq	1.10E-02	1.10E-02	1.71E-02	1.71E-02	1.29E-02	1.29E-02	2.02E-02
Resource use, fossils	MJ	2.07E+01	2.07E+01	3.24E+01	3.24E+01	4.91E+01	4.91E+01	7.68E+01
Resource use, minerals and metals	kg Sb eq	6.91E-04	6.91E-04	1.08E-03	1.08E-03	1.51E-04	1.51E-04	2.36E-04
Water use	m3 depriv.	5.16E-01	5.16E-01	8.06E-01	8.06E-01	1.16E+00	1.16E+00	1.81E+00

Table C.3: Cradle-to-grave environmental impacts of the transportation for different packaging alternatives

Impact category	Unit	TV delivery with EPS package	TV delivery with EPP package	TV delivery with paperboard package	TV delivery with molded pulp package	washing machine delivery with EPS package	washing machine delivery with EPP package	washing machine delivery with paperboard package
Acidification	mol H+ eq	2.93E-04	4.53E-04	4.88E-04	9.26E-04	9.79E-04	1.91E-03	2.94E-03
Climate change	kg CO2 eq	6.37E-02	9.89E-02	1.06E-01	2.02E-01	2.13E-01	4.17E-01	6.41E-01
Ecotoxicity, freshwater	CTUe	2.59E-01	4.00E-01	4.32E-01	8.20E-01	8.66E-01	1.69E+00	2.61E+00
Particulate matter	disease inc.	5.67E-09	8.84E-09	9.46E-09	1.79E-08	1.90E-08	3.73E-08	5.70E-08
Eutrophication, marine	kg N eq	1.15E-04	1.77E-04	1.92E-04	3.64E-04	3.84E-04	7.48E-04	1.16E-03
Eutrophication, freshwater	kg P eq	4.74E-06	7.34E-06	7.91E-06	1.50E-05	1.59E-05	3.10E-05	4.77E-05
Eutrophication, terrestrial	mol N eq	1.25E-03	1.94E-03	2.09E-03	3.97E-03	4.19E-03	8.16E-03	1.26E-02
Human toxicity, cancer	CTUh	4.51E-10	6.97E-10	7.52E-10	1.43E-09	1.51E-09	2.94E-09	4.53E-09
Human toxicity, non-cancer	CTUh	6.26E-10	9.71E-10	1.04E-09	1.98E-09	2.10E-09	4.10E-09	6.30E-09
Ionising radiation	kBq U-235 eq	1.42E-03	2.19E-03	2.37E-03	4.49E-03	4.74E-03	9.24E-03	1.43E-02
Land use	Pt	6.27E-01	9.86E-01	1.04E+00	1.98E+00	2.10E+00	4.16E+00	6.30E+00
Ozone depletion	kg CFC11 eq	1.28E-09	1.98E-09	2.13E-09	4.04E-09	4.27E-09	8.37E-09	1.28E-08
Photochemical ozone formation	kg NMVOC eq	4.44E-04	6.87E-04	7.40E-04	1.40E-03	1.48E-03	2.90E-03	4.47E-03
Resource use, fossils	MJ	9.08E-01	1.41E+00	1.51E+00	2.87E+00	3.04E+00	5.95E+00	9.14E+00
Resource use, minerals and metals	kg Sb eq	2.28E-07	3.52E-07	3.81E-07	7.23E-07	7.63E-07	1.49E-06	2.30E-06
Water use	m3 depriv.	4.07E-03	6.33E-03	6.78E-03	1.29E-02	1.36E-02	2.67E-02	4.09E-02

Table C.4: Total cradle-to-grave environmental impacts of different packaging alternatives

Impact category	Unit	TV delivery with EPS package	TV delivery with EPP package	TV delivery with paperboard package	TV delivery with molded pulp package	washing machine delivery with EPS package	washing machine delivery with EPP package	washing machine delivery with paperboard package
Acidification	mol H+ eq	2.35E-02	2.40E-02	3.46E-02	3.64E-02	3.26E-02	3.82E-02	5.30E-02
Climate change	kg CO2 eq	2.38E+00	2.51E+00	3.03E+00	3.45E+00	5.73E+00	7.29E+00	8.94E+00
Ecotoxicity, freshwater	CTUe	5.65E+01	6.21E+01	9.02E+01	9.36E+01	5.09E+01	7.53E+01	1.00E+02
Particulate matter	disease inc.	1.64E-07	1.74E-07	2.31E-07	2.51E-07	3.94E-07	4.74E-07	6.27E-07
Eutrophication, marine	kg N eq	3.20E-03	3.38E-03	5.03E-03	5.71E-03	5.21E-03	6.62E-03	1.12E-02
Eutrophication, freshwater	kg P eq	2.52E-03	2.63E-03	4.02E-03	4.25E-03	2.06E-03	2.66E-03	4.36E-03
Eutrophication, terrestrial	mol N eq	3.59E-02	3.80E-02	5.49E-02	6.05E-02	5.27E-02	6.77E-02	1.02E-01
Human toxicity, cancer	CTUh	1.01E-08	1.20E-08	1.68E-08	1.84E-08	7.21E-08	8.05E-08	1.22E-07
Human toxicity, non-cancer	CTUh	1.10E-07	1.14E-07	1.75E-07	1.79E-07	1.52E-07	1.72E-07	2.65E-07
Ionising radiation	kBq U-235 eq	2.11E-01	2.19E-01	3.42E-01	4.45E-01	3.40E-01	4.52E-01	9.37E-01
Land use	Pt	1.42E+01	1.62E+01	3.16E+01	5.03E+01	2.04E+01	3.00E+01	9.70E+01
Ozone depletion	kg CFC11 eq	4.43E-08	5.33E-08	7.29E-08	8.00E-08	4.45E-08	8.66E-08	1.18E-07
Photochemical ozone formation	kg NMVOC eq	1.46E-02	1.64E-02	1.93E-02	2.11E-02	2.29E-02	3.47E-02	3.37E-02
Resource use, fossils	MJ	3.46E+01	3.77E+01	4.05E+01	4.70E+01	8.67E+01	1.17E+02	1.27E+02
Resource use, minerals and metals	kg Sb eq	6.91E-04	6.96E-04	1.08E-03	1.08E-03	1.52E-04	1.71E-04	2.47E-04
Water use	m3 depriv.	9.22E-01	7.00E-01	9.70E-01	1.07E+00	2.24E+00	1.90E+00	2.84E+00

Appendix D
Review Statement

CE Delft
Committed to the Environment

Review statement

Study title	Life Cycle Assessment (LCA) of different packaging solutions for white and brown goods (Version 25 February 2025)
LCA practitioner	TNO (Pouya Samani)
Commissioner	EUMEPS and BASF
Reviewed by	CE Delft (Martijn Broeren, Jan van de Pol)
Review period	Review period: October 2024 - February 2025 Review statement: 27 February 2025

The reviewers consider TNO's LCA on different packaging solutions for white and brown goods in line with the requirements of the ISO 14040:2006 and ISO 14044:2006 standards on life cycle assessment.

Study overview

The life cycle assessment (LCA) compares the environmental performance of several packaging solutions for white and brown goods. This is done for a scenario with high package return rates (for reuse or recycling), which is explicitly not intended to represent current practice. The assessment is intended to inform industrial decision-makers and technical exports on environmental benefits and drawbacks between packaging options to help decision making. Additionally, the study aims to help policymakers develop policies based on the results of the study.

This comparison is made for the use of expanded polypropylene (EPP), expanded polystyrene (EPS), honeycomb paperboard and moulded pulp for delivery of a TV and washing machine. A scenario for reusable EPP packaging is compared with a scenario with a recycling scenario for the other single use packaging options. For both scenarios it is assumed that after the first 5 life cycles products were returned at a 70% rate for reuse or recycling. After the sixth life cycle conventional end of life pathways are considered.

The study shows that the environmental performance of the studied alternatives depends strongly on various uncertain parameters, including the damage rate, the mass of the package, and modelling choices such as whether damaged products during transportation are taken into account. This means it is not straightforward to draw definitive conclusions between the different packaging materials and highlights the need for more robust data.

Review process

The critical review took place in several rounds and was based on ISO 14040-44 requirements. The main improvements made based on the critical review were:
- The scenarios with high reuse or recycling in the first life cycles were better introduced.
- Improved reproducibility as a result of more extensive LCI.
- Better reflection on data quality and the effect on the robustness of conclusions.
- Improved structure of the report.

All comments and recommendations were addressed in the updated versions, resulting in a more transparent and complete LCA report. Note that the LCA modelling in LCA software was not included in this critical review.

CE Delft
Committed to the Environment

Review statement

The LCA on packaging material by TNO is well executed, the used method and outcomes are transparently and appropriately documented for the goal and intended audience of the study. The data used have a large degree of uncertainty. These uncertainties are qualitatively discussed throughout the report and quantitively in the sensitivity analysis. The uncertainties are also properly reflected in the overall conclusion.

This study provides key insights into the contributing factors and influential parameters of the comparative performance of packaging solutions for white and brown goods for a variety of environmental impacts. Sensitivity analyses only reflects on climate change impacts. However, as the results of the sensitivity analysis are used to conclude that the results are highly uncertain, we understand this from a practical perspective.

The LCA methodology has been followed adequately and modelling choices are explained sufficiently throughout the report, although the presentation of the modelling and underlying data can be streamlined. The reviewers therefore consider the LCA in line with the requirements of the ISO 14040:2006 and ISO 14044:2006 standards on life cycle assessment. The modelling in LCA software was not checked as part of this critical review. However, based on the report the model can be reproduced and the reviewers have no reason to doubt its correctness.

When interpreting the results, it is important to note that the study focuses on a scenario with very high package return rates, which is not representative of current practices. Future research can focus on increasing the robustness of data points/assumptions to enable stronger conclusions on the environmental superiority of one of the alternatives. In addition, it could be relevant to compare a business-as-usual scenario to the (currently modelled) high-reuse or recycling scenarios, as this could help the intended audience in decision-making.

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