



Life Cycle Inventories of Single Use Plastic Products and their Alternatives

Part of “Study to explore links
between production, the
environment and environmental
policy”

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1 Introduction

The EU Strategy on Plastics seeks to integrate reuse and recycling into production chains in order to curb the negative environmental and economic impacts of littering of single-use plastics. Products bring about impacts not just from their manufacturing, but also from the sourcing of raw materials for their production, their usage and end-of-life, as well as due to logistics for transportation. However, work exists that has shown that substitution of plastics with alternative materials need not bring resource efficiency benefits due to the higher demands for energy and resources of alternative materials (Denkstatt, 2010; Franklin Associates, 2014) or due to benefits brought about by plastics in the use phase such as longer shelf lives for food (Williams and Wikström, 2011; Roy et al., 2009) or larger impacts of alternatives due to washing of reusable containers' use of energy and water (Humbert et al., 2009).

Thus, decisions on promotion of alternatives to single-use plastics need to consider the full life-cycle impacts of said plastics and their alternatives. For this study, life-cycle assessment (LCA) has been performed for nine widely-used single-use plastics products (SUPs) and their single-use non-plastic alternatives (SUNPs), as well as reusable alternatives (multi-use; MU), with the aim of answering the following question:

"If single-use plastics products were replaced by either single-use non-plastics alternatives or multi-use items, what would the impact be on greenhouse gas and air pollutant emissions?"

The aim of the life-cycle study was to build life-cycle inventories of the single-use plastics and their alternatives under analysis in the Strategy on Plastics Impact Assessment. CO₂, CH₄ as well as sixteen types of air pollutants have been considered. The life-cycle inventories of the product systems under consideration are fed into the wider Strategy on Plastics Impact Assessment model, where they supplement the analysis of plastics' & their alternatives' end-of-life, thus contributing to the overall life-cycle view of the Impact Assessment. Consequently, no separate life-cycle impact assessment (as done in LCA) has been conducted.

2 Methodology

2.1 Functional unit

In order to align the modelling of all products under consideration, the functional unit used throughout this work is one use of a product in question or of its alternative(s). For single-use plastic and non-plastic items, this equates to the production of 1 item. For multi-use items, this is the production of 1 item divided by its number of reuses, plus the burdens of 1 wash cycle. The product & washing systems are further detailed in section 2.3 *Product systems studied*.

2.2 Data sources & system boundaries

The life-cycle inventories compiled for all products under consideration are fully based on Ecoinvent v3.4 for both foreground and background data (Wernet et al., 2016). This was necessitated due to the breadth of the study but also in order to ensure comparability between all modelled systems. All stages from raw materials extraction up to and including use phase are considered. End-of-life treatment is excluded from the LCI scope due to end-of-life fates being considered separately in the Strategy on Plastics Impact Assessment model. For dealing with co-product allocation, the system expansion method is used via the Ecoinvent “consequential” model, as is generally recommended for studies with decision support in mind (Ekvall and Weidema, 2004). Via system expansion, the consequences of changes in demand for products from unconstrained suppliers (such that can respond to changes in demand, i.e. those that are expected to change) are modelled. Under system expansion, the products modelled receive the full burdens of the impacts of their inputs and emissions but also receive benefits (“credits”, i.e. impacts that are subtracted) for any by-products produced that can substitute other products (such as waste heat used for energy generation). For a fuller discussion on consequential modelling, refer to Ekvall and Weidema (2004) and Wernet et al. (2016).

Where possible, Ecoinvent market datasets have been used. Market datasets represent the consumption mixes of products in different regions, including also transport burdens, as well as additional product inputs in order to compensate for losses at the transportation stage (e.g. transmission losses for electricity). Thus, market datasets offer geographical representation, as well as a fuller view of the supply chains of product systems. Where market datasets have not been available, such have been constructed with generic Ecoinvent transport data used (Borken-Kleefeld and Weidema, 2013).

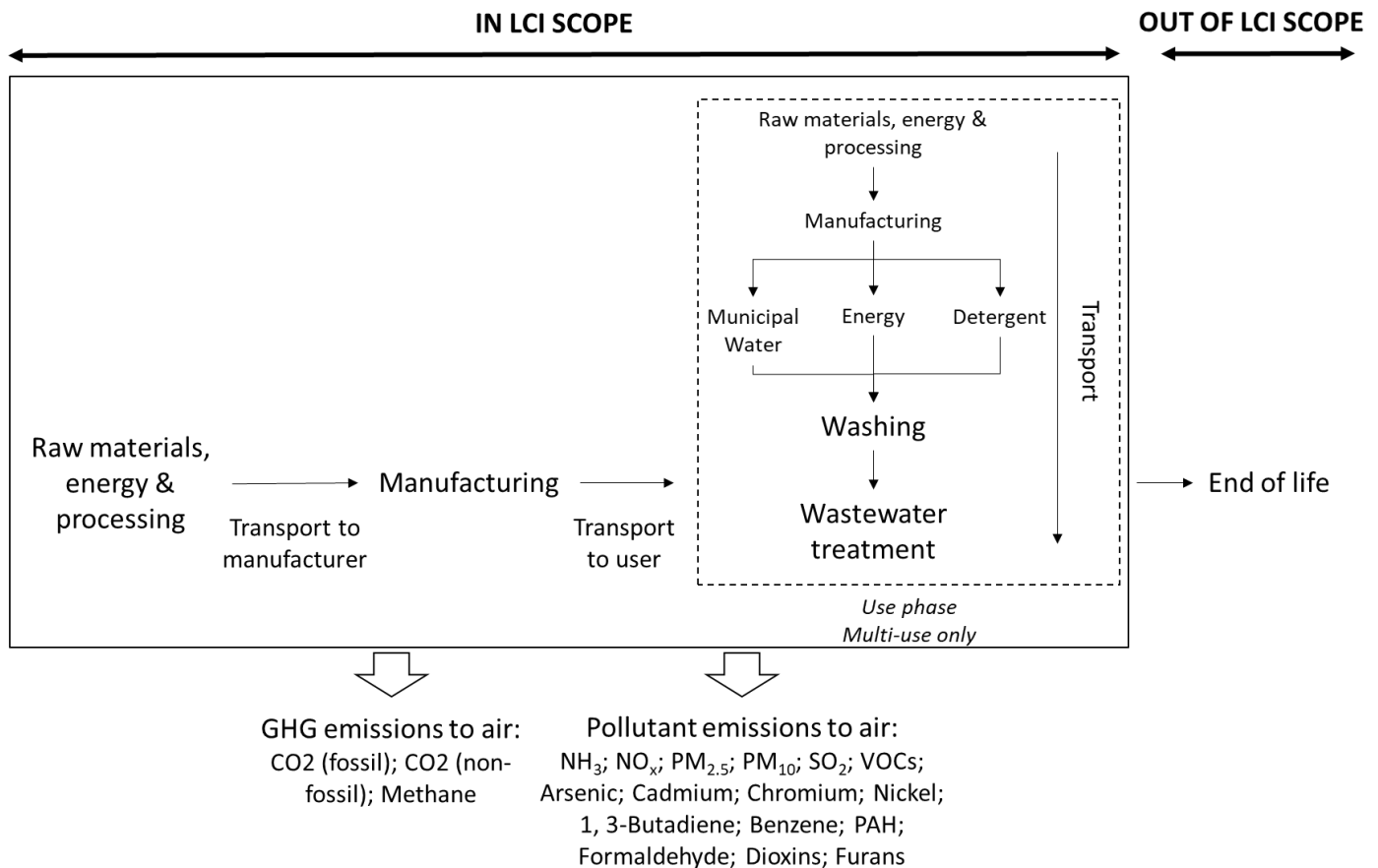
With regards to geography, geographic differentiation in products’ life cycles was out of scope for this work. Thus, market datasets with global geographies (*GLO*) have been used, except for the use phase of products, where data representative for Europe has been utilised (“RER”, “Europe without Switzerland” or other appropriate Ecoinvent geography). The use of globally-representative data is for avoiding the need for accounting for the geographical origins of the products used, which is increasingly difficult further up their life cycles (e.g. w.r.t. sourcing of primary materials such as fuels or metals). In contrast, the use phase is known to occur within Europe and thus representative datasets are used.

Ecoinvent datasets typically also include infrastructure burdens where appropriate. This has thus been included in the analysis where bundled in existing datasets but no special effort has been made to add infrastructure burdens where such are missing. The same treatment is applied for secondary and tertiary packaging. For products such as drinks bottles, only the packaging itself is considered, i.e. filling of bottles etc. has not been considered.

The use phase - consisting of washing of items and wastewater treatment, as well as the life cycles of the aforementioned - is modelled for multi-use items only as the use phase of non-MU items was not deemed significant for inclusion. Wastewater treatment is included (with European datasets) in contrast to other end-of-life pathways as this is in addition to what is considered in the overall Impact Assessment model.

Figure 1 illustrates the system boundary of all products considered, as well as the emissions included in the compilation of their life-cycle inventories.

Figure 1 System boundaries of the life-cycle inventories compiled, and emissions considered



2.3 Product systems studied

In total, twelve products & their potential alternatives were originally considered for modelling (Table 1). The criteria for selection of plastics alternatives (SUNP and MU products) were that:

1. The materials of which SUNP items are composed avoid the generation of microplastics. This thus excluded biodegradable plastics from the study scope as such biodegradability can only be insured in specific conditions which are seldom met in the marine environment (Thompson, 2006; Kershaw, 2015)
2. Alternative products meet the same function as the plastic products that they substitute in terms of properties that the materials ensure. Such products were not identified for product groups Crisps packets and Sweet wrappers (transmission of O₂ and water vapour, opacity), as well as for SUNP Drinks cups and lids (permeability and resistance of insulating layer to heat) and sanitary towels (permeability and absorbency).
3. Multi-use items need to ensure that use of single-use plastics is avoided. This ruled out reusable cigarette filters, as such are used in addition of a traditional cigarette (as an additional filter) and would thus not displace the use of a cellulose acetate filter.

4. Alternatives need to satisfy broadly the same market. This ruled out items such as e-cigarettes, which are tobacco substitutes and thus not necessarily targeting an analogous market segment.

Table 1 Product systems considered - with materials specified - for single-use plastic items (SUPs), single-use non-plastic items (SUNPs) and multi-use items (MU)

Product category	SUP	SUNP	MU
Cigarette butts	Cellulose acetate filter	Natural fibre filter (hemp/cotton)	-
Drinks bottles	Average volume PET bottle	Average non-plastic container (Aluminium/glass)	Average multi-use container: Consumer-led: PET/Aluminium Industry-led: PET/Glass
Cotton buds	PP bud	Paper bud	Reusable MDPE bud
Crisps packets	Excluded from scope		
Sweet wrappers			
Sanitary towels	Ultrathin pad (PE, PP, PET, SAP)	-	Washable cotton pad
Wet wipes	Synthetic fibre wipe (w/ lotion)	Cotton ball + lotion	Cotton handkerchief + lotion
Cutlery	Average PP utensil	Average wooden utensil	Average steel utensil
Straws	PP straw	Paper straw	Average reusable straw (steel/silicone)
Stirrers	PP stirrer	Wooden stirrer	Steel stirrer
Food containers	PS clamshell container	Paperboard + wax container	PE tupperware box
Drinks cups and lids	Paper cup w/ PE coating and LDPE lid	-	Reusable PP cup (w/ LDPE, rubber, silicone components)

Note(s) : Products with materials separated by forward slash are market averages of separate products made

In choosing the reference products for each product category in Table 1, generally most widely used products have been selected. Where multiple such products exist (such as different volumes of drinks bottles), averaged products have been modelled, either in terms of mass (in the case of different sizes of the same product) or in terms of composition (in the case of alternatives from different materials existing for SUNP and MU items). Where possible, market reports have been used in order to derive average reference products.

The specification of each reference product is detailed in [Appendix 1](#).

2.4 Washing and reusability of multi-use items

For modelling the washing of multi-use items, representative datasets were compiled from Ecoinvent data. Three markets for washing were compiled, representing an aggregate dataset consisting of inputs of water, energy, detergent and wastewater treatment (Figure 1). Due to the reusability of multi-use items, their burdens up to and including the manufacturing stage would be small and the product system would thus be dominated by its use (washing) phase. Washing impacts can strongly differ based on the technology used, especially w.r.t. EU Ecodesign criteria and uptake of newer appliances over time. Thus, we model a best-case and worst-case washing scenario, representing new and old technologies. The modelling of washing distinguishes between washing of sanitary and non-sanitary items (Figure 2), as well as includes an industrial washing process for industry-led drinks bottles (i.e. as in a deposit-refund scheme). Table 2 depicts the

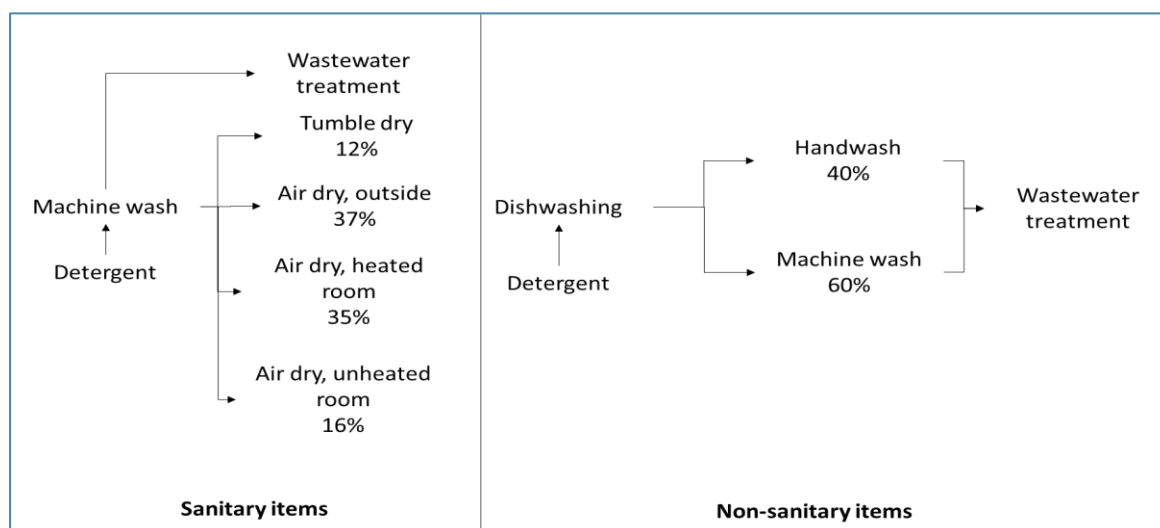
applicable washing market for different product groups. Burdens of infrastructure/building of machinery are taken as-is from Ecoinvent for input datasets but no additional effort has been made for full inclusion.

Table 2 Use of market datasets for different product groups considered

Product category	Market for dishwashing	Market for laundry	Market for industrial washing	Number of reuses
Cigarette butts	-	-	-	-
Drinks bottles	Consumer-led		Industry-led	2808
Cotton buds	X			734
Sanitary towels		X		426
Wet wipes		X		6330
Cutlery	X			4416
Straws	X			5412
Stirrers	X			11274
Food containers	X			515
Drinks cups and lids	X			564

Dash depicts product groups where no multi-use items are modelled. Further given are the number of reuses assumed for multi-use products.

Figure 2 Structure of washing models for sanitary and non-sanitary items, including shares of technologies used



3 Compiled life-cycle inventories, interpretation and limitations

The following section presents the results of the life-cycle inventory compilation that feeds into the rest of the model for the Strategy on Plastics Impact Assessment. These results are summarised in Table 3.

As the compiled life-cycle inventories are fed into the general Impact Assessment model, they should not be interpreted in vacuum w.r.t. to preference of SUP, SUNP or MU items. However, it is worth noting some subtleties in interpretation owing to the limitations of the modelling procedure:

3.1 Negative emissions

Inspection of the compiled life-cycle inventories shows that they contain results with both positive and negative signs, i.e. respectively burdens (impacts) and credits (avoided impacts). This emergence of avoided impacts is due to the treatment of co-product allocation in the consequential modelling framework.

Careful interpretation is necessary. Impacts with a negative sign in the life-cycle inventories do not mean that the use of the reference product (e.g. a cotton ball for SUNP wet wipes) has caused a positive impact on the environment for a particular emission. Rather, through inclusion of the use of co-products (such as cotton seeds leftover from cotton yarn production) in the system boundary of the product, this use has displaced production of an input somewhere else in the economy (e.g. the animal feed sector where cotton meal produced from cotton seeds is sometimes used). Upon close inspection, the most important contributions of avoided burdens in the products systems are due to:

- The use of co-produced heat for energy generation – utilised process heat displaces production of electricity from the grid
- For products with cotton as inputs, the use of co-produced cotton seeds for production of cottonseed oil (typically used in the food industry) and meal (typically used as animal feed or organic fertiliser).

3.2 Impacts of washing of non-sanitary items

It can be seen from Table 3 that multi-use Straws, Stirrers and Cutlery are consistently the worse-performing of all alternatives in these product groups. Due to their reusability, the manufacturing & raw materials impacts of MU items for a single use are very small compared to the impacts of a single washing cycle. Thus, the latter would dominate their results.

A limitation of the market for dishwashing model (seeA Appendix 1) is that usage impacts are modelled on a per item basis, which entails that each item washed uses the same amount of resource no matter its size, shape or other differences. This is in contrast to the market for laundry model, where impacts are on a per kg basis.

This stems from the fact that appliance characteristics for dishwashers and dishwashing studies are typically given on a per place setting basis (a place setting being a collection of items). As water use per item would be inversely proportional to the item's weight, small items such as straws, cutlery and stirrers would be burdened disproportionately more than larger reusables.

This model limitation can be viewed as a conservative assumption on the resource use of washing of small items and the results need to be interpreted in its light.

3.3 Product characteristics not considered

While care has been taken in the selection of reference products & alternatives, life-cycle assessment studies cannot and do not account for all possible characteristics of particular items. What is more, the preference for certain items over others may lie with characteristics that have not been accounted for in this work. For example, Table 3 shows that multi-use sanitary towels perform better than their single-use variant across most emissions considered. However, the issue of practicality of reusable sanitary wipes to do with hygiene and ease of use concerns may limit their adoption as an alternative to single-use variants.

Thus, due consideration must be given of the full breadth of issues that may arise from switching between product alternatives - such as to do with costs, consumer preference and ease-of-use - which lie outside the scope of the present life-cycle inventory compilation.

Table 3 Summary of the life-cycle inventories compiled for all products and emissions considered in the assessment

Product group	Product	CO2 (fossil)	CO2 (non-fossil)	Methane	NH3	NOx	PM2.5	PM10	SO2	VOCs
Cigarette butts	SUP	4.12E-04	7.00E-05	1.37E-06	1.18E-08	7.49E-07	5.26E-07	8.94E-08	9.15E-07	5.43E-07
	SUNP	2.85E-04	8.20E-05	1.25E-06	2.36E-07	8.11E-07	3.46E-07	3.23E-08	6.47E-07	7.02E-08
	MU, best MU, worst									
Drinks bottles	SUP	2.00E-01	2.27E-02	8.36E-04	6.09E-06	3.73E-04	2.65E-04	5.97E-05	4.42E-04	1.69E-04
	SUNP	4.01E-01	8.07E-02	7.69E-04	1.32E-04	1.13E-03	5.53E-04	1.07E-04	1.77E-03	1.91E-04
	MU, consumer, best MU,	2.13E-03	1.45E-03	4.86E-06	7.50E-07	4.25E-06	3.80E-06	8.34E-07	5.87E-06	1.72E-06
	consumer, worst MU,	4.64E-03	3.99E-03	1.01E-05	2.26E-06	9.62E-06	8.96E-06	1.99E-06	1.21E-05	4.24E-06
	MU, industry	6.17E-03	3.04E-03	1.75E-05	-4.24E-07	2.18E-06	-1.58E-07	-1.57E-07	2.16E-06	2.10E-06
Cotton buds	SUP	6.87E-04	3.43E-05	3.57E-06	2.75E-07	1.68E-06	5.89E-07	1.35E-07	1.78E-06	6.67E-07
	SUNP	4.66E-04	2.19E-04	1.74E-06	2.73E-07	1.43E-06	5.93E-07	1.09E-07	1.11E-06	1.01E-07
	MU, best	1.68E-03	1.42E-03	3.34E-06	7.21E-07	3.35E-06	3.40E-06	6.95E-07	4.14E-06	1.37E-06
	MU, worst	4.20E-03	3.97E-03	8.53E-06	2.23E-06	8.72E-06	8.56E-06	1.85E-06	1.04E-05	3.89E-06
Wet wipes	SUP	9.49E-03	2.71E-03	3.30E-05	8.47E-07	1.91E-05	1.72E-05	3.05E-06	2.46E-05	5.65E-06
	SUNP	1.13E-02	4.03E-03	5.05E-05	9.96E-06	3.19E-05	1.10E-05	1.06E-06	2.02E-05	4.86E-06
	MU, best	8.45E-04	6.61E-04	1.62E-06	3.12E-07	1.65E-06	1.71E-06	3.35E-07	2.08E-06	6.09E-07
	MU, worst	1.11E-03	8.83E-04	2.15E-06	4.35E-07	2.18E-06	2.23E-06	4.48E-07	2.74E-06	8.26E-07
Sanitary towels	SUP	1.03E-02	5.72E-03	4.51E-05	1.76E-06	2.97E-05	1.25E-05	3.86E-06	3.03E-05	1.51E-05
	SUNP									
	MU, best	3.13E-03	1.60E-03	7.54E-06	1.16E-06	6.33E-06	6.22E-06	1.16E-06	7.66E-06	1.70E-06
	MU, worst	3.77E-03	2.15E-03	8.84E-06	1.46E-06	7.66E-06	7.51E-06	1.44E-06	9.29E-06	2.24E-06
Cutlery	SUP	3.41E-03	-2.26E-05	1.26E-05	2.66E-08	5.15E-06	3.27E-06	6.84E-07	5.70E-06	2.30E-06
	SUNP	7.63E-04	4.18E-03	6.15E-06	1.05E-06	1.27E-05	5.86E-06	7.73E-07	1.23E-06	4.10E-06
	MU, best	1.72E-03	1.44E-03	3.39E-06	7.24E-07	3.42E-06	3.55E-06	7.54E-07	4.20E-06	1.38E-06
	MU, worst	4.23E-03	3.98E-03	8.59E-06	2.24E-06	8.79E-06	8.71E-06	1.91E-06	1.04E-05	3.90E-06
Straws	SUP	1.03E-03	1.22E-04	5.79E-06	4.59E-08	2.21E-06	7.02E-07	2.59E-07	2.88E-06	1.74E-06
	SUNP	1.39E-03	1.56E-03	3.91E-06	1.04E-07	3.84E-06	2.20E-06	4.82E-07	3.70E-06	9.22E-07
	MU, best	1.68E-03	1.43E-03	3.29E-06	7.22E-07	3.35E-06	3.43E-06	7.04E-07	4.14E-06	1.35E-06
	MU, worst	4.19E-03	3.97E-03	8.49E-06	2.24E-06	8.72E-06	8.58E-06	1.86E-06	1.04E-05	3.87E-06
Stirrers	SUP	1.55E-03	1.84E-04	8.68E-06	6.88E-08	3.31E-06	1.05E-06	3.89E-07	4.32E-06	2.61E-06
	SUNP	2.35E-04	1.29E-03	1.89E-06	3.22E-07	3.91E-06	1.80E-06	2.38E-07	3.77E-07	1.26E-06
	MU, best	1.68E-03	1.43E-03	3.29E-06	7.22E-07	3.35E-06	3.44E-06	7.08E-07	4.14E-06	1.35E-06
	MU, worst	4.19E-03	3.97E-03	8.49E-06	2.24E-06	8.72E-06	8.59E-06	1.86E-06	1.04E-05	3.87E-06
Drinks cups and lids	SUP	3.16E-02	1.35E-02	1.13E-04	2.88E-06	5.67E-05	7.03E-05	1.15E-05	1.11E-04	2.94E-05
	SUNP									
	MU, best MU, worst	2.19E-03 4.70E-03	1.43E-03 3.98E-03	6.04E-06 1.12E-05	7.26E-07 2.24E-06	4.32E-06 9.69E-06	3.68E-06 8.84E-06	7.99E-07 1.95E-06	5.23E-06 1.15E-05	2.17E-06 4.69E-06
Food containers	SUP	2.32E-02	1.73E-03	1.79E-04	3.33E-07	4.49E-05	1.79E-05	4.73E-06	6.06E-05	9.27E-05
	SUNP	1.70E-02	2.34E-02	5.10E-05	2.99E-06	5.58E-05	3.00E-05	6.35E-06	5.05E-05	2.72E-05
	MU, best	2.53E-03	1.43E-03	8.83E-06	7.26E-07	4.96E-06	3.84E-06	8.62E-07	6.01E-06	2.90E-06
	MU, worst	5.04E-03	3.97E-03	1.40E-05	2.24E-06	1.03E-05	8.99E-06	2.02E-06	1.22E-05	5.43E-06

Note(s) : Length of blue data bars represents impacts with a positive sign (burdens), while length of red data bars represents impacts with a negative sign (credits, i.e. avoided burdens). Blank rows are not modelled. All numbers are for one use of item and in kg of emissions to air. Scale is separate for each product group and emission. Continued on next page.

Product group	Product	Arsenic	Cadmium	Chromium	Nickel	1, 3 Butadiene	Benzene	PAH	Formaldehyde	Dioxins	Furans
Cigarette butts	SUP	8.01E-11	2.43E-11	2.42E-10	1.99E-10	4.71E-12	1.78E-09	4.29E-10	1.20E-09	2.24E-16	7.50E-12
	SUNP	5.23E-11	1.55E-11	3.34E-10	1.67E-10	5.17E-12	7.38E-10	-1.62E-10	-1.04E-08	5.05E-17	-3.54E-08
	MU, best MU, worst										
Drinks bottles	SUP	6.24E-08	2.01E-08	4.14E-07	3.79E-07	1.48E-13	3.16E-06	2.25E-08	3.58E-07	6.73E-14	1.59E-09
	SUNP	1.26E-07	5.39E-08	4.09E-07	3.01E-07	6.23E-13	6.19E-06	4.39E-07	1.86E-06	1.50E-13	6.10E-09
	MU, consumer, best MU,	8.60E-10	2.70E-10	4.37E-09	2.08E-09	6.97E-13	4.72E-08	3.47E-09	2.22E-08	1.11E-15	4.99E-08
	consumer, worst MU, industry	2.07E-09	6.58E-10	1.15E-08	4.59E-09	2.32E-12	1.01E-07	4.68E-09	6.76E-08	2.70E-15	1.66E-07
		-1.16E-09	-3.73E-10	-1.33E-09	-2.49E-09	2.83E-16	-2.85E-08	3.92E-10	-1.32E-08	-9.57E-16	-1.50E-10
Cotton buds	SUP	2.91E-10	9.85E-11	6.48E-10	6.52E-10	2.71E-12	1.85E-09	1.30E-10	-1.07E-08	1.24E-16	-3.83E-08
	SUNP	8.52E-11	3.33E-11	5.78E-10	3.79E-10	7.89E-12	3.60E-09	1.24E-10	-2.18E-09	7.65E-16	-3.82E-08
	MU, best MU, worst	7.72E-10	2.46E-10	3.95E-09	1.59E-09	7.65E-13	3.02E-08	6.35E-10	2.17E-08	9.16E-16	4.99E-08
		1.98E-09	6.34E-10	1.11E-08	4.11E-09	2.39E-12	8.38E-08	1.84E-09	6.71E-08	2.51E-15	1.66E-07
Wet wipes	SUP	1.79E-09	5.63E-10	9.81E-09	9.05E-09	-1.32E-10	3.93E-08	1.36E-09	3.01E-08	6.34E-15	2.76E-09
	SUNP	2.02E-09	6.34E-10	1.50E-08	7.02E-09	-2.17E-11	-6.12E-08	-7.24E-09	-4.78E-07	2.01E-15	-1.60E-06
	MU, best MU, worst	3.83E-10	1.22E-10	1.88E-09	7.91E-10	2.57E-13	1.41E-08	2.83E-10	8.96E-09	4.37E-16	1.88E-08
		5.05E-10	1.60E-10	2.63E-09	1.04E-09	3.65E-13	1.92E-08	3.83E-10	1.23E-08	5.94E-16	2.66E-08
Sanitary towels	SUP	2.49E-09	9.32E-10	1.41E-08	1.58E-08	2.09E-09	8.43E-07	1.22E-09	2.38E-07	1.72E-14	2.73E-09
	SUNP	1.26E-09	4.00E-10	5.52E-09	2.65E-09	4.11E-11	3.91E-08	5.80E-10	1.01E-08	1.37E-15	-2.19E-11
	MU, best MU, worst	1.56E-09	4.95E-10	7.38E-09	3.28E-09	4.14E-11	5.18E-08	8.28E-10	1.84E-08	1.76E-15	1.93E-08
Cutlery	SUP	1.63E-10	4.47E-11	2.73E-09	8.34E-10	8.56E-11	1.39E-07	3.33E-10	4.14E-09	1.57E-15	6.58E-12
	SUNP	7.94E-10	3.71E-10	4.34E-09	3.80E-09	-2.12E-17	6.06E-08	1.03E-09	9.17E-07	2.45E-15	1.15E-09
	MU, best MU, worst	8.13E-10	2.49E-10	9.87E-09	1.69E-09	6.97E-13	3.16E-08	6.49E-10	2.18E-08	9.97E-16	4.99E-08
		2.03E-09	6.37E-10	1.70E-08	4.20E-09	2.32E-12	8.52E-08	1.85E-09	6.72E-08	2.59E-15	1.66E-07
Straws	SUP	5.64E-10	1.94E-10	6.02E-10	1.16E-09	4.39E-12	6.27E-09	1.18E-10	1.59E-09	1.88E-16	5.64E-12
	SUNP	1.58E-10	7.96E-11	1.08E-09	1.07E-09	1.80E-11	2.55E-08	3.03E-10	2.07E-08	3.59E-15	4.46E-10
	MU, best MU, worst	7.80E-10	2.47E-10	5.03E-09	1.61E-09	7.21E-13	3.05E-08	6.38E-10	2.17E-08	9.30E-16	4.99E-08
		1.99E-09	6.35E-10	1.21E-08	4.12E-09	2.35E-12	8.40E-08	1.84E-09	6.71E-08	2.52E-15	1.66E-07
Stirrers	SUP	8.46E-10	2.91E-10	9.02E-10	1.74E-09	6.58E-12	9.41E-09	1.76E-10	2.38E-09	2.82E-16	8.46E-12
	SUNP	2.44E-10	1.14E-10	1.34E-09	1.17E-09	-6.51E-18	1.86E-08	3.16E-10	2.82E-07	7.54E-16	3.54E-10
	MU, best MU, worst	7.82E-10	2.47E-10	5.45E-09	1.62E-09	6.97E-13	3.04E-08	6.38E-10	2.17E-08	9.35E-16	4.99E-08
		1.99E-09	6.35E-10	1.26E-08	4.13E-09	2.32E-12	8.40E-08	1.84E-09	6.71E-08	2.53E-15	1.66E-07
Drinks cups and lids	SUP	2.67E-09	9.85E-10	1.92E-08	1.44E-08	3.63E-10	2.83E-07	2.02E-09	2.05E-07	6.60E-15	1.26E-08
	SUNP	8.12E-10	2.59E-10	4.19E-09	1.72E-09	6.30E-12	4.30E-08	6.78E-10	2.20E-08	1.05E-15	4.99E-08
	MU, best MU, worst	2.02E-09	6.47E-10	1.13E-08	4.23E-09	7.93E-12	9.66E-08	1.88E-09	6.74E-08	2.64E-15	1.66E-07
Food containers	SUP	7.24E-10	1.92E-10	1.43E-08	1.67E-08	1.62E-10	4.05E-07	1.08E-09	2.19E-08	4.01E-15	9.99E-11
	SUNP	3.81E-09	1.89E-09	2.49E-08	2.53E-08	5.87E-11	2.92E-07	3.56E-09	2.79E-07	5.86E-14	4.17E-08
	MU, best MU, worst	7.93E-10	2.52E-10	4.29E-09	1.71E-09	1.05E-11	4.62E-08	6.77E-10	2.22E-08	1.10E-15	4.99E-08
		2.00E-09	6.40E-10	1.14E-08	4.22E-09	1.21E-11	9.98E-08	1.88E-09	6.76E-08	2.69E-15	1.66E-07

Note(s): Length of blue data bars represents an impact with a positive sign (burdens), while length of red data bars represents impacts with a negative sign (credits, i.e. avoided burdens). All numbers are for one use of item and in kg of emissions to air. Blank rows are not modelled. Scale is separate for each product group and emission. Continued from previous page.

A Appendix 1

A.1 Specification of washing datasets:

The following section details the modelling of washing of multi-use items and the construction of its life-cycle inventories:

Market for laundry

Washing of sanitary items is modelled as carried out via a household washing machine and dried via a weighted average process representative for shares of drying behaviours in Europe (Schmitz and Stamminger, 2014). Best and worst-case washing machines and tumble driers are modelled based on Boyano et al. (2017a) and is representative of EU Ecodesign and Energy Label criteria for household washing machines and washer-dryers. Best and worst-case options are based on the average lifetime of the appliances, 10 and 8 years respectively (ibid.). Energy use for drying in a heated room is based on the residual moisture content on cotton (62%) and calculated via the latent heat of vaporisation of water of 2257 kJ/kg (Schmitz and Stamminger, 2014). Detergent use per cycle is based on a common-sense assumption of 0.035 kg/cycle as for a typical household washing machine. All water used is treated.

Table 4 details the assumptions behind the washing model, represented by the market for laundry dataset.

Table 4 Assumptions behind the market for laundry process

		Best-case	Worst-case
Machine wash	Energy use (kWh/kg)	0,11	0,19
	Water use (l/kg)	6,29	9,95
	Capacity (kg/cycle)	7,22	5,16
	Technology (year)	2014	2004
Tumble dry	Energy use (kWh/kg)	0,58	0,69
	Technology (year)	2013	2006
Air dry, heated room	Energy use (kWh/kg)	0,39	0,39
Air dry, unheated room or outside	Energy use (kWh/kg)	0,00	0,00
Detergent	Use (kg/kg)	0,005	0,007

Note(s): Appliance data is sourced via the European Committee of Domestic Equipment Manufacturers (CECED) in Boyano et al. (2017a).

Market for dishwashing

Washing of non-sanitary items is modelled as a mix between dishwasher use and handwashing, assuming a dishwasher penetration of 60% (Boyano et al., 2017b). The modelling of the dishwasher appliance is representative of EU Ecodesign and Energy label criteria for household dishwashers and assumes 12 items per place setting, 140 items per cycle and an average appliance age of 12 years (ibid.). Handwashing and detergent use best and worst cases are taken from Stamminger et al. (2007). For the former, these are values for Germany and Spain/Portugal respectively, while for the latter these are for Germany and Italy. Table 5 details the non-sanitary item washing model, represented by the market for dishwashing dataset.

Table 5 Assumptions behind the market for dishwashing process

		Best-case	Worst-case
Machine wash	Energy use (kWh/item)	0,006	0,008
	Water use (l/item)	0,070	0,115
	Technology (year)	2014	2002
Handwash	Energy use (kWh/item)	0,009	0,030
	Water use	0,319	1,181
Detergent	Use (kg/item)	0,0002	0,0005

Note(s): Appliance data is sourced from the European Committee of Domestic Equipment Manufacturers (CECED) in Boyano et al. (2017b).

Market for industrial washing

The washing of industry-led drinks bottles is modelled as done via an industrial bottle washer (Jade Trading Equipment, 2017). The modelled machine is a 2006 model and thus possibly not representative of current technology so can be considered a conservative assumption. Table 6 details the assumptions behind the industrial washer model, represented by the market for industrial washing dataset.

Table 6 Assumptions behind the market for industrial washing dataset

Industrial washing	Capacity (bottles/h)	60 000
	Water use (l/bottle)	0,22
	Heat use (MJ/bottle)	0,04

A.2 Specification of reference products

The following appendix details the specification of reference products for all product groups considered for life-cycle inventory compilation:

Cigarette butts

SUP cigarette butts are modelled as a typical cellulose acetate filter, the mass of which taken as per O'Connor et al. (2008) and with composition following Bin et al. (2017). As Ecoinvent 3.4 does not provide a cellulose acetate tow dataset, this is modelled following its chemical reaction with stoichiometry as per Campbell et al. (1973) and with magnitudes of energy inputs from Ecoinvent 3.4 dataset *viscose production, GLO* (Althaus et al., 2017) but with European market datasets used. Process electricity is taken from dataset *market for spinning, bast fibre, GLO* (Ecoinvent, 2017a) and transport burdens to end-users are added from category group *1200 Tobacco products* from Borcken-Kleefeld and Weidema (2013).

SUNP cigarette butts are modelled in the same way as SUP cigarette butts but with typical composition of filter tow taken from Lisauskas, Van Osten and Greenbutts Llc (2012). In order to ensure that both modelled filters achieve the same filterability, the mass of alternative materials used has been adjusted based on the difference in densities between cellulose acetate and the cotton/hemp mix serving as alternative.

The full composition of reference products for the Cigarette butts product group is given in Table 7.

Table 7 Composition of reference products for modelling the Cigarette butts product group

Cigarette butts			
SUP		SUNP	
Material	Weight	Material	Weight
Cellulose acetate filter	0.12	Natural fibre filter	0.13
Acetate tow	0.10	Natural fibre tow	0.11
Plug wrap paper	0.01	Hemp	0.03
Tipping paper	0.01	Cotton	0.06
		Plug wrap paper	0.01
		Tipping paper	0.01

Note(s): Indents represent modelled sub-compositions of individual components. All weights given in grams.

Drinks bottles, caps and lids

Drinks packaging is a diverse market in terms of volume capacity of packages, as well as in terms of materials used. Market report data from GlobalData (2017) is used for determining averaged reference products.

SUP drinks bottles are taken to be made of PET and modelled in volume as the weighted average of what is most common on the European market (80+% market share), with weights taken from industry data. Bottle-grade PET data is taken directly from Ecoinvent and bottle manufacturing is assumed to be comprised of injection and stretch-blow moulding. Transport data to end-users for product group *2220 Plastics products* is used (Kleefeld and Weidema, 2013).

The reference SUNP drinks container is modelled as an average mix between an aluminium can and a glass bottle, with market shares from GlobalData used assuming full substitution of plastics by aluminium/glass. Transport data is for product group 2310 Glass and glass products only due to absence of a suitable category for aluminium packaging (a conservative assumption given larger burdens due to higher weight of glass).

The reference MU item is modelled in two ways:

- A “consumer-led” MU item, representing a market-averaged refillable flask of PET/aluminium. Market shares are determined assuming a 50:50 split between materials. Transport data is for *2220 Plastics products*. Consumer-led MU bottles receive washing burdens from the market for dishwashing dataset. The weight and composition of an aluminium flask is taken from Simon et al. (2016).
- An “industry-led” MU item, representing the packaging mix as in a deposit-refund scheme. Market shares for PET/Glass are taken assuming 100% coverage of the market and with transport data mixed between the two. Industry-led MU bottles receive washing burdens from the market for industrial washing dataset. Burdens related to a deposit-refund scheme itself are excluded.

Table 8 details the composition of reference products for the Drinks bottles, caps and lids product group.

Table 8 Composition of reference products for modelling the Drinks bottles product group

Drinks bottles, caps and lids							
SUP		SUNP		MU, consumer-led		MU, industry-led	
Material	Weight	Material	Weight	Material	Weight	Material	Weight
PP bottle (w/ cap)	36	Container, average of:		Container, average of:		Container, average of:	
		Glass bottle (72%)	350	PET flask (w/ cap) (50%)	125	PP bottle (w/ cap) (46%)	36
		Aluminium can (17%)	24	Aluminium flask (50%)	180	Glass bottle (54%)	350
				Flask	171		
				PET cap	9		

Note(s): Indents represent modelled sub-compositions of individual components. All weights given in grams.

Cotton buds

SUP and SUNP cotton buds are modelled as having the same weights but with PP and paper sticks respectively. The MU reference product is a washable MDPE bud. All weights have been estimated. The MU item receives washing burdens from the market for dishwashing dataset. Transport to end-user data for product group *2023 Soap and detergents, polishes, perfumes, toilet preparations* is used.

The SUP product is modelled as the extrusion of a plastic pipe via the *market for earth tube heat exchanger, polyethylene, DN 200, GLO* (Ecoinvent, 2017b) dataset but with polypropylene substituting PE. Process burdens are included via the *market for spinning, bast fibre, GLO* (Ecoinvent, 2017a) dataset, the assumption being that the process burdens for working cotton are similar to those of modelled textile products. The modelling of SUNP buds is identical save for the extrusion process, where kraft paper production is used instead (50:50 mix of bleached vs non-bleached paper assumed). The MU product is assumed to be injection moulded, with a 50:50 mix of HDPE and LDPE used to represent MDPE.

Table 9 represents the composition of the Cotton buds reference products.

Table 9 Composition of reference products for modelling the Cotton buds product group

Cotton buds					
SUP		SUNP		MU	
Material	Weight	Material	Weight	Material	Weight
Cotton bud	0.23	Paper bud	0.23	MDPE washable bud	3
PP stick	0.17	Paper stick	0.17		
Cotton	0.60	Cotton	0.60		

Note(s): Indents represent modelled sub-compositions of individual components. All weights given in grams.

Sanitary towels

The SUP reference product is taken to be an ultrathin sanitary pad with composition taken from the EDANA nonwovens association Sustainability Report for 2008. This is stated to be the most common pad on the market and is also the lightest of all variants listed therein. The superabsorbent polymer (SAP) of the ultrathin pad is modelled as polyacrylamide. Transport to end-user data for product group *2023 Soap and detergents, polishes, perfumes, toilet preparations* is used.

The MU reference product is a washable cotton towel. Transport is modelled as for product group *1300 Textiles*, weight is estimated. The MU product receives washing burdens from the market for laundry dataset.

Table 10 details the composition of the Sanitary pads reference products.

Table 10 Composition of reference products for modelling the Sanitary towels product group

Sanitary towels			
SUP		MU	
Material	Weight	Material	Weight
Ultrathin pad	6.20	Washable cotton pad	30
Paper	0.21		
Adhesive	0.43		
Superabsorbent polymer	0.35		
Pulp	2.99		
PE	0.997		
PP	0.997		
PET	0.997		

Note(s): Indents represent modelled sub-compositions of individual components. All weights given in grams.

Wet Wipes

SUP synthetic fibre wipes are modelled via a market average mix of materials in use in Europe based on market report data from Smithers Pira (2016). The weight and lotion content of the reference wipe are taken from industry data, with the composition of the lotion itself from Faught et al. (2014). Transport to end-user data for product group *2023 Soap and detergents, polishes, perfumes, toilet preparations* is used. Process burdens are modelled via the *market for spinning, bast fibre, GLO* dataset as for all other textile products.

SUNP wipes are modelled as cotton balls with the same proportion of lotion by mass assumed as for SUP wipes. Weights have been estimated. All other modelling is analogous to SUP wipes.

The MU reference product is a washable cotton handkerchief. The kerchief is modelled analogously to the above but with double the lotion usage as a conservative assumption due to more wasteful application by end-users. The MU product receives washing burdens from the market for laundry dataset.

Table 11 Composition of reference products for modelling the Wet wipes product group

Wet wipes					
SUP		SUNP		MU	
Material	Weight	Material	Weight	Material	Weight
Synthetic wipe	3,80	Cotton ball + lotion	4,30	Cotton handkerchief	12
Fibre	1,10	Cotton ball	2,50	Cotton	6,70
Viscose fibre	0,47	Lotion	1,80	Lotion	5,40
PET fibre	0,53	Water	1,18	Water	3,59
PP fibre	0,10	Glycerine	0,32	Glycerine	0,97
Lotion	2,70	Colloidal oatmeal	0,04	Colloidal oatmeal	0,11
Water	1,80	Benzyl alcohol	0,01	Benzyl alcohol	0,03
Glycerine	0,49	Sodium Chloride	0,00	Sodium Chloride	0,00
Colloidal oatmeal	0,05	Cetyl alcohol	0,05	Cetyl alcohol	0,16
Benzyl alcohol	0,01	Petrolactum	0,01	Petrolactum	0,03
Sodium Chloride	0,00	Isopropyl Palmitate	0,05	Isopropyl Palmitate	0,17
Cetyl alcohol	0,08	Distearyldimonium Chloride	0,09	Distearyldimonium Chloride	0,27
Petrolactum	0,02	Dimethicone	0,02	Dimethicone	0,07
Isopropyl Palmitate	0,08				
Distearyldimonium Chloride	0,14				
Dimethicone	0,04				

Note(s): Indents represent modelled sub-compositions of individual components. All weights given in grams.

Cutlery

The SUP reference cutlery item is an average polypropylene utensil with mass taken from Öko-Institut eV (2017). It is assumed that injection moulding represents process burdens. Transport to end-users is modelled via the *2200 Plastics products* product group.

The SUNP reference product is a wooden utensil and is assumed to have the same weight as for SUP. It is modelled via *the market for plywood, for indoor use, RER* dataset (Ecoinvent, 2017c; due to lack of a global dataset). This is the lowest-density wood product available in Ecoinvent and is assumed to represent the typical low-grade wood that would be used for manufacturing of wooden utensils. Transport to end-use is via the *1629 Other wood products* product group.

MU cutlery is an average steel utensil from Öko-Institut eV (2017). Material inputs are via the *market for steel, chromium steel 18/8, hot rolled, GLO* dataset (Ecoinvent, 2017d) and a 4-stroke impact extrusion process is assumed (expert consultation). The MU reference product receives washing burdens from the market for dishwashing dataset. Transport is via the *2500 Articles of base metal* product group.

Table 12 gives the Cutlery reference products modelled.

Table 12 Composition of reference products for modelling the Cutlery product group

Cutlery					
SUP		SUNP		MU	
Material	Weight	Material	Weight	Material	Weight
PP utensil	2,60	Wooden utensil	3	Steel utensil	31

Note(s): All weights given in grams.

Straws

SUP straws are modelled as a polypropylene extrusion process analogous to that for SUP cotton buds via the *market for earth tube heat exchanger, polyethylene, DN 200*,

GLO dataset (Ecoinvent, 2017b). Transport burdens are also analogous, product weight is based on industry data.

The SUNP straw is modelled as made of kraft paper (50:50 bleached/unbleached paper assumed) analogous to SUNP cotton buds. Weight is assumed same as for the SUP reference product.

MU straws are modelled as a 50:50 market average between silicone and steel straws. The silicone item is modelled via the generic Ecoinvent silicone product dataset, while the steel straw model is analogous to that for MU cutlery.

Table 13 gives the modelled Straws reference products.

Table 13 Composition of reference products for modelling the Straws product group

Straws					
SUP		SUNP		MU	
Material	Weight	Material	Weight	Material	Weight
PP straw	0,40	Paper straw	0,80	Straw, average of:	
				Steel straw (50%)	13,90
				Silicone straw (50%)	8,20

Note(s): All weights given in grams.

Stirrers

SUP stirrers are modelled analogous to SUP straws and cotton buds. Assumed weight is an industry average from multiple sources.

SUNP stirrers are assumed made of wood and modelled analogous to SUNP cutlery. Weight is estimated.

MU stirrers are assumed to be analogous to MU cutlery (i.e. a steel spoon). Table 14 presents the Stirrers reference products.

Table 14 Composition of reference products for modelling the Stirrers product group

Stirrers					
SUP		SUNP		MU	
Material	Weight	Material	Weight	Material	Weight
PP stirrer	0,60	Wooden stirrer	1,90	Steel stirrer	20,10

Note(s): All weights given in grams.

Food containers

An average polystyrene clamshell container is modelled as the SUP reference item, sourced from Frankin Associates (2006). Transport burdens to end-user are via the *2200 Plastics products* product group.

The above reference is also used for the SUNP reference item – a wax-lined paperboard container. Transport burdens are via the *1702 Corrugated board and containers* product group.

The MU reference product is a reusable polyethylene tupperware container, its weight estimated (lid inclusive). Transport is analogous to the SUP food container; the MU product receiving washing burdens from the market for dishwashing dataset.

Table 15 details the composition of Food containers reference products.

Table 15 Composition of reference products for modelling the Food containers product group

Food containers					
SUP		SUNP		MU	
Material	Weight	Material	Weight	Material	Weight
PS clamshell	5	Paperboard + wax box	10	PE tuppleware	150
		Paperboard	9		
		Wax	1		

Note(s): Indents represent modelled sub-compositions of individual components. All weights given in grams.

Drinks cups and lids

The SUP reference drinks cup is a composite corrugated board cup with polyethylene lining and an LDPE lid. Total product weight is estimated, with shares of individual components from Vercauteren et al. (2006). Transport burdens are for product group *2200 Plastics products*. The product is assumed to be injection moulded.

The MU drinks cup is modelled via an LCA analysis conducted for KeepCup (Edge Environment, 2017). Transport burdens are analogous to the SUP product, washing burdens are received via the market for dishwashing dataset.

Table 16 presents the Drinks cups and lids reference products' compositions.

Table 16 Composition of reference products for modelling the Drinks cups and lids product group

Drinks cups and lids			
SUP		MU	
Material	Weight	Material	Weight
Paper cup w/ PE coating	11	Washable plastic cup	96
Corrugated board	10,34	PP lid	18
PE	0,66	Thermoplastic rubber	9
LDPE lid	3,00	LDPE plug	6
		PP cup	49
		Silicone band	14

Note(s): Indents represent modelled sub-compositions of individual components. All weights given in grams.

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