European Commission

Screening LCA study: Absorbent Hygiene Products in Europe

- *Baby diapers*
- *Sanitary towels*

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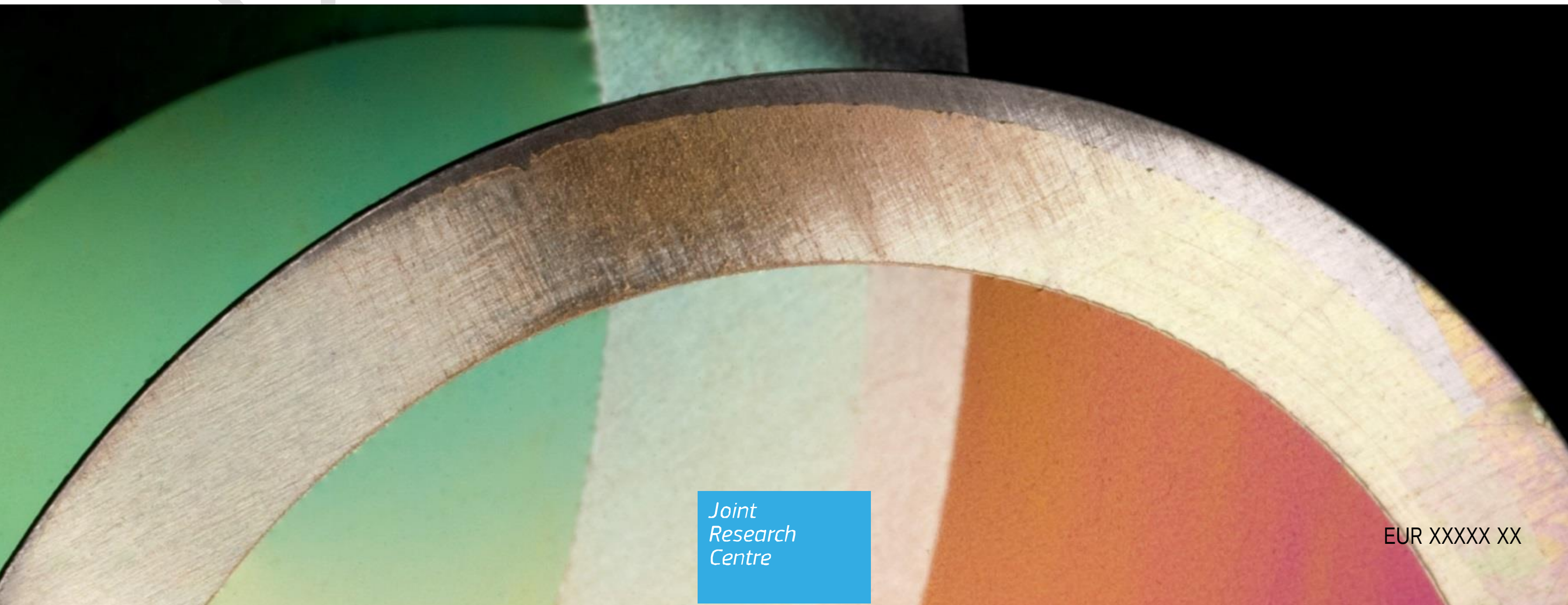

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SUMMARY

The present study is part of an initiative for the revision and update of EU Ecolabel criteria on absorbent hygiene products (AHPs). The goal of the study is to assess environmental impacts of average disposable open baby diapers and sanitary towels using Product Environmental Footprint (PEF) methodology. Results of the assessment will be used in the update of EU Ecolabel criteria for AHPs. The results are not intended to define thresholds, but to find hotspots for which the criteria should focus on. It should be noted that only data on open baby diapers was received, and thus used in the assessment, although EU Ecolabel criteria includes all types of diapers, i.e. also pant diapers. There is not Product Environmental Footprint Category Rules (PEFCR) for absorbent hygiene product, thus this study is performed as a screening study following general PEF methodology rules defined in Zampori & Pant (2019). The study is not intended to define PEF category rules for AHPs.

System boundary includes all life cycle stages from the raw material acquisition to the End of Life. Raw material acquisition includes production of raw materials used in the product manufacturing, production of packaging, and their transport to the manufacturing site. Manufacturing of products includes energy and other inputs used in the AHPs manufacturing process and treatment of scraps from the manufacturing process. Distribution includes transport from manufacturing site to the retail and final user. Use phase was assumed to have zero burdens, as product is ready to use and disposed after use. End of Life phase includes both the end of life of main product and packaging. Retail was assumed to have only small impacts in the AHP life cycle, and to be similar for all AHPs, thus retail was excluded from the assessment.

The environmental hotspots identified in this study are mainly production of raw materials. More specifically, the raw materials showing highest contributions in case of baby diapers are SAP, fluff pulp, and PP, LDPE and PET granulates, depending on impact category. In addition to raw materials, waste landfilling was identified among the most relevant processes in Climate Change impact category. For sanitary towels, the most contributing raw materials are viscose, fluff pulp, and PET, PP and LDPE granulates. In addition to LDPE used in the sanitary towel production, the LDPE granulates used for sanitary towel packaging were also identified as a hotspot in some impact categories.

In addition to production of raw materials, also transportation of raw materials and packaging to manufacturing site are identified to have high contribution in some impact categories (Acidification and Eutrophication - terrestrial), mainly due to the train transportation, which distance is based on default scenarios in EF method (Zampori & Pant, 2019) due to lack of supply chain specific data.

Data Quality Level is good (score 2.04) for baby diapers and very good (score 1.66) for sanitary towels. Although the score for both baby diaper and sanitary towel is good, it can be noticed that while geographical and technological representativeness of dataset is high (<3), precision and time representativeness have lower scores. Only manufacturing of baby diapers and sanitary towels is based on primary data, all other data is secondary data from databases or literature. This is due to the nature of the study which uses data from the manufacturing companies, while most of the relevant processes are out of the control of these companies. To increase the quality of the study, more primary data should be used, especially for the processes identified as most relevant ones. In addition, it is not known how well the data received from companies represent the average baby diaper and sanitary towel production, because the market shares or sizes of these companies are not known. Also, it is not known, if other companies, which did not provide data, use different raw materials with higher or lower impacts.

The third-party verification concluded that the study is technically performed correctly. Due to the character of the study, not all PEF reporting requirements could be fully met, but this makes no difference to the results. The limitations and representativeness of the conclusions are sufficiently explained, and the study finds and discusses the environmental hotspots in a way that they can be used for the goal.

LCIA results of open baby diapers:			
Impact category	Characterized impact	Normalized impact	Weighted impact
Climate Change [kg CO_2 eq.]	9.00E-02	1.11E-05	2.34E-06
Climate Change (fossil) [kg CO_2 eq.]	7.33E-02	-	-
Climate Change (biogenic) [kg CO_2 eq.]	1.67E-02	-	-
Climate Change (LU and LUC) [kg CO_2 eq.]	6.84E-05	-	-
Ozone Depletion [kg CFC-11 eq.]	3.46E-09	6.45E-08	4.07E-09
Ionising Radiation [kBq U^{235} eq.]	9.71E-03	2.30E-06	1.15E-07
Photochemical Ozone Formation [kg NMVOC eq.]	5.92E-04	1.46E-05	6.97E-07
Particulate matter [Disease incidence]	5.39E-09	9.05E-06	8.11E-07
Human toxicity - non-cancer [CTUh]	1.04E-09	4.54E-06	8.35E-08
Human Toxicity - cancer [CTUh]	1.02E-10	6.03E-06	1.28E-07
Acidification [mol of H^+ eq.]	5.44E-04	9.80E-06	6.07E-07
Eutrophication - freshwater [kg P eq.]	3.85E-06	2.40E-06	6.72E-08
Eutrophication - marine [kg N eq.]	1.96E-04	1.00E-05	2.97E-07
Eutrophication - terrestrial [mol N eq.]	2.23E-03	1.26E-05	4.69E-07
Ecotoxicity - freshwater [CTUe]	9.15E-01	2.14E-05	4.12E-07
Land Use [Pt]	2.65E+00	3.24E-06	2.57E-07
Water Use [m^3 world eq.]	4.93E-02	4.30E-06	3.66E-07
Resource Use - fossils [MJ]	1.61E+00	2.48E-05	2.06E-06
Resource Use - mineral and metals [kg Sb eq.]	3.86E-07	6.06E-06	4.58E-07

LCIA results of sanitary towels:			
Impact category	Characterized impact	Normalized impact	Weighted impact
Climate Change [kg CO_2 eq.]	1.56E-02	1.93E-06	4.06E-07
Climate Change (fossil) [kg CO_2 eq.]	1.50E-02	-	-
Climate Change (biogenic) [kg CO_2 eq.]	6.12E-04	-	-
Climate Change (LU and LUC) [kg CO_2 eq.]	1.92E-05	-	-
Ozone Depletion [kg CFC-11 eq.]	6.08E-10	1.13E-08	7.15E-10
Ionising Radiation [kBq U^{235} eq.]	1.42E-03	3.36E-07	1.68E-08
Photochemical Ozone Formation [kg NMVOC eq.]	1.73E-04	4.25E-06	2.03E-07
Particulate matter [Disease incidence]	1.51E-09	2.53E-06	2.27E-07
Human toxicity - non-cancer [CTUh]	4.54E-10	1.98E-06	3.64E-08
Human Toxicity - cancer [CTUh]	6.11E-11	3.62E-06	7.70E-08
Acidification [mol of H^+ eq.]	1.51E-04	2.73E-06	1.69E-07
Eutrophication - freshwater [kg P eq.]	3.45E-07	2.15E-07	6.01E-09
Eutrophication - marine [kg N eq.]	5.62E-05	2.87E-06	8.51E-08
Eutrophication - terrestrial [mol N eq.]	6.54E-04	3.70E-06	1.37E-07
Ecotoxicity - freshwater [CTUe]	2.77E-01	6.49E-06	1.25E-07
Land Use [Pt]	9.54E-01	1.16E-06	9.24E-08
Water Use [m^3 world eq.]	1.44E-02	1.26E-06	1.07E-07
Resource Use - fossils [MJ]	3.68E-01	5.66E-06	4.71E-07
Resource Use - mineral and metals [kg Sb eq.]	4.40E-07	6.92E-06	5.22E-07

1 Introduction

The EU Ecolabel is a label of environmental excellence that is awarded to products and services meeting high environmental standards throughout their life cycle: from raw material extraction, to production, distribution and disposal. In 2012-2013, Cordella et al. (2013) made a study to define EU Ecolabel criteria for absorbent hygiene products, AHPs. These criteria are published in the Commission Decision (2014/763/EU). According to the Commission Decision (2014/763/EU) the product group 'absorbent hygiene products' "shall comprise baby diapers, feminine care pads, tampons and nursing pads (also known as breast pads), which are disposable and composed of a mix of natural fibres and polymers, with the fibre content lower than 90 % by weight (except for tampons)". AHPs represent an important product group on the market in terms of production volume, function provided to consumers and visibility. This study focusses on baby diapers and feminine care pads.

First two or three years of our lives, we usually use diapers, of which over 95% are single-use in Europe (Cordella et al., 2013). Baby diapers can be divided in four main types: new born diapers, standard diapers, junior diapers and single-use pants. In this study, environmental impacts of an average open diaper is assessed, i.e. pant diapers are not included in the study.

Feminine care pads, or sanitary towels, are products designed to meet the hygiene needs of women during the menstrual cycle. There are five types of pads in the market: panty liners, standard pads with or without wings, and ultra-thin pads with or without wings (Cordella et al., 2013). This study assesses environmental impacts of an average feminine care pad (later referred as sanitary towel).

Original study to define the EU Ecolabel criteria used life cycle assessment (LCA) approach as defined by ISO standards to assess environmental impacts of AHPs (Cordella et al., 2016). Also this study uses LCA approach, but more specifically Product Environment Footprint (PEF) method as described in Zampori & Pant (2019). PEF method builds on existing approaches and international standards, but provides more detailed requirements and guidance for modelling the environmental impacts of products. PEF method uses attributional approach, i.e. it estimates what share of the global environmental burdens belongs to a product. The rules provided in PEF method enable to conduct studies that are more reproducible, comparable and verifiable compared to alternative approaches. However, comparability is only possible if the results are based on the same Product Environmental Footprint Category Rules (PEFCR). In case of AHPs, there is not any PEFCR available, which means that the study cannot be a full PEF study. Thus, this study is performed as a screening LCA study using manufacturing data from industries, and PEF method as well as PEF compliant datasets as much as possible.

This study was subject to third-party verification between February and April 2022. Two iterations were carried out by the third-party verifiers (who had access to the Bill of Material – BoM – of the model), and therefore an updated version of the study was developed. The high-level executive conclusion from the third-party verifier of the updated study is presented below:

"The study is technically performed correctly. Due to the character of the study not all PEF reporting requirements are fully met, but that makes no difference to the results. The updated version pays sufficient attention to the limitations and representativeness of the conclusions. The goal of the study is 'to find hotspots for which the criteria should focus on'. The hotspots are mentioned in a way that they can be used for the goal."

2 Goal of the study

The present study is part of an initiative for the revision and update of EU Ecolabel criteria on absorbent hygiene products (AHPs). The goal of the study is to assess environmental impacts of average disposable open baby diapers and sanitary towels using PEF methodology to find out the most relevant impacts categories, life cycle stages, processes and flows of absorbent hygiene products. Results of the assessment will be used in the update of EU Ecolabel criteria for AHPs. The results are not intended to define thresholds, but to find hotspots for which the criteria should focus on. It should be noted that only data on open baby diapers was received, and thus used in the assessment, although EU Ecolabel criteria includes all types of diapers, i.e. also pant diapers. There is not PEFCR for absorbent hygiene product, thus this study is performed as a screening study following general PEF methodology rules defined in Zampori & Pant (2019). The study is not intended to define PEF category rules for AHPs.

The study is targeted for all the stakeholders who are following or involved in the revision of the EU Ecolabel criteria for AHPs, namely AHP EU Ecolabel applicants and other manufacturers, suppliers of AHP materials, competent bodies, NGOs, EU Ecolabel board and other EU Commission services.

The study was performed by D3 Land Resources Unit in JRC Ispra with support from B5 Circular Economy and Industrial Leadership in JRC Seville.

3 Scope of the study

3.1 Functional unit and reference flow

The functional unit of the study is one piece of the average product marketed in the European Union. The average product is defined using the average composition of the products from companies providing data, i.e. four baby diaper manufacturing companies and three sanitary towel manufacturing companies, without taking into account their absorbent capacity (not known). In particular, the functional unit is as follows:

— An average open baby diaper based on data from four manufacturing companies

— An average sanitary towel based on data from three manufacturing companies

3.2 System boundary

System boundary includes all life cycle stages from the raw material acquisition to the End of Life (Figure 1). Raw material acquisition includes production of raw materials used in the product manufacturing, production of packaging, and their transport to the manufacturing site. Manufacturing stage includes energy and other inputs used in the AHPs manufacturing process, and treatment of scraps from the manufacturing process. Distribution includes transportation of product from the manufacturing site to the retail and end user. Use phase was assumed to have zero burdens, as product is ready to use and disposed after use. End of Life phase includes both end of life of main product and packaging, but EoL of faeces were excluded (i.e. increased mass to transport diapers and sanitary towels to EoL processes and impacts of landfill or incineration of faeces). Retail was assumed to have only small impacts in the AHP life cycle, and to be similar for all AHPs, thus retail was excluded from the assessment. No other cut offs were included in the study.

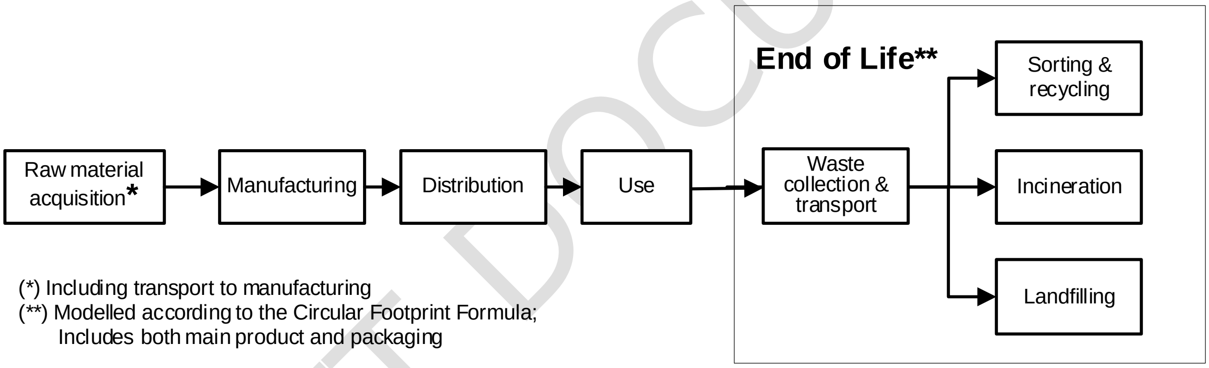

Figure 1: System boundary of absorbent hygiene products.

3.3 Environmental Footprint impact categories

EF 3.0 method, as implemented in SimaPro 9.1 software, was used in the study. List of impact categories with respective impact category indicators, units and impact assessment models are presented in Table 1. Climate Change results are presented separately for three sub-indicators in the result section.

Table 1: Impact categories with respective impact category indicators, units and impact assessment models used in the assessment.

Impact Category	Impact Category indicator	Unit	Impact Assessment Model
Climate Change, total (1)	Radiative forcing as Global Warming Potential (GWP_{100})	kg CO_2 eq	Baseline model of the IPCC over a 100 year time horizon (IPCC, 2013)

Impact Category	Impact Category indicator	Unit	Impact Assessment Model
Ozone Depletion	Increase of stratospheric ozone breakdown as Ozone Depletion Potential (ODP)	kg CFC-11 eq	Steady-state model of the World Meteorological Organization over an infinite time horizon (WMO, 2014 + integrations)
Human Toxicity – cancer	Comparative Toxic Unit for humans (CTU_h)	CTU_h	USEtox model 2.1 (Fankte et al., 2017)
Human Toxicity – non-cancer	Comparative Toxic Unit for humans (CTU_h)	CTU_h	USEtox model 2.1 (Fankte et al., 2017)
Particulate Matter	Impact on human health	Disease incidence	PM method recommended by UNEP (UNEP, 2016)
Ionising Radiation – human health	Human exposure efficiency relative to U^{235}	kBq U^{235} eq	Human Health effect model (Dreicer et al., 1995)
Photochemical Ozone Formation - human health	Tropospheric ozone concentration increase	kg NMVOC eq	LOTOS-EUROS model (Van Zelm et al., 2008) as implemented in ReCiPe 2008
Acidification	Accumulated Exceedance (AE) of the critical load	mol H^+ eq	Accumulated Exceedance model (Seppälä et al., 2006; Posch et al., 2008)
Eutrophication – terrestrial	Accumulated Exceedance (AE) of the critical load	mol N eq	Accumulated Exceedance model (Seppälä et al., 2006; Posch et al., 2008)
Eutrophication – freshwater	Fraction of nutrients (P) reaching freshwater end compartment	kg P eq	EUTREND model (Struijs et al., 2009) as implemented in ReCiPe
Eutrophication – marine	Fraction of nutrients (N) reaching marine end compartment	kg N eq	EUTREND model (Struijs et al., 2009) as implemented in ReCiPe
Ecotoxicity –freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	USEtox model 2.1 (Fankte et al, 2017)
Land Use	• Soil quality index (2) • Biotic production • Erosion resistance • Mechanical filtration • Groundwater replenishment	• Dimension less (pt) • kg biotic production • kg soil • m^3 water • m^3 ground-water	Soil quality index based on LANCA (Beck et al., 2010 and Bos et al., 2016)
Water Use	User deprivation potential (deprivation-weighted water consumption)	m^3 world eq	Available WAter REmaining (AWARE) as recommended by UNEP, 2016
Resource use – minerals and metals	Abiotic resource depletion (ADP, based on ultimate reserves)	kg Sb eq	CML 2002 (Guinée et al., 2002) as updated in Van Oers et al. (2002)

Impact Category	Impact Category indicator	Unit	Impact Assessment Model
Resource use –fossils	Abiotic resource depletion –fossil fuels (ADP-fossil)	MJ	CML 2002 (Guinée et al., 2002) and Van Oers et al. (2002)

([1]) The indicator "Climate Change, total" consists of three sub-indicators: Climate Change – fossil; Climate Change – biogenic; and Climate Change – land use and land use change.

([2]) This index is the result of the aggregation, performed by JRC, of the 4 indicators provided by LANCA model as indicators for land use.

3.3.1 Additional environmental information

Biodiversity impacts are mainly related to raw material acquisition. In case of AHPs, the raw materials are not known as typical high biodiversity impact materials, and thus biodiversity impacts are not assessed in this study.

3.4 Assumptions and limitations

Main assumptions in the modelling are related to transport distances and End of Life, which are modelled according to PEF method, using values and scenarios included in the method (Zampori & Pant, 2019). It was also assumed that storage and retail have only small impacts in the AHP life cycle, and it is similar for all AHPs, thus these life cycle stages were excluded from the assessment.

Limitation of the study are related to data availability, more specifically:

— Only manufacturing process is based on primary data, all other data is secondary data from databases and literature, which affect the quality of the study.

— EF database 2.0 was used due to lack of EF 3.0 datasets and therefore secondary data are older. This affects the time representativeness of the secondary dataset.

— The average data of manufacturing of baby diapers is based only on four companies, and sanitary towels on three companies, without knowledge/taking into account their market share. Also, there are different sizes of the baby diapers for different age groups, and sanitary towels with different absorbing capacity, but it was not specified in the data received that for which size it refers to. In addition, different manufacturers might use different raw materials, with higher or lower impacts, compared to the companies providing data. Because of these issues, the conductor of the study cannot be sure how well the data used in the modelling represents the average products in Europe.

— Pant diapers were excluded from the study, and differences in product design compared to open diapers may lead to different results.

— The lack of primary data on relevant materials (i.e. SAP) and use of proxy dataset for adhesives increase the uncertainty on the results of the study.

— Baby diapers and sanitary towels can be considered as lightweight materials, but due to data on density or volume of the products, distribution was assumed to be mass limited.

— Potential impacts from additional washing of clothes because of possible leakage had insufficient data and it is excluded from the assessment.

— Data on absorbent capacity of baby diapers and sanitary towels was not known, thus EoL impacts of faeces are not accounted in the study, i.e. the increased weight of the product is not included in the transport of products to EoL processes, and incineration and landfilling impacts of the faeces. However, municipal waste incineration dataset takes into account 34% humidity of the material, thus energy credits from the waste incineration should not be overestimated.

4 Life cycle inventory analysis

Included life cycle stages are following:

- Raw material acquisition (including packaging production and transport of raw materials and packaging);
- Manufacturing of the product, including disposal of waste produced in the manufacturing site;
- Distribution of the product from the manufacturing site to the retail and final user; and
- End of Life (including both main product and packaging).

Detailed description and modelling choices of each life cycle stage is provided in the following sections. Storage and retail are assumed to have almost zero impact in the total life cycle, being similar for all AHPs, and these impacts are not included in the assessment. In addition, potential impacts from additional washing of clothes because of possible leakage is assumed to be small, and it is excluded from the assessment. Capital goods are not otherwise included in the assessment, but in case of use of EF and ecoinvent datasets, they are included.

4.1 Modelling choices

4.1.1 Raw material acquisition

For the modelling of the production of raw materials used in the baby diaper and sanitary towel manufacturing, secondary data was used from the EF database 2.0, whenever available. In case the dataset was not available, Ecoinvent 3.6 (Wernet et al., 2016) was used as an alternative data source to model impacts of that raw material, as described later. List of datasets used are presented in Table 2.

Table 2: List of raw materials used in the production of AHPs. EF = dataset from EF database, EI = dataset from Ecoinvent 3.6 database.

Raw material	Dataset
Cellulose	Bleached kraft pulp softwood {US and CA} | production mix | at plant | per kg pulp (EF)*
SAP	Not available (see Table 3)
Polyethylene (PE)**	LDPE granulates {EU-28+EFTA} | Polymerisation of ethylene | production mix at plant | 0.91- 0.96 g/cm3 28 g/mol per repeating unit (EF)
Polypropylene (PP)**	PP granulates {EU-28+EFTA} | polymerisation of propene | production mix at plant | 0.91 g/cm3 42.08 g/mol per repeating unit (EF)
Polyethyleneterephtalate (PET)**	PET amorphous {EU-28+EFTA} | Polymerisation of ethylene | production mix at plant | 0.91- 0.96 g/cm3 28 g/mol per repeating unit (EF)
Adhesives	Dicyclopentadiene based unsaturated polyester resin {RER}| production | APOS, S (EI)
Elastics	Ethylene propylene dien elastomer (EPDM) {World w/o EU-28+EFTA} | copolymerization of ethylene and propylene | production mix at plant | 69% ethylene 38% propylene (EF)
Silicone paper	Silicone, low viscosity {EU-28+EFTA} | hydrolysis and methanolysis of dimethyldichloro silane | production mix, at plant | <30 000 centi Poise | LCI result (EF)
	Graphic paper {EU-28+3} | production mix | at plant | per kg graphic paper | LCI result (EF)
Viscose	Fibre, viscose {GLO}| fibre production, viscose | APOS, S (EI)

* Used as approximation for specialized absorbent materials

** Plastic granulate production process is complemented by the process: "Film Extrusion (blowing) {EU-28+EFTA} | plastic extrusion | production mix, at plant | for PP, PE, PVC, PET and PS"

SAP was modelled according to the production process for sodium polyacrylate documented in US patent[1]. Table 3 reports the input data and datasets used in the modelling.

Table 3: Summary of the input data and datasets used for SAP modelling.

Raw material	Quantity (per kg SAP)	Unit	EF Dataset
Acrylic acid	319	g	Acrylic acid production {RER} | technology mix | production mix
Sodium Hydroxide	354	g	Sodium hydroxide production {RER} | technology mix | production mix
Ethylene glycol	6.38	g	Ethylene glycol production {RER} | technology mix | production mix
Sodium persulfate	1.7	g	Sodium persulphate production {GLO} | technology mix | production mix
Zinc acetate*	319	g	
- Zinc oxide	140	g	Zinc oxide production {RER} | technology mix | production mix to consumer | 1kV - 60kV | LCI result
- Acetic acid	209	g	Acetic acid production {RER} | technology mix | production mix
Water	5.01	kg	Tap water {EU-28+3} | technology mix | at user | per kg water | LCI result
Electricity	7.8	MJ	Residual grid mix {EU-28+3} | AC technology mix | consumption mix

* The quantity of the chemicals needed to obtain zinc acetate is more than the quantity of zinc acetate due to the stoichiometry of reaction.

All raw materials are assumed to come from Europe, except fluff pulp used for baby diapers was assumed to be transported from US. For European raw materials, the EF default scenario from supplier to factory was used:

- 130 km by truck
- 240 km by train
- 270 km by barge

For fluff pulp from US, the EF transport scenario for suppliers located outside of Europe was used:

- 1000 km by truck (between factory and harbour, EF default)
- 10 000 km by transoceanic ship (according to distance from US to Europe)

Both baby diaper and sanitary towels include the similar primary and secondary packaging, i.e., polyethylene wrap and bag, and cardboard box. Raw materials and datasets used for packaging modelling are presented in Table 4. Packaging production was assumed to take place in Europe, with the following EF transport scenario for packaging materials:

- 230 km by truck
- 280 km by train
- 360 km by barge

[1] https://patents.google.com/patent/US4295987A/en

Table 4: List of packaging materials and datasets used for packaging modelling.

Material	EF dataset
Polyethylene (PE)*	LDPE granulates {EU-28+EFTA} | Polymerisation of ethylene | production mix at plant | 0.91- 0.96 g/cm3 28 g/mol per repeating unit
Cardboard box	Corrugated board, uncoated {EU-28+EFTA} | Kraft Pulping Process, pulp pressing and drying | production mix, at plant | flute thickness 0.8- 2.8 mm, R1=88% | LCI result

* Plastic granulate production process is complemented by the process: "Film Extrusion (blowing) {EU-28+EFTA} | plastic extrusion | production mix, at plant | for PP, PE, PVC, PET and PS"

4.1.2 Manufacturing

Manufacturing of baby diapers and sanitary towels is a dry process, thus only electricity is needed, in addition to raw materials. According to data collected from industries, electricity used in the manufacturing is 100% renewable. Taking into account that manufacturing data was based on only limited amount of industries, sensitivity analysis was performed to see the impact of electricity choice (Section 7). Average renewable energy mix for Europe was built using EUROSTAT data for the year 2019 (Eurostat 2021). Table 5 reports the composition of EU average renewable electricity mix and datasets used in the modelling.

No outputs, beside the main product, was reported in the data collection form, however it is acknowledged that during the production process some pieces are discarded on the manufacturing line due to errors in the process. To account for this, a literature data from Cordella et al. (2015) of 4% of scrapped product is used. This percentage is applied only to the product without packaging, since the hypotheses is that the pieces are discarded before the application of primary and secondary packaging. This waste material is treated with a worst-case scenario as municipal solid waste, similarly to the end of life of the whole product, although it is not the actual practise in manufacturing companies. Details of this scenario can be retrieved in Section 4.1.4. In addition, this amount was added to the raw materials needed in the production including same origin and transportation distances as reported in Section 4.1.1.

Table 5: Composition of the EU renewable electric mix.

Electricity source	Share	EF Dataset
Wind	39%	Electricity from wind power {EU-28+3} | AC technology mix of onshore and offshore | production mix at plant | 1kV - 60kV
Hydro	32%	Electricity from hydro power {EU-28+3} | AC technology mix of run-off-river storage and pump storage | production mix at power plant | 1kV - 60kV
Solar	14%	Electricity from photovoltaic {FR} | AC technology mix of CIS CdTE mono crystalline and multi crystalline | production mix at plant | 1kV - 60kV
Solid biomass	10%	Electricity from biomass (solid) {EU-28+3} | AC mix of direct and CHP technology mix regarding firing and flue gas cleaning | production mix at power plant | 1kV - 60kV
Gaseous biomass	6%	Electricity from biogas {EU-28+3} | AC mix of direct and CHP technology mix regarding firing and flue gas cleaning | production mix at power plant | 1kV - 60kV
Geothermal	1%	Electricity from geothermal {IT} | AC CHP technology mix | production mix at power plant | 1kV - 60kV

4.1.3 Distribution

Distribution from the manufacturing site to final client is modelled considering the default transport scenario in the PEF method (Zampori & Pant, 2019). The products are first transported to retail stores and from there to the final client. The underlying hypothesis is that 100% of the products are marketed via retail stores, and all the products are produced in Europe, therefore the EF scenario of a local supply chain is used as following: the transport from the factory to the retail is done with a truck, while for the transport from retail to final client, 5% of the products is considered to be delivered by van, 62% by passenger car, and the remaining 33% of the products is considered without impacts, i.e. on foot, bike or other human-powered transport. The car travel is representative of the consumer travel to a retail shop (e.g. a supermarket); hence the 5 km are allocated to the product proportionally to its weight, considering an average shop of 10 kg. This assumption was made by the authors due to lack of data, however its influence on the final results is negligible. Summary of datasets and transport distances per unit of product is presented in Table 6.

Table 6: Summary of the mode of transport, distance and dataset used to model the distribution of products.

Mode of transport	Share of products transported	Distance	EF Dataset
Truck from factory to retail	100%	1200 km	Articulated lorry transport, Euro 4, Total weight >32 t (with fuel) {EU-28+3} | diesel driven, Euro 4, cargo | consumption mix, to consumer | more than 32t gross weight / 24,7t payload capacity | Unit process, single operation
Car from retail store to final client	62%	5 km	Passenger car, average {GLO} | technology mix, gasoline and diesel driven, Euro 3-5, passenger car | consumption mix, to consumer | engine size from 1,4l up to >2l | LCI result
Van from retail store to final client	5%	5 km	§ Articulated lorry transport, Euro 3, Total weight <7.5 t (with fuel) {EU-28+3} | diesel driven, Euro 3, cargo | consumption mix, to consumer | up to 7,5t gross weight / 3,3t payload capacity | Unit process, single operation

4.1.4 End of Life

The end of life of the products was modelled using the Circular Footprint Formula (CFF) and considering separate scenarios for the end of life of the product and its packaging. The parameters used in the CFF are:

— R1 is the share of recycled content in the raw materials. This parameter has been considered 0 due to lack of data on the supply chain of materials. The only exception is cardboard used for the packaging, which according to the EF dataset used has a recycled content of 88%

— R2 is the share of materials sent to recovery at the end-of-life of the product. For the disposal of product is considered to be 0 as the AHPs at the end of their life cannot be recovered. For the packaging, Annex C in PEF method (Zampori & Pant, 2019) provide the average value of R2 in the European market.

— R3 is the share of material sent to energy recovery. For the product the average value of R3 for municipal solid waste was used (45%, from Annex C in PEF method (Zampori & Pant, 2019)). For packaging, the share was calculated considering the share of packaging not recovered (1-R2) and considering it as MSW (45%*(1-R2))

- A is the allocation factor of environmental burdens between the supplier and user of recycled material. Lower values allocate more burden on the waste producer. The values are suggested in Annex C of the PEF method (Zampori & Pant, 2019) and they are based on extensive evaluation performed during the development of the pilot phase PEFCRs.
- Qsout/Qp represents the different quality of the secondary material produced in the recycling process compared to the quality of the virgin material.

The values reported in Table 7 were retrieved from the latest version of Annex C of the PEF method (Zampori & Pant, 2019), except R2 value for PE packaging, which is based on recycled amount of PE packaging from households in EU (Eunomia, 2020). The table also report the dataset used for the activity of landill (E_D), incineration with energy recovery (E_R) and recycling at the end of life ($E_{recyclingEoL}$). For the recycling activity of PE a proxy dataset for PP in US has been used, while for cardboard a custom dataset was create using data on energy consumption in the cardboard production from Ecoinvent 3.6 (Wernet et al., 2016).

Table 7: Summary of the Circular Footprint Formula parameters used in the end of life modelling.

Material	A	R1	R2	R3	Qsout/ Qp	Dataset used
Main product (municipal solid waste)	-	0%	0%	45%	-	E_R including credits from electricity and heat recovery: Waste incineration of municipal solid waste {EU-28+EFTA} | waste-to-energy plant with dry flue gas treatment including transport and pre-treatment | production mix at consumer | municipal solid waste
						E_D: Landfill of municipal solid waste {EU-28+EFTA}
PE packaging	0.5	0%	17%	14%	0.75	E_R including credits from electricity and heat recovery: Waste incineration of plastics (unspecified) {EU-28+EFTA} | waste-to-energy plant with dry flue gas treatment including transport and pre-treatment | production mix
						E_D: Landfill of plastic waste {EU-28+EFTA} | landfill including leachate treatment and with transport without collection and pre-treatment | production mix (region specific sites) at landfill site
						$E_{recyclingEoL}$: Recycling of polypropylene (PP) plastics {US} | from post-consumer waste via washing, granulation, pelletization | production mix at plant| 90% of recycling rate
Cardboard packaging	0.2	88%	75%	14%	0.85	E_R including credits from electricity and heat recovery: Waste incineration of paper and board {EU-28+EFTA} | waste-to-energy plant with dry flue gas treatment including transport and pre-treatment | production mix at consumer | paper waste
						E_D: Landfill of paper and paperboard waste {EU-28+EFTA}
						$E_{recyclingEoL}$: custom dataset* including: 0.16 kWh/kg of "Residual grid mix {EU-28+3} | AC, technology mix | consumption mix, to consumer | 1kV - 60kV | LCI result" 0.51 kJ/kg of "Thermal energy from natural gas {EU-28+3} | technology mix regarding firing and flue gas cleaning | production mix, at heat plant | MJ, 100% efficiency | LCI result"

* The quantity of energy used for the dataset was retrieved from the dataset "Containerboard, linerboard {RER} containerboard production, linerboard, testliner | APOS" of Ecoinvent 3.6 (Wernet et al., 2016).

4.2 Handling multi-functional processes

There are not any multifunctional processes in the foreground system. The only multifunctional processes are present in the background datasets and are already handled according to the PEF method.

4.3 Data collection

Data on bill of materials, and inputs and outputs in manufacturing stage was collected from manufacturing companies of baby diapers and sanitary towels. EDANA collected data from their member companies using data collection form provided by JRC. Manufacturing data was received from four companies producing open baby diapers and three companies producing sanitary towels. According to the data from individual companies, EDANA calculated arithmetic mean data for JRC, without taking into account market shares of the companies. Data collected from companies are classified as confidential and cannot be published.

4.4 Data quality requirements and rating

Data Quality Rating (DQR) of the two products was assessed using the criteria described in the PEF methodology. The most relevant processes (i.e. the ones accounting for more than 80% of the overall impact) were included in the rating.

The data quality assessment uses four criteria that are scored independently from 1 to 5, with 1 being the highest score. The criteria are precision (P), time representativeness: (TiR), geographical representativeness (GeR) and technological representativeness (TeR). Then, the score of each dataset is weighted, according to its share of impact, to give the final Data Quality Rating. Data Quality Rating is presented in Table 8 (baby diapers) and Table 9 (sanitary towels).

The final result is a good Data Quality Level (score 2.04) for baby diapers, and very good (score 1.66) for sanitary towels. Although the score for both baby diaper and sanitary towel is good, it can be noticed that while geographical and technological representativeness of dataset is high (<3), precision and time representativeness have lower scores. This is due to the nature of the study which used data from the manufacturing companies while most of the relevant processes are out of the control of these companies.

Table 8: Data Quality Rating of open baby diapers.

<table>
<tr><th>Dataset</th><th>Weight</th><th>TeR</th><th>GeR</th><th>TiR</th><th>P</th><th>DQR</th></tr>
<tr><td colspan="6">Baby Diaper</td><td>2.04</td></tr>
<tr><td>SAP production</td><td>27.1%</td><td>2</td><td>2</td><td>4</td><td>3</td><td>2.75</td></tr>
<tr><td>Freight train, average (with fuel) {EU-28+3} | technology mix, electricity and diesel driven, cargo | consumption mix, to consumer | average train, gross tonne weight 1000t / 726t payload capacity | Unit process, single operation</td><td>16.5%</td><td>1</td><td>1</td><td>3</td><td>4</td><td>2.25</td></tr>
<tr><td>PP granulates {EU-28+EFTA} | polymerisation of propene | production mix, at plant | 0.91 g/cm3, 42.08 g/mol per repeating unit | LCI result</td><td>13.6%</td><td>1</td><td>1</td><td>1</td><td>3</td><td>1.5</td></tr>
<tr><td>Bleached kraft pulp, softwood {US and CA} | production mix | at plant | per kg pulp | LCI result</td><td>8.4%</td><td>1</td><td>1</td><td>1</td><td>3</td><td>1.5</td></tr>
<tr><td>LDPE granulates {EU-28+EFTA} | Polymerisation of ethylene | production mix, at plant | 0.91- 0.96 g/cm3, 28 g/mol per repeating unit | LCI result (main product)</td><td>5.9%</td><td>1</td><td>1</td><td>1</td><td>3</td><td>1.5</td></tr>
<tr><td>Landfill of municipal solid waste {EU-28+EFTA} | LCI result</td><td>5.7%</td><td>1</td><td>1</td><td>4</td><td>4</td><td>2.5</td></tr>
<tr><td>Dicyclopentadiene based unsaturated polyester resin {RER}| production | APOS, S</td><td>4.2%</td><td>2</td><td>1</td><td>1</td><td>3</td><td>1.75</td></tr>
<tr><td>PET granulates, amorphous {EU-28+EFTA} | Polymerisation of ethylene | production mix, at plant | 0.91- 0.96 g/cm3, 28 g/mol per repeating unit | LCI result</td><td>4.0%</td><td>1</td><td>1</td><td>1</td><td>3</td><td>1.5</td></tr>
<tr><td>Ethylene propylene dien elastomer (EPDM) {World w/o EU-28+EFTA} | copolymerization of ethylene and propylene | production mix, at plant | 69% ethylene, 38% propylene | LCI result</td><td>3.0%</td><td>1</td><td>1</td><td>1</td><td>3</td><td>1.5</td></tr>
<tr><td>Transoceanic ship, containers {GLO} | heavy fuel oil driven, cargo | consumption mix, to consumer | 27.500 dwt payload capacity, ocean going | LCI result</td><td>2.4%</td><td>1</td><td>1</td><td>3</td><td>4</td><td>2.25</td></tr>
<tr><td>Articulated lorry transport, Euro 4, Total weight >32 t (with fuel) {EU-28+3} | diesel driven, Euro 4, cargo | consumption mix, to consumer | more than 32t gross weight / 24,7t payload capacity | Unit process, single operation</td><td>2.2%</td><td>1</td><td>1</td><td>3</td><td>4</td><td>2.25</td></tr>
<tr><td>Film Extrusion (blowing) {EU-28+EFTA} | plastic extrusion | production mix, at plant | for PP, PE, PVC, PET and PS | LCI result</td><td>2.1%</td><td>1</td><td>1</td><td>1</td><td>3</td><td>1.5</td></tr>
<tr><td>LDPE granulates {EU-28+EFTA} | Polymerisation of ethylene | production mix, at plant | 0.91- 0.96 g/cm3, 28 g/mol per repeating unit | LCI result (packaging)</td><td>1.5%</td><td>1</td><td>1</td><td>1</td><td>3</td><td>1.5</td></tr>
<tr><td>Passenger car, average {GLO} | technology mix, gasoline and diesel driven, Euro 3-5, passenger car | consumption mix, to consumer | engine size from 1,4l up to >2l | LCI result</td><td>1.3%</td><td>1</td><td>1</td><td>3</td><td>4</td><td>2.25</td></tr>
</table>

Table 9: Data Quality Rating of sanitary towels.

Dataset	Weight	TeR	GeR	TiR	P	DQR
Sanitary towel						1.66
Freight train, average (with fuel) {EU-28+3} | technology mix, electricity and diesel driven, cargo | consumption mix, to consumer | average train, gross tonne weight 1000t / 726t payload capacity | Unit process, single operation	19.0%	1	1	3	4	2.25
PET granulates, amorphous {EU-28+EFTA} | Polymerisation of ethylene | production mix, at plant | 0.91- 0.96 g/cm3, 28 g/mol per repeating unit | LCI result	15.2%	1	1	1	3	1.5
LDPE granulates {EU-28+EFTA} | Polymerisation of ethylene | production mix, at plant | 0.91- 0.96 g/cm3, 28 g/mol per repeating unit | LCI result (main product)	13.2%	1	1	1	3	1.5
Fibre, viscose {GLO}| fibre production, viscose | APOS, S	12.9%	1	1	1	3	1.5
LDPE granulates {EU-28+EFTA} | Polymerisation of ethylene | production mix, at plant | 0.91- 0.96 g/cm3, 28 g/mol per repeating unit | LCI result (packaging)	8.1%	1	1	1	3	1.5
Bleached kraft pulp, softwood {EU-28+3} | production mix | at plant | per kg pulp | LCI result	7.4%	1	1	1	3	1.5
Dicyclopentadiene based unsaturated polyester resin {RER}| production | APOS, S	4.4%	2	1	1	3	1.75
PP granulates {EU-28+EFTA} | polymerisation of propene | production mix, at plant | 0.91 g/cm3, 42.08 g/mol per repeating unit | LCI result	4.3%	1	1	1	3	1.5
SAP production	3.1%	2	2	4	3	2.75
Silicone, low viscosity {EU-28+EFTA} | hydrolysis and methanolysis of dimethyldichloro silane | production mix, at plant | <30 000 centi Poise | LCI result	2.6%	1	1	1	3	1.5
Film Extrusion (blowing) {EU-28+EFTA} | plastic extrusion | production mix, at plant | for PP, PE, PVC, PET and PS | LCI result	2.6%	1	1	1	3	1.5
Articulated lorry transport, Euro 4, Total weight >32 t (with fuel) {EU-28+3} | diesel driven, Euro 4, cargo | consumption mix, to consumer | more than 32t gross weight / 24,7t payload capacity | Unit process, single operation	2.0%	1	1	3	4	2.25
Passenger car, average {GLO} | technology mix, gasoline and diesel driven, Euro 3-5, passenger car | consumption mix, to consumer | engine size from 1,4l up to >2l | LCI result	1.2%	1	1	3	4	2.25

5 Impact assessment results

Tables 10 and 11 presents characterised, normalised and weighted results of open baby diapers and sanitary towels, respectively. Characterised results are presented per life cycle stages, and Climate Change sub-categories are reported separately. As there are not additional environmental burdens added to the system at the use stage results are excluded from the tables.

Table 10: Characterised, normalised and weighted impacts of open baby diapers.

Impact category	Characterised impact					Normalised impact	Weighted impact
	Raw material acquisition	Manufacturing	Distribution	End of Life	Total		
Climate Change [kg CO_2 eq.]	6.80E-02	1.39E-03	3.89E-03	1.68E-02	9.00E-02	1.11E-05	2.34E-06
Climate Change (fossil) [kg CO_2 eq.]					7.33E-02	-	-
Climate Change (biogenic) [kg CO_2 eq.]					1.67E-02	-	-
Climate Change (land use and land use change) [kg CO_2 eq.]					6.84E-05	-	-
Ozone Depletion [kg CFC-11 eq.]	3.46E-09	-7.15E-15	8.71E-15	-9.25E-13	3.46E-09	6.45E-08	4.07E-09
Ionising Radiation [kBq U^{235} eq.]	1.09E-02	-1.42E-05	8.86E-06	-1.14E-03	9.71E-03	2.30E-06	1.15E-07
Photochemical Ozone Formation [kg NMVOC eq.]	5.65E-04	6.00E-06	1.64E-05	4.60E-06	5.92E-04	1.46E-05	6.97E-07
Particulate matter [Disease incidence]	5.11E-09	8.20E-11	2.90E-10	-9.83E-11	5.39E-09	9.05E-06	8.11E-07
Human toxicity - non-cancer [CTUh]	8.93E-10	3.98E-11	1.95E-11	9.00E-11	1.04E-09	4.54E-06	8.35E-08
Human Toxicity - cancer [CTUh]	1.01E-10	7.58E-13	7.78E-13	-3.01E-13	1.02E-10	6.03E-06	1.28E-07
Acidification [mol of H^+ eq.]	4.97E-04	7.61E-06	4.66E-05	-7.14E-06	5.44E-04	9.80E-06	6.07E-07
Eutrophication - freshwater [kg P eq.]	3.41E-06	8.78E-08	1.01E-08	3.43E-07	3.85E-06	2.40E-06	6.72E-08
Eutrophication - marine [kg N eq.]	1.81E-04	2.86E-06	8.78E-06	3.27E-06	1.96E-04	1.00E-05	2.97E-07
Eutrophication - terrestrial [mol N eq.]	1.98E-03	2.50E-05	2.15E-04	1.19E-05	2.23E-03	1.26E-05	4.69E-07
Ecotoxicity - freshwater [CTUe]	8.17E-01	5.48E-02	4.52E-02	-1.72E-03	9.15E-01	2.14E-05	4.12E-07
Land Use [Pt]	2.89E+00	1.08E-01	3.62E-03	-3.47E-01	2.65E+00	3.24E-06	2.57E-07
Water Use [m^3 world eq.]	4.60E-02	3.65E-03	2.81E-04	-6.20E-04	4.93E-02	4.30E-06	3.66E-07
Resource Use - fossils [MJ]	1.64E+00	2.32E-03	5.39E-02	-8.63E-02	1.61E+00	2.48E-05	2.06E-06
Resource Use - mineral and metals [kg Sb eq.]	3.71E-07	1.57E-08	2.01E-10	-1.05E-09	3.86E-07	6.06E-06	4.58E-07

Table 11: Characterised, normalised and weighted impacts of sanitary towels.

Impact category	Characterised impact					Normalised impact	Weighted impact
	Raw material acquisition	Manufacturing	Distribution	End of Life	Total		
Climate Change [kg CO_2 eq.]	1.45E-02	2.35E-04	1.06E-03	-1.30E-04	1.56E-02	1.93E-06	4.06E-07
Climate Change (fossil) [kg CO_2 eq.]					1.50E-02	-	-
Climate Change (biogenic) [kg CO_2 eq.]					6.12E-04	-	-
Climate Change (land use and land use change) [kg CO_2 eq.]					1.92E-05	-	-
Ozone Depletion [kg CFC-11 eq.]	6.08E-10	-4.16E-15	2.37E-15	-8.21E-14	6.08E-10	1.13E-08	7.15E-10
Ionising Radiation [kBq U^{235} eq.]	1.62E-03	-6.01E-06	2.43E-06	-9.55E-05	1.42E-03	3.36E-07	1.68E-08
Photochemical Ozone Formation [kg NMVOC eq.]	1.71E-04	9.45E-07	4.67E-06	-3.77E-06	1.73E-04	4.25E-06	2.03E-07
Particulate matter [Disease incidence]	1.44E-09	1.24E-11	9.38E-11	-3.45E-11	1.51E-09	2.53E-06	2.27E-07
Human toxicity - non-cancer [CTUh]	4.51E-10	6.37E-12	5.23E-12	-7.90E-12	4.54E-10	1.98E-06	3.64E-08
Human Toxicity - cancer [CTUh]	6.21E-11	1.18E-13	2.08E-13	-1.32E-12	6.11E-11	3.62E-06	7.70E-08
Acidification [mol of H^+ eq.]	1.39E-04	1.16E-06	1.48E-05	-3.62E-06	1.51E-04	2.73E-06	1.69E-07
Eutrophication - freshwater [kg P eq.]	1.20E-06	1.40E-08	2.60E-09	-4.01E-09	3.45E-07	2.15E-07	6.01E-09
Eutrophication - marine [kg N eq.]	5.45E-05	4.51E-07	2.56E-06	-1.12E-06	5.62E-05	2.87E-06	8.51E-08
Eutrophication - terrestrial [mol N eq.]	5.92E-04	3.95E-06	6.85E-05	-1.05E-05	6.54E-04	3.70E-06	1.37E-07
Ecotoxicity - freshwater [CTUe]	2.62E-01	8.43E-03	1.24E-02	-5.80E-03	2.77E-01	6.49E-06	1.25E-07
Land Use [Pt]	1.12E+00	1.67E-02	9.36E-04	-1.82E-01	9.54E-01	1.16E-06	9.24E-08
Water Use [m^3 world eq.]	1.43E-02	5.66E-04	7.37E-05	-5.16E-04	1.44E-02	1.26E-06	1.07E-07
Resource Use - fossils [MJ]	3.69E-01	5.18E-05	1.47E-02	-1.58E-02	3.68E-01	5.66E-06	4.71E-07
Resource Use - mineral and metals [kg Sb eq.]	4.38E-07	2.43E-09	5.37E-11	-3.79E-10	4.40E-07	6.92E-06	5.22E-07

6 Interpretation of results

The most relevant impact categories, life cycle stages, processes and flows are presented in Tables 12 (baby diapers) and 13 (sanitary towels). In these tables, the contribution analysis of impact category was calculated based on the normalised and weighted impacts, whereas characterised results were used to identify the most relevant life-cycle stages, processes and elementary flows. The respective contribution (in %) for each of the life cycle stages, processes and elementary flows refers to the individual contribution for a specific impact category. Negative values were kept as negative to be able to see benefits from End of Life, although the PEF method suggest to use absolute values.

For baby diapers, Climate Change is the most relevant impact category with 26% share, followed by Resource Use – fossils (23%), Particulate Matter (9%), Photochemical Ozone Formation (8%), Acidification (7%), Eutrophication – terrestrial (5%) and Resource Use – minerals and metals (5%). When comparing the results with other studies, the most relevant impact categories for disposable baby diapers are Eutrophication Potential, Climate Change and Primary Energy Demand (Mendoza et al., 2019). Also Hoffman et al. (2020) concluded that Climate Change is the most contributing impact category for disposable baby diapers.

For sanitary towels the most relevant impact category is Resource Use – Minerals and metals with 19% share, followed by Resource Use – fossils (17%), Climate Change (15%), Particulate Matter (8%), Photochemical Ozone Formation (7.5%), Acidification (6%), Eutrophication - terrestrial (5%) and Ecotoxicity - freshwater (5%).

Raw material acquisition is always the most relevant life cycle stage, having contribution between 76% (Climate Change) and 102% (Resource Use - fossils) for baby diapers, and between 91% (Eutrophication, terrestrial) and 100% (Resource Use – fossils and Resource Use - minerals and metals) for sanitary towels. Resource Use – fossils exceeds 100% due to negative values in the End of Life.

The most relevant processes related to raw material acquisition of the baby diaper include production of SAP, fluff pulp, and PP, LDPE and PET granulates (the complete list by impact categories and shares can be seen in the Table 12). These raw materials are also the main raw materials in the baby diaper production, especially SAP which was assumed to have 40% share of the all raw materials, and are thus identified to have the highest contributions of the impacts. In addition to raw materials, also waste landfilling (in Climate Change), train transportation of raw materials and packaging (in Particulate Matter, Photochemical Ozone Formation, Acidification and Eutrophication – terrestrial), ship transportation of fluff pulp from US to Europe (in particulate Matter and Photochemical Ozone Formation), and lorry transportation of raw materials and in product distribution phase (in Particulate Matter, Acidification and Eutrophication – terrestrial) are identified among the most relevant processes for baby diapers in some impact categories. Results obtained are in line with the overview of published LCA studies (sections 4.4.1 and 4.4.2 in the Preliminary Report[2]), as explained in the next paragraph.

The raw material acquisition is the main contributing life cycle stage also in Cordella et al. (2015) and Mendoza et al. (2019) studies. However, in Hoffman et al. (2020) study, the End of Life is the most contributing life cycle stage with 75% contribution in Climate Change impact category due to emissions from landfilling, which is also identified as a hotspot in this study, but with lower importance. It has to be noted, that results cannot be fully compared because of the differences in the definition of the functional unit (FU) and different characterisation method used in the different studies. For example, in Aumonier et al. (2008) Climate Change impact is 568 kg CO_2-eq for the 'one toilet trained child' or '4550 used diapers', while Hoffman et al. (2020) obtained an impact of 1236 kg CO_2-eq for same functional unit. In Cordella et al. (2015) the overall CO_2-eq is 592 kg and in the present study Climate Change impact is 410 kg CO_2-eq, if the impact is converted as a use of 4550 diapers.

The most relevant processes related to raw material acquisition of the sanitary towel include production of viscose, fluff pulp, and PET, LDPE and PP granulates (the complete list by impact categories and shares can be seen in the Table 13). Also production of LDPE granulates and film extrusion of LDPE for packaging production were identified among the most relevant processes in some impact categories, mainly in Resource Use – fossils (17%), Climate Change (11% granulates, 6% extrusion) and Ecotoxicity –freshwater (14%). In case of sanitary towel, LDPE packaging has the higher contribution in the most relevant processes compared to the baby diapers, because of the higher share of the packaging materials compared to the product mass in sanitary towels. This also explains the presence of an additional impact category (Ecotoxicity -freshwater) in the group of the most relevant ones for sanitary towels and the difference in the ranking of the other six. In addition to the raw materials and packaging production, also train transportation of raw materials and packaging and lorry

[2] Preliminary Report, October 2021. Available at: https://susproc.jrc.ec.europa.eu/product-bureau//sites/default/files/2021-09/Absorbent%20Hygiene%20Products_Draft%20Preliminary%20report_FINAL.pdf

transportation of raw materials and in product distribution phase are identified among the most relevant processes for sanitary towels in some impact categories. In contrary to baby diapers, waste landfilling was not identified among the most relevant processes, because of the smaller mass of the product compared to LDPE packaging, when the credits from packaging recycling compensates the emissions from the landfilling.

When comparing the results with other studies, Mazgaj at al. (2021), observed that the most contributing process in the sanitary towels is the production of the LDPE foil, while Hait and Powers (2019) and Vilabrille Paz et al. (2020) (as cited in the United Nations Environment Programme report, UNEP (2021)) found that manufacturing of raw materials contributed the most to the overall impact. According to Hait and Powers (2019), the most contributing raw materials in sanitary towel manufacturing are polyethylene (66% of Energy Resource Use and 34% of Climate Change impact), and absorbent fluff from softwood pulp (23% of Climate Change impact).

Distribution has typically contributions around 5%, but in Acidification and Eutrophication, terrestrial it is around 10%. The high contribution of the transport during distribution is in all cases mainly due to the transportation of product by lorry. In some impact categories train transportation was identified among the most relevant processes, which is the part of raw material (240 km) and packaging (280km) transportation scenario, which are taken from (Zampori & Pant, 2019). For baby diapers train transportation has contributions of 46% (Particulate Matter), 58% (Photochemical Ozone Formation), 42% (Acidification), and 59% (Eutrophication - terrestrial), being the most relevant process in those impact categories. For sanitary towels train transport has contributions of 56% (Particulate Matter), 67% (Photochemical Ozone Formation), 51% (Acidification), and 68% (Eutrophication - terrestrial), being again the most relevant process in those impact categories.

Manufacturing and End of Life stages have only small share of impacts in almost all impact categories. Only in Climate Change impact of baby diapers End of Life has 19% of contribution, because of emissions of the landfilling of the product. For sanitary towels this is not the case because the mass of the packaging is relatively high compared to the mass of the product itself, thus the credits received from the end of life of the packaging (assumed to be partly recycled) are partly compensating the impacts of landfilling the product. The credits from the end of life of the packaging (assumed to be partly recycled) also explains why the End of Life stage has negative share in some impact categories, i.e. benefits from the end of life of the packaging are bigger than the impacts of landfilling the main product.

It is to note that currently several countries in Europe such as The Netherlands (ARN/Elsinga)[3] or Italy (FATER)[4] offer options for partial recycling of baby diapers rather than incineration or landfill disposal as it has been considered in the PEF modelling with SimaPro for this study. As recycling is not yet available in the majority of EU countries this option was not explored in the present study. Generally, used baby diapers are disposed within the MSW (Municipal Solid Waste) and send to landfill or incineration without further recovery. As more countries are expected to set alternative recovery of used absorbent hygiene products, the recyclability could then be explored in future scenarios concerning the impacts of AHP. However the management and final disposal of used AHP are out of the scope of the EU Ecolabel criteria. The EU Ecolabel could encourage recycling once each waste management system establishes the possibility at the national level of the Member States.

[3] Comparative mLCA on waste treatment of diaper and incontinence material Revised. Commissioned by Rijkswaterstaat Water, Verkeer & Leefomgeving (WVL). 2021. Available at: https://lap3.nl/publish/pages/138145/2021-02-24-vergelijkende-mlca-luier-afvalverwerking-herzien.pdf

[4] Khoo, S. C., Phang, X. Y., Ng, C. M., Lim, K. L., Lam, S. S. and Ma, N. L., 'Recent technologies for treatment and recycling of used disposable baby diapers', Process Safety and Environmental Protection, Vol. 123, Elsevier, 2019, pp. 116-129.

Table 12: The most relevant impact categories, life cycle stages, processes and elementary flows of baby diapers.

Most relevant impact category	[%]	Most relevant life cycle stage	[%]	Most relevant processes	[%]	Most relevant elementary flows	[%]
Climate Change	25.5%	Raw material acquisition	76%	SAP production	35%	Carbon dioxide, fossil	72%
				Landfill of municipal solid waste	20%		
		End of Life	19%	PP granulates production	13%		
				Pulp production	6%		
		Distribution	4%	LDPE granulates production for the main product	5%	Methane, biogenic	19%
		Manufacturing	2%	Polyester resin production	4%		
Resource Use - fossils	22.5%	Raw material acquisition	102%	SAP production	39%	Energy, from oil	46%
		Distribution	3%	PP granulates production	29%	Energy, from gas, natural	28%
		Manufacturing	0%	LDPE granulates production for the main product	10%	Energy, from uranium	10%
		End of Life	-5%	Polyester resin production	6%		
Particulate Matter	8.8%	Raw material acquisition	95%	Transport, train	46%	Particulates, <2.5 µm	65%
				SAP production	19%		

Most relevant impact category	[%]	Most relevant life cycle stage	[%]	Most relevant processes	[%]	Most relevant elementary flows	[%]
		Distribution	5%	Pulp production	7%		
		Manufacturing	2%	Transport, transoceanic ship	6%	Sulfur dioxide	16%
		End of Life	-2%	Transport, lorry	5%		
Photochemical Ozone Formation	7.6%	Raw material acquisition	95%	Transport, train	58%	Nitrogen dioxide	72%
				SAP production	10%		
		Distribution	3%	Pulp production	6%	NMVOC	11%
		Manufacturing	1%	PP granulates production	5%		
		End of Life	1%	Transport, transoceanic ship	5%		
Acidification	6.6%	Raw material acquisition	91%	Transport, train	42%	Nitrogen dioxide	58%
				SAP production	17%		
		Distribution	9%	Transport, lorry	8%	Sulfur dioxide	27%
		Manufacturing	1%	Transport, transoceanic ship	7%		

Most relevant impact category	[%]	Most relevant life cycle stage	[%]	Most relevant processes	[%]	Most relevant elementary flows	[%]
		End of Life	-1%	Pulp production	6%		
Eutrophication - terrestrial	5.1%	Raw material acquisition	89%	Transport, train	59%	Nitrogen dioxide	82%
		Distribution	10%	Transport, lorry	9%		
		Manufacturing	1%	SAP production	8%		
		End of Life	1%	Bleached kraft pulp production	6%		
Resource Use – minerals and metals	5.0%	Raw material acquisition	96%	PET granulate production	59%	Antimony	59%
		Manufacturing	4%	SAP production	20%	Gold	21%
		Distribution	0%	Polyester resin production	12%	Copper	6%
		End of Life	0%				

Table 13: The most relevant impact categories, life cycle stages, processes and elementary flows of sanitary towels.

Most relevant impact category	[%]	Most relevant life cycle stage	[%]	Most relevant processes	[%]	Most relevant elementary flows	[%]
Resource Use – minerals and metals	19.4%	Raw material acquisition	100%	PET granulates production	58%	Antimony	58%
		Manufacturing	1%				
		Distribution	0%	Viscose production	32%	Gold	35%
		End of Life	0%				
Resource Use - fossils	17.4%	Raw material acquisition	100%	LDPE granulates production for the main product	28%	Energy, from oil	48%
				LDPE granulates production for the packaging	17%		
		Distribution	4%	PP granulates production	12%	Energy, from gas, natural	26%
				PET granulates production	9%		
		Manufacturing	0%	Polyester resin production	8%	Energy, from uranium	6%
		End of Life	-4%	SAP production	6%		
Climate Change	15.1%	Raw material acquisition	93%	LDPE granulate production for the main product	18%	Carbon dioxide, fossil	84%
				LDPE granulate production for the packaging	11%		

Most relevant impact category	[%]	Most relevant life cycle stage	[%]	Most relevant processes	[%]	Most relevant elementary flows	[%]
				Viscose production	11%		
		Distribution	7%	PET granulate production	8%		
				Pulp production	7%		
		Manufacturing	2%	PP granulate production	7%		
				Polyester resin production	7%		
		End of Life	-1%	SAP production	7%		
				Film extrusion of LDPE	6%		
Particulate Matter	8.4%	Raw material acquisition	95%	Transport, train	56%	Particulates, <2.5 µm	68%
				Viscose production	12%		
		Distribution	6%	Pulp production	5%	Nitrogen dioxide	13%
		Manufacturing	1%	Transport, lorry	4%		
		End of Life	-2%	LDPE granulates production for the main product	4%		

Most relevant impact category	[%]	Most relevant life cycle stage	[%]	Most relevant processes	[%]	Most relevant elementary flows	[%]
Photochemical Ozone Formation	7.5%	Raw material acquisition	99%	Transport, train	67%	Nitrogen dioxide	71%
		Distribution	3%	LDPE granulates production for the main product	6%		
		Manufacturing	1%	Pulp production	6%	NMVOC	12%
		End of Life	-2%	Polyester resin production	4%		
Acidification	6.3%	Raw material acquisition	92%	Transport, train	51%	Nitrogen dioxide	60%
				Viscose production	10%		
		Distribution	10%	Transport, lorry	8%	Sulfur dioxide	23%
		Manufacturing	1%	Pulp production	6%		
		End of Life	-2%	LDPE granulates production for the main product	5%		
Eutrophication - terrestrial	5.1%	Raw material acquisition	91%	Transport, train	68%	Nitrogen dioxide	80%
		Distribution	10%	Transport. lorry	8%		

Most relevant impact category	[%]	Most relevant life cycle stage	[%]	Most relevant processes	[%]	Most relevant elementary flows	[%]
		Manufacturing	1%	Pulp production	5%	Ammonia	8%
		End of Life	-2%				
Ecotoxicity - freshwater	5.0%	Raw material acquisition	95%	LDPE granulates production for the main product	23%	Chloride to water	59%
				Viscose production	21%		
		Distribution	4%	LDPE granulates production for the packaging	14%	Aluminium to air	12%
				PP granulate production	9%		
		Manufacturing	3%	PET granulate production	6%		
				Pulp production	6%	Aluminium to soil	9%
		End of Life	-2%	Polyester resin production	5%		

7 Sensitivity analysis

According to the data collected from industry, electricity used during manufacturing is 100% renewable (Section 4.1.2). Taking into account that manufacturing data was based on a limited amount of industries, a sensitivity analysis was performed to see the impact of electricity choice. When the EF dataset "Residual grid mix {EU-28+3} | AC, technology mix | consumption mix, to consumer | 1kV - 60kV", which represents the European average mix, was used instead of the "EU renewable electricity mix", no significant differences could be appreciated in the results in the majority of the impact categories (see Figure 2). The difference is significant only for Ionising Radiation, due to the presence of nuclear energy in the average electricity mix (the "residual grid mix" dataset). However, Ionising Radiation is not among the most relevant impact categories for this modelling, so the main conclusions would not change if a different electricity mix was used.

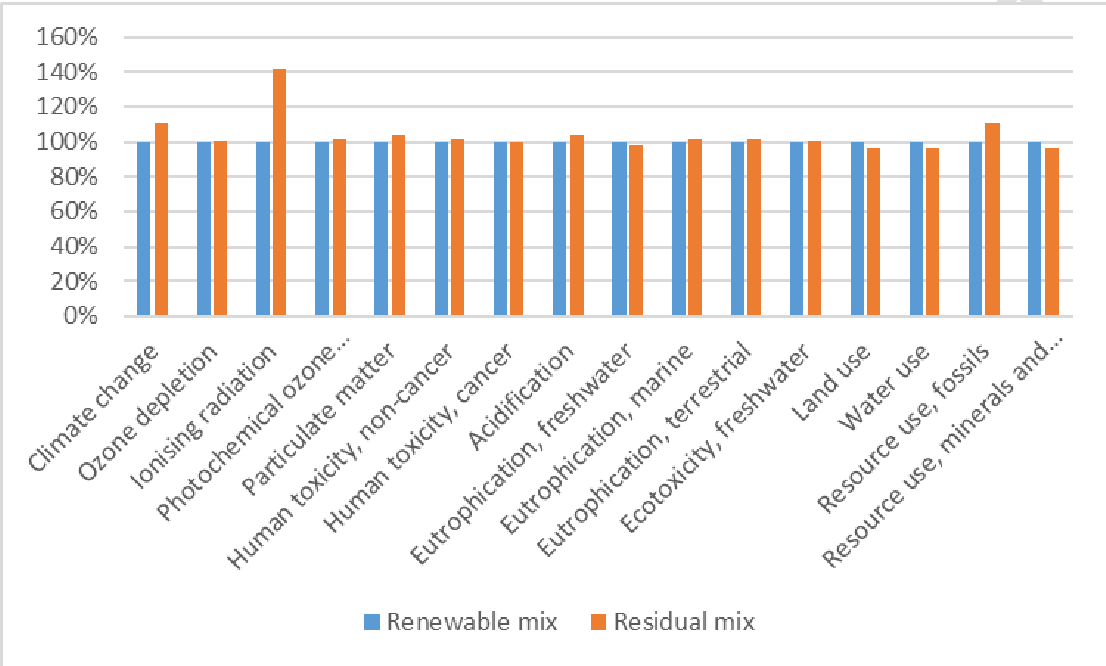

Figure 2: Comparison of baby diaper results when electricity used in manufacturing process is 100% renewable (Renewable mix) or EU average mix (Residual mix).

SAP production was identified as a hotspot in almost all most relevant impact categories. Because SAP production data was based on literature, and modelled for this purpose, it was possible to further investigate the most relevant processes inside the SAP production dataset. It was noticed, that electricity consumption has the highest share of the impacts in many impact categories. Thus the assumption of electricity amount was also explored in the sensitivity analysis. In the absence of knowledge of the range of electricity consumption for SAP production, an arbitrary choice of -20% was decided to be tested. The analysis showed that such a decrease in electricity consumption would have very limited impact on the total results for baby diapers. Only in the case of Ionising Radiation the impact decrease is significant, 11% (see Figure 3), but since Ionising Radiation is not among the most relevant impact categories for this model, the main conclusions would not be affected by a change in electricity consumption.

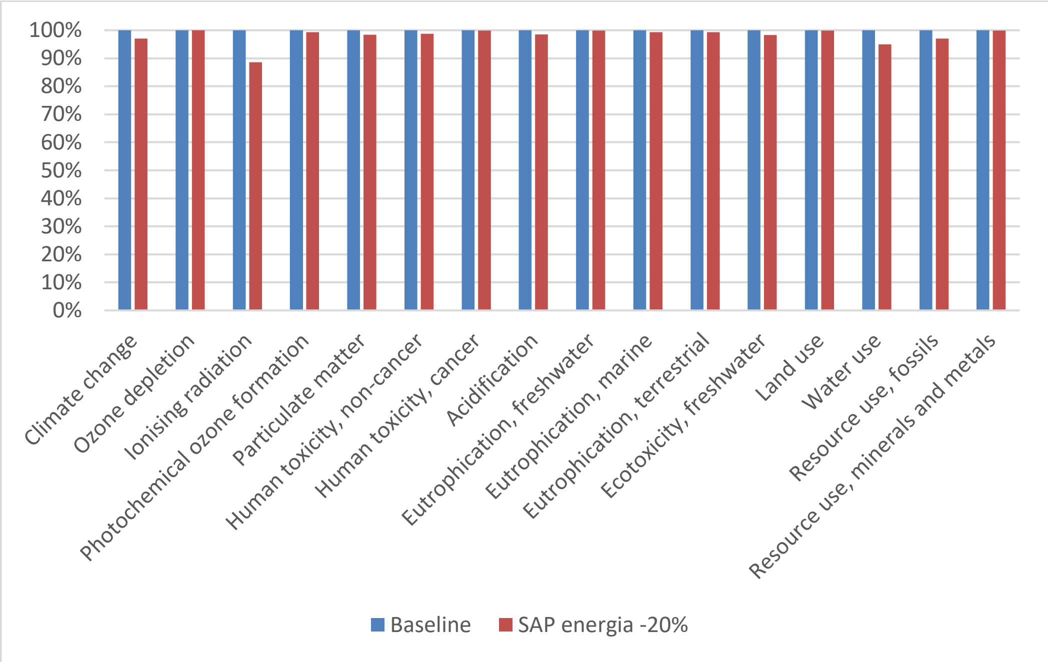

Figure 3: Comparison of baby diaper results when electricity used in SAP manufacturing process would be 20% lower than in the baseline assumption.

8 Conclusions

The environmental hotspots identified in this study are mainly related to production of raw materials, having contribution between 76% (Climate Change) and 102% (Resource Use - fossils) for baby diapers, and between 91% (Eutrophication, terrestrial) and 100% (Resource Use – fossils and Resource Use - minerals and metals) for sanitary towels. These findings are in line with the other studies (Cordella et al., 2015; Mendoza et al., 2019; Hait and Powers, 2019; UNEP, 2021).

The raw materials showing highest contributions in case of baby diapers are SAP (which also has the highest share of materials used in the diapers), fluff pulp, and PP, LDPE and PET granulates. For sanitary towels, the most contributing raw materials are viscose, fluff pulp, and PET, PP and LDPE granulates. In addition to LDPE used in the sanitary towel production, the LDPE granulates used for sanitary towel packaging were also identified as a hotspot in some impact categories. Also Mazgai et al. (2021) observed the high importance of LDPE foil in the sanitary towel life cycle.

In addition to raw materials and packaging, also transportation of raw materials and packaging are identified to have high contribution in some impact categories (Acidification and Eutrophication - terrestrial) mainly due to the train transportation, for which the EF transport scenarios were used (Zampori & Pant, 2019). In case of baby diapers, emissions from the landfilling of diapers have also high contribution in the Climate Change impact category, which had high importance also in Hoffman et al. (2020) study.

Product manufacturing has only very small share of the impacts, which is also in line with other studies. However, in this study, all companies reported to use only renewable energy in the manufacturing. The impact of the use of only renewable energy was explored in the sensitivity analysis. According to the results of the sensitivity analysis, the change from renewable electricity to European average mix would not cause significant differences in the results in the majority of the impact categories. The difference is significant only for Ionising Radiation, due to the presence of nuclear energy in the average electricity mix However, since Ionising Radiation is not among the most relevant impact categories, the main conclusions would not change by using a different electricity mix.

SAP production was identified as a hotspot in almost all most relevant impact categories. Electricity consumption was identified as the most relevant process in the SAP production in many impact categories. SAP production was modelled according to literature data in this study, thus the assumption of electricity amount was also explored in the sensitivity analysis. The analysis showed that 20% decrease in electricity consumption would have very limited impact on the total results for baby diapers. Only in the case of Ionising Radiation the impact decrease is significant (11%), but since Ionising Radiation is not among the most relevant impact categories for this model, the main conclusions would not be affected by a change in electricity consumption.

Data Quality Level is good (score 2.04) for baby diapers and very good (score 1.66) for sanitary towels. Although the score for both baby diaper and sanitary towel is good, it can be noticed that while geographical and technological representativeness of dataset is high (<3), precision and time representativeness have lower scores. Only manufacturing of baby diapers and sanitary towels is based on primary data, all other data is secondary data from databases or literature. This is due to the nature of the study which uses data from the manufacturing companies, while most of the relevant processes are out of the control of these companies. To increase the quality of the study, more primary data should be used, especially for the processes identified as most relevant ones, i.e. main raw materials. In addition, it is not known how well the data received from companies represent the average baby diaper and sanitary towel production, because the market shares or sizes of these companies are not known. Also, it is not known, if other companies, which did not provide data, use different raw materials with higher or lower impacts.

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List of abbreviations

AHP	Absorbent Hygiene Product
CFF	Circular Footprint Formula
DQR	Data Quality Rating
GR	Geographical representativeness
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
MSW	Municipal Solid Waste
P	Precision
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
SAP	Superabsorbent Polymer
TeR	Technological representativeness
TiR	Time representativeness

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