



Evolution of disposable baby diapers in Europe: life cycle assessment of environmental impacts and identification of key areas of improvement



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ABSTRACT

An assessment of the environmental aspects related to the life cycle of disposable baby diapers in Europe is presented in this paper with the aim of analysing recent improvements and identifying key environmental areas on which to focus in order to further decrease impacts.

Average products available on the European market in recent years have been modelled and evaluated from “cradle to grave”. Results point out the importance of materials in the definition of the environmental profile of the product. These are followed by the end of life for some impact categories, while the contribution of manufacturing, packaging and transport to the overall LCA (Life Cycle Assessment) results seems of minor relevance.

Significant environmental improvements at European level have been achieved in recent years through the design of lighter products and the introduction of superabsorbent polymers. Careful selection and use of materials at the design stage could allow life cycle impacts of products to be further decreased, while ensuring that human health and environmental risks are controlled and that functionality and performance requirements are fulfilled. Indeed, potential malfunctioning of products would result in increasing consumption. Resource efficiency is also important at the manufacturing level to optimise the demand for materials and limit waste production. Special forms of treatment at the end of life stage of the product could instead require significant structural changes of the waste management system.

The outcomes of this paper could be applied to support the design and environmental labelling of disposable baby diapers for promoting the production and consumption of product options characterised by lower environmental impacts.

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1. Introduction

Promoting and following sustainable practices of production and consumption is one of the key challenges of modern society and it concerns all industrial sectors and products. Disposable baby diapers represent an important product on the market in terms of production volume, function provided to consumers and visibility. Production in the EU and Turkey has increased from about 18 000

million product units in 1997 to more than 22 000 million in 2009, for a market value of about 5000 million euros (EDANA, 2011). Trends suggest that a further increase of the production volume in the EU is likely, which could create additional pressures on the environment in the absence of appropriate technical measures to improve the environmental performance of the products.

Research and development at product design level has focused on finding innovative solutions for the potential reduction and control of the environmental impacts of disposable baby diapers. In particular, one of the most important achievements of industry has been the reduction of the average weight of products in the EU by more than 44% in the last 25 years (EDANA, 2011), which was mainly associated with the introduction of superabsorbent polymers (SAP) (Horie et al., 2004). Improvements to product design

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List of abbreviations

ADL	acquisition and distribution layer
ADP	abiotic depletion potential
AP	acidification potential
BOM	bill of materials
CED _{NR}	cumulative energy demand for non-renewable energy resources
CED _R	cumulative energy demand for renewable energy resources
CED _T	cumulative energy demand for the total amount of energy resources
EoL	end of life
EP	eutrophication potential
Et–Nb	ethylene–norbornene
EU	European Union

GWP	global warming potential
ILCD	the international reference life cycle data system
LCA	life cycle assessment
LCI	life cycle inventory
LDPE	low-density polyethylene
MSW	municipal solid waste
NMVOCS	non-methane volatile organic compounds
NO	nitric oxide
NO _x	nitrogen oxides
PE	polyethylene
POP	photochemical oxidation potential
PP	polypropylene
SAP	superabsorbent polymer
SBR	styrene–butadiene rubber
TPU	thermoplastic polyurethane

could be boosted through the labelling of product options considered to be excellent from an environmental point of view ([Global Ecolabelling Network, 2004](#)).

A historical analysis of how diapers and related environmental impacts have evolved over time would be useful for understanding critical aspects of the product and identifying areas on which technical innovation and labelling could focus in order to decrease environmental impacts.

A core role in the assessment of the environmental impacts of products is played by the Life Cycle Assessment (LCA) methodology, which is defined in the ISO 14040–44 standards ([International Organization for Standardization, 2006a,b](#)).

Diapers have been the subject of LCA studies since the last decade of the twentieth century, when the comparison between disposable and reusable diapers became a relevant topic for investigation after the introduction of disposable products on the market ([Fava et al., 1990](#); [Hakala et al., 1997](#); [Lentz et al., 1989](#); [O'Brien et al., 2009](#); [UK Environmental Agency, 2005, 2008](#); [Vizcarra et al., 1994](#)). It is clear that trade-offs exist between disposable and reusable diapers. While consumption of material resources and waste management are particularly critical for disposable diapers, use of water and energy can be higher for reusable diapers and depends dramatically on the use patterns.

A second important field of study, under the supervision of industry, was the analysis of the environmental effects due to the redesign of products and the introduction of innovative materials ([EDANA, 2005, 2008](#); [Weisbrod and Van Hoof, 2012](#); [Mirabella et al., 2013](#)). Positive environmental consequences related to the introduction of SAP in the product were first pointed out by [EDANA \(2005, 2008\)](#), although the assumptions of the assessment are not detailed there. A more recent study ([Weisbrod and Van Hoof, 2012](#)) assessed the environmental impacts of a specific product whose weight was decreased after the replacement of cellulose with a fossil-based superabsorbent material. Environmental improvement was registered in most of the environmental categories considered in the study. However, the weights of the materials were not disclosed. An LCA for a disposable diaper based on biodegradable polymers ([Mirabella et al., 2013](#)) showed that the environmental performance of the specific product under study was better than that of standard diapers, especially if composting is included as the end of life scenario in the assessment.

However, taking into account the existing literature on the environmental performance of disposable diapers, a cautious approach should be taken before generalising outcomes of individual studies. The available LCA information on diapers may in

particular benefit from an integrative and updated assessment in terms of time and market representativeness.

This paper complements the literature with an assessment of the environmental impacts associated with the production and consumption of average units of disposable baby diapers in Europe during an extensive timeline. An LCA has been conducted for this task, as described in Section 2. The study aims at providing technical indications about the potential for reducing the environmental impacts of the product. To this purpose, findings from the LCA have been coupled with a targeted analysis of sectorial literature and industry initiatives of relevance for diapers. It is anticipated that the outcomes of the study could be applied to support the design and the labelling of products.

2. Materials and methods

2.1. Assessment of environmental impacts

The environmental impacts of disposable baby diapers have been assessed following the LCA methodology ([International Organization for Standardization, 2006a, 2006b](#)). An LCA has been carried out to quantify the environmental impacts associated with average products available on the European market in 2011 and in previous years (i.e. 1987, 1995, and 2005) and to identify critical environmental aspects of the products' life cycles. A streamlined and attributional approach has been embraced to achieve these goals.

The functional unit of this LCA is the production and consumption of one unit of product that is representative of the average conditions of purchase and use in Europe in a specific year. The average product is defined taking into account the range of disposable baby diapers on the market. A quantitative assessment of the direct influence of user behaviour is outside the scope of the study. Results could be scaled up by considering the total annual consumption of diapers of a certain population or the average number of units of products used during the diapering period.

The assessment has covered the product's life cycle from “cradle to grave” (see [Fig. 1](#)), which has been subdivided into four subsystems:

- S1. Production and supply of materials and packaging;
- S2. Manufacturing of the product;
- S3. Distribution;
- S4. Product disposal (End of Life).

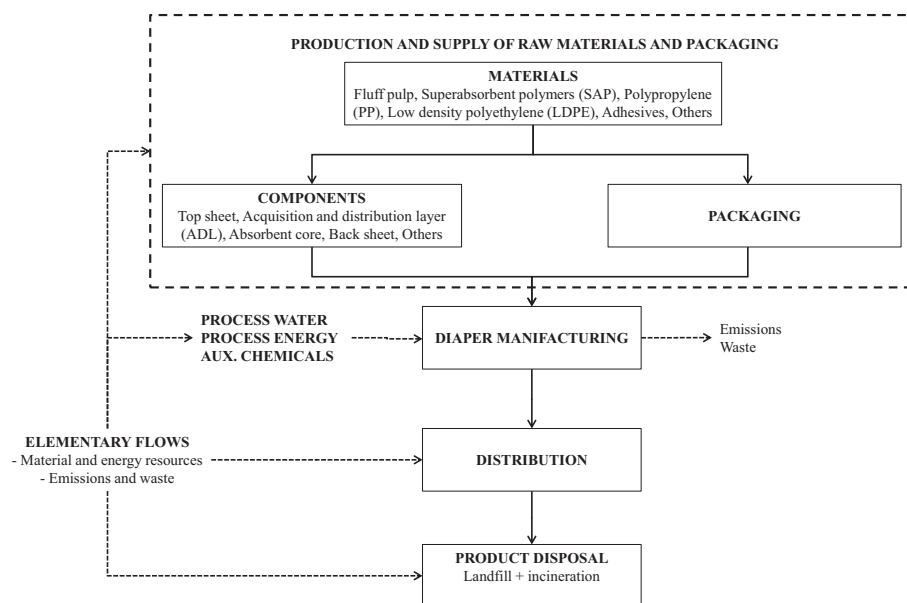


Fig. 1. Flow diagram representing the life cycle of a generic disposable diaper.

All processes and material and energy flows of relevance for the analysis have been quantified, including: upstream processes related to the production and supply of materials and energy resources; consumption of main resources and production of waste and emissions for the manufacturing stage; transportation of the final product to the end users; product disposal. Further details about the life cycle modelling are provided in Section 2.3.

2.2. Key environmental indicators

General recommendations on impact categories and related impact assessment methods to consider in LCA studies are for instance provided in the Product Environmental Footprint (PEF) Guide (European Commission, 2013). The methodology proposes 14 environmental impact categories and indicators, building on information contained in the ILCD Handbook (European Commission's Joint Research Centre – Institute for Environment and Sustainability, 2011), where existing impact assessment methods have been reviewed and classified according to different evaluation criteria. The ILCD Handbook indicates that, at the state of the art, “recommended and satisfactory” assessment methods exist only for Climate change, Ozone depletion, Particulate matter/Respiratory inorganics. The need for further research and development of methods has instead been assessed for other impact categories.

In order to streamline the assessment while ensuring coherence with the goal of the study and covering the most relevant aspects for disposable baby diapers, a narrow set of key indicators has been selected. The selection has been based on the methodological requirements contained in the Product Categories Rules (PCRs) defined and applied for diapers by Type III Environmental Declaration programmes (AFNOR, 2012; The International EPD® System, 2011):

- Abiotic Depletion Potential for mineral resources (ADP elements), measured as equivalent mass of antimony (Sb_{eq});
- Acidification Potential (AP), measured as equivalent mass of SO_2 ($SO_{2,eq}$);
- Eutrophication Potential (EP), measured as equivalent mass of phosphate (PO_4^{3-});

- Global Warming Potential (GWP), for a time horizon of 100 years, measured as equivalent mass of CO_2 ($CO_{2,eq}$);
- Photochemical Oxidation Potential (POP), measured as equivalent mass of ethene ($C_2H_{4,eq}$).

Impacts have been quantified according to CML 2001 (November 2010 version) (Guinée et al., 2002), which is a well-established method that is applicable to the European context and which is used by the LCA community at both scientific and industrial levels.

Broader impact assessment metrics have for instance been used for this product by Mirabella et al. (2013) and by Weisbrod and Van Hoof (2012). However, the consideration of a limited number of key environmental indicators for diapers is supported by Weisbrod and Van Hoof (2012). That study compared results obtained using four different methods (IMPACT 2002+ (Joliet et al., 2003), CML 2000, Eco-indicator'99 (Goedkoop and Spriensma, 2001), and TRACI (Bare et al., 2006)), ending up with the identification of five parameters of actual relevance for disposable diapers: cumulative demand for primary energy and non-renewable energy, global warming potential, generation of solid waste and respiratory health risks due to the emissions of inorganic pollutants into the air.

With respect to the generation of solid waste, it should be considered that disposable baby diapers are estimated to constitute up to 2–3% of municipal solid waste (MSW) in Europe (EDANA, 2008; Weisbrod and Van Hoof, 2012), which is between 6% and 15% of the entire continent's waste (EDANA, 2008). Moreover, from an environmental point of view, the most important issue is not the amount of waste generated itself but the impacts associated with the disposal of such streams. Of the other indicators identified by Weisbrod and Van Hoof (2012), only GWP is included within the metric selected for this study. Notwithstanding, depletion of energy resources has been considered another important parameter to take into account in the sustainability assessment of industrial activities (Bunse et al., 2011; Cordella et al., 2013; Feng et al., 2014). The cumulative demand for primary energy (CED) along the life cycle of the product (Frischknecht et al., 2007) has been calculated distinguishing between contributions from renewables (CED_R), non-renewables (CED_{NR}) and the total amount of energy resources (CED_T) (Cordella et al., 2013).

The outcomes of the assessment have been critically compared with those from the available literature to check if differences in methodological choices lead to convergence or divergence of findings.

2.3. Product's life cycle modelling: tools, data sources and assumptions

The LCA software GaBi 5 (PE International, 2011) has been used as computational support for the assessment. Input and output elementary flows have been quantified relying on the GaBi database (version 5 of November 2011) (PE International, 2011) as the source of Life Cycle Inventory (LCI) data. With reference to the scheme outlined in Fig. 1, material and energy flows have been modelled for the European context as described below.

2.3.1. Bill of materials (BOM) for average units of disposable baby diapers

A typical disposable baby diaper consists of four main components: a top sheet, an acquisition and distribution layer (ADL), an absorbent core and a back sheet (or outer cover) (EDANA, 2005). The main structure of the product is given by the top and back sheets.

The top sheet is the layer in direct contact with the body and through which urine easily passes for further absorption. This is typically made of polypropylene (PP) nonwovens to have a soft, smooth and highly permeable surface.

The ADL is the next material of contact for liquid excreta from the body. The ADL stores the liquid temporarily before it is distributed through capillaries to the absorbent core.

Materials commonly used for this purpose are fluff pulp, which is a material made of cellulose, and/or SAP. SAPs are synthetic materials, manufactured primarily as sodium polyacrylate (McCormack et al., 2011), that can absorb and retain very large amounts of liquids, up to 1000 times their own mass (Horie et al., 2004). The liquid is stored within a gel structure and is not even released under pressure, which is an important functional and performance characteristic for baby diapers.

The back sheet sustains the diaper and prevents liquids from leaking. For this reason, it must be strong but also thin enough to be fit for use. The materials typically used are low-density polyethylene (LDPE) films or composites made of LDPE films and nonwovens. Micropores are usually present in the back sheet. These allow air to reach the human body and to keep it dry, thus preventing the occurrence of irritations and infections. Hydrophobic treatments can also be applied depending on the designed conditions of use.

Additional materials used in disposable baby diapers can include, for instance, fastening systems (tapes and elastics), inks and dyes.

Data on the weight and composition of disposable baby diapers sold in Europe has been collected from producers by EDANA, the roof organization for the European nonwovens industry. In particular, information on the average weights and compositions of products in 1987, 1995, 2005, 2011 is made available in EDANA (2008, 2011). Figures are considered to represent over 85% of the European market in Europe and have been used to model BOMs for average products in different years, as reported in Table 1.

The environmental inputs and outputs associated with the production of materials have been quantified through the use of LCI datasets of the GaBi database (version 5 of November 2011) (PE International, 2011). This is aligned with the general nature of the study and supports the determination of indications on key areas of improvement.

The production of the main materials has been modelled based on specific datasets available for chemical pulp, sodium polyacrylate, PP nonwoven, and LDPE film. Thermoplastic polyurethane (TPU) and a copolymers mixture of styrene–butadiene rubber (SBR) and ethylene–norbornene (Et–Nb) were considered for elastic and adhesive, respectively. Other components contained in the product in smaller amounts (e.g. tape, elastic back ear, other synthetic polymers) have been added together and modelled as PP tape. Assumptions considered for the supply of materials are described in Section 2.3.3.

Due to a lack of data, it has not been possible to take into account technological variations over space and time. The environmental impacts assessed for different years thus depend uniquely on variations in the average weight and composition of products. This could underestimate environmental impacts in the past because technological innovations are in general expected to have taken place over the years (Dewulf, 2013; Huber, 2008; Mendiivil et al., 2006). However, situations for which environmental performance worsens with time cannot be excluded a priori.

In 1987 the average disposable baby diaper in Europe had a mass of 65 g and consisted of 81% by weight fluff pulp. The average weight of the product decreased between 1987 and 1995 by 14% and between 1995 and 2005 by 27%. This was mainly due to the increased use of other materials instead of fluff pulp. The relative presence of SAP in particular increased dramatically from 1% in 1987 to 32% by weight in 2005. In more recent years, the average weight decreased further: by 12% between 2005 and 2011. Since the composition of average diapers did not change significantly between 2005 and 2011 and the average amount of SAP contained in the product diminished, it can be deduced that this further decrease in weight may have been associated with the improved functionality of materials, components and layout of the product.

2.3.2. Product manufacturing and packaging

Manufacturing of disposable baby diapers is typically a continuous automated process. Indications of typical inputs of energy, water, main auxiliary materials (i.e. lubricants and solvents/inks)

Table 1
Bills of materials (BOMs) for average units of disposable baby diapers sold in Europe in 1987, 1995, 2005 and 2011 and related LCI datasets.

Material/component	Average weight per 1 unit of baby diaper (g)				LCI dataset modelled
	1987	1995	2005	2011	
Fluff pulp	52.8	37.4	14.1	13.2	Chemical pulp
Superabsorbent polymers (SAP)	0.7	5.1	13.2	11.1	Sodium polyacrylate
Polypropylene (PP)	4.1	4.5	7.0	5.8	PP nonwoven
Low density polyethylene (LDPE)	4.2	3.8	2.6	2.2	LDPE film
Elastic	1.3	1.6	1.7	1.0	TPU
Adhesives	0.8	0.4	0.6	0.1	SBR and Et–Nb copolymer
Others (e.g. tape, elastic back ear, other synthetic polymers)	1.1	3.2	1.8	2.6	PP tape
Total	65.0	56.0	41.0	36.0	–

and packaging for this stage have been gathered from industry and applied for the year 2011. Water is normally used for the treatment of fluff pulp and evaporates almost completely during the manufacturing process.

Specific data on types and quantities of waste produced during the manufacturing stage was not available. In order to take material losses into account, and based on the information contained in Weisbrod and Van Hoof (2012), it has been assumed that the amount of waste generated during the manufacturing stage and which is not recycled constitutes roughly 4% by mass of the final product weight. The disposal scenario considered for this waste stream includes landfilling and incineration (with/without recovery of energy) and it has been modelled as described in Section 2.3.4 for the final product. This approximation is effectively a worst case disposal scenario whose environmental impacts would decrease by increasing material recycling and energy recovery. However, the effects would be limited and are not expected to affect the overall outcomes because of the relatively small amount of waste produced.

Due to a lack of information and in analogy with the assumption made in Section 2.3.1, the above data has been kept constant and also used to model the product manufacturing in the years prior to 2011. The same considerations apply here.

Based on the information gathered and reported in EDANA (2008), it has been considered that the average weight of packaging allocated to one unit of product has proportionally decreased from 8 g in 1987 to 6.5 g in 1995, 4.7 g in 2005 and 4.2 g in 2011. As a simplified estimate, the average composition of the packaging has been kept constant over time: cardboard box (about 83% by weight), PE bag (about 11%), wooden pallet (about 5%), PE stretch wrap (about 1%), PP tape (less than 1%).

Table 2 summarises data and LCI datasets used for modelling product manufacturing in 2011.

2.3.3. Supply of materials and distribution of the final product

To model European conditions of production and consumption, a transportation distance of 1000 km by truck (Euro 3, 27.4 t payload capacity) has been considered for both the supply of materials used in the product manufacturing and for the distribution of the final product from the factory gate to customers.

According to manufacturers of fluff pulp, 90% of the production of this material takes place in North America. To take into account that some producers will source fluff pulp from there, an average transportation distance of 2000 km by container ship has additionally been considered for this material.

The same assumptions have been applied for the different years considered in the analysis, in analogy with the previous sections.

Table 2

Data on product manufacturing and packaging materials for 1 average unit of product in 2011.

Data (reference flow = 1 unit of product)			LCI dataset modelled
Energy and material use	Electrical energy (MJ)	0.19	EU-27 electricity grid mix
	Thermal energy (MJ)	0.02	EU-27 thermal energy from natural gas
	Water use (mL)	2.00	Deionised water
	Lubricants (mg)	3.30	Lubricants
	Solvents/Inks (mg)	5.10	Solvent mix
Packaging	Cardboard box (g)	3.50	Corrugated cardboard
	PE bag (g)	0.45	LDPE film
	Wooden pallet (g)	0.20	Wooden pallet (40% moisture content)
	PE stretch wrap (g)	0.05	LDPE film
	PP tape (g)	0.02	PP tape

2.3.4. End-of-life (EoL) of the product

After their use, disposable baby diapers are normally mixed with conventional municipal solid waste (MSW). All waste streams have been considered to be treated as MSW.

Based on Blumenthal (2011), 40% of municipal solid waste in the EU-27 is recycled or composted, 38% is landfilled, and 22% is incinerated. Since recycling and composting do not seem to be a common disposal practice for diapers for the time being, shares have been re-calculated without taking into account recycled and composted fractions. Considering that about one third of the EU-27 waste treated through incineration or other forms of energy recovery were incinerated without energy recovery in 2010 (Eurostat, 2012), the following disposal scenario has been modelled: 63% landfill, 25% incineration with energy recovery, and 12% incineration without energy recovery.

The same assumptions have been applied for the different years considered in the analysis, in analogy with the previous sections.

3. Results and discussion

3.1. LCA results for an average disposable baby diaper in Europe in 2011

The LCA results for an average disposable baby diaper on the European market in 2011 are shown in Table 3. The results are presented both as aggregated absolute values and as relative contributions to the impacts of the different life cycle stages.

From observation of Table 3 it is apparent that the key environmental hotspot in the life cycle of disposable baby diapers is the production and supply of materials. Depending on the indicator considered, the relative contribution of this subsystem to the total impacts varies from 63% to 99%. This is essentially due to the production of materials itself (62–99% of the total impacts).

The end of life phase contributes with 29% to GWP, 25% to EP and 13% to POP. This is inherently dependent on the assumptions considered for the waste disposal scenario: 63% landfill, 25% incineration with energy recovery, and 12% incineration without energy recovery. It can be expected that the end of life could produce reduced or beneficial effects for the environment if waste treatment practices for the recovery of materials and/or energy were promoted.

The manufacturing and distribution of the product are of much less importance in terms of environmental impacts:

- The contribution of the manufacturing process to the total impacts varies from 1% to 8%, depending on the impact category considered.

Table 3

Environmental impacts of an average disposable baby diaper on the European market in 2011 (total weight of product and packaging: 40.2 g) and relative contributions to the impacts of the different life cycle stages.

Indicator	Total	Relative contribution ^a			
		S1	S2	S3	S4
ADP elements (mg Sb _{eq})	0.07	98%	1%	0%	1%
AP (g SO _{2eq})	0.55	91%	5%	2%	2%
EP (g PO ₄ ³⁻ _{eq})	0.13	70%	2%	3%	25%
GWP (kg CO _{2eq})	0.13	63%	6%	2%	29%
POP (g C ₂ H _{4eq})	0.06	88%	8%	–9%	13%
CED _T (MJ)	4.30	96%	3%	1%	0%
CED _R (MJ)	1.50	99%	1%	0%	0%
CED _{NR} (MJ)	2.80	94%	5%	1%	0%

^a S1: materials and packaging production and supply; S2: product manufacturing; S3: product distribution; S4: end of life.

- The contribution of product distribution to the total impacts varies from –9% to 3%, depending on the category considered.

The contribution of transport is relevant only for the POP and it is –9% of the total impact quantified for this impact category. This is a direct consequence of the emission profile modelled for the selected transportation process and of the characterisation method used in CML 2001 for the calculation of the POP.

Transportation is responsible for the emission of NO_x in the ground layer atmosphere. The dataset for road transportation used in the LCA includes emissions of NO, which is evaluated to have an ozone-depleting effect in CML 2001 and which thus has a negative characterisation factor. However, considering that NO can be oxidised to NO₂ in contact with air, it is possible that the effect of this substance has been overestimated.

Although the obtained negative value may appear unusual, it should be considered that POP is only one of the environmental impact categories analysed. All other potential impacts would increase with greater transportation distances, showing that transportation is a process leading to net environmental burdens. Furthermore, even for POP, transportation processes needed for supply of materials and product distribution only have limited effects on the overall LCA results.

The results obtained for this impact category have been reassessed through the characterisation of the corresponding photochemical oxidant formation potential (POFP) according to the ReCiPe method (Goedkoop et al., 2009). It has to be noted that the absolute results from the two methods are not directly comparable due to the different units of measure used: CML provides results as C₂H₄ equivalents while ReCiPe provides them as NMVOC equivalents. The new calculation has yielded 0.64 g of NMVOC_{eq} as the result, which can be attributed, rounding percentages: to 92% for S1 (materials and packaging production and supply), to 4% for S2 (product manufacturing), to 0% for S3 (product distribution) and to 4% for S4 (end of life). The more precise contribution of S3 is 0.46%, thus being positive but negligible for the overall results. In this case, ReCiPe assigns the same positive characterisation factor to all NO_x.

It should be pointed out that the assessment methods are based on different methodologies which are defined by specific characterisation factors. Advantages and disadvantages may be associated to each impact assessment method and analysing and comparing different assessment approaches can help to understand the underlying environmental mechanism. However, this should not distract from the aim of the study, which is to identify critical aspects of the product life cycle. No matter the method considered for this product, transportation processes do not appear to be the most important contributing factor for POP.

All in all, results are in accordance with Weisbrod and Van Hoof (2012), in which materials were found to contribute between 63% and 92% of the total impacts, followed by the end of life stage (1–12%

of the total impacts), although the study refers to a specific product on the market and applies different impact characterisation methods.

Further insights into materials are necessary to analyse which are the most significant contributors to the environmental impacts. Table 4 shows the breakdown of the impacts from materials for the average European product modelled for 2011.

The relative contribution of single materials to the environmental impacts is not necessarily proportional to the mass content in the final product.

Fluff pulp is the material that formed most of the final mass of average products in 2011 (33% by weight, also considering the packaging). As shown in Table 4, this is also the material which contributes the largest share to the potential environmental impacts of materials. Contributions of fluff pulp to the impacts are proportional to its mass content in the final product and variable among the indicators (from 29% for GWP to 96% for CED_R).

Contributions of the superabsorbent polymer, the second most important material in terms of weight, vary from 1% for CED_R to 25% for GWP, less than its mass content in the average product (28% by weight).

Contributions of packaging (1–4%) and PP tape (0–2%) are marginal compared to their mass content (10% by weight for packaging and 6% for PP tape).

Contributions of PP nonwoven (1–25%), LDPE film (0–10%) and adhesive (0–6%) are more variable compared to the mass content (14% for PP nonwoven, 5% for LDPE film and 2% for adhesive).

Contributions of elastic (0–29%) can instead be relatively high, considering that the mass content of this material in the average product is negligible.

CED_R is almost entirely due to fluff pulp (96%). Wood represents an important renewable contribution for fluff pulp, both as feedstock and process energy. The energy embodied in other materials typically comes instead from non-renewable resources.

The contribution of fluff pulp is also predominant for EP (80%), AP (67%), CED_T (54%), and POP (51%). For these categories, the following contributions of other materials are also appreciable, considering a 5% cut-off threshold:

- 9% for superabsorbent polymer in EP;
- 15% for superabsorbent polymer and 7% for PP nonwoven in AP;
- 16% for PP nonwoven, 14% for superabsorbent polymer and 5% for LDPE film in CED_T;
- 16% for superabsorbent polymer, 11% for PP nonwoven, 10% for LDPE film and 5% for elastic in POP.

Results show a more homogenous distribution for the other indicators. For ADP the contribution of fluff pulp is 42%, followed by elastic (29%), SAP (16%) and PP nonwoven (9%). Contributions for GWP and CED_{NR} are similar and more proportional to the mass content in the average product.

Table 4

Breakdown of the environmental impacts of materials for an average disposable baby diaper in Europe in 2011.

Indicator	Fluff pulp	SAP	PP nonwoven	PP tape	LDPE film	Adhesive	Elastic	Packaging
ADP elements	42%	16%	9%	0%	1%	1%	29%	2%
AP	67%	15%	7%	1%	4%	2%	2%	3%
EP	80%	9%	4%	0%	2%	1%	2%	2%
GWP	29%	25%	22%	2%	7%	6%	8%	1%
POP	51%	16%	11%	1%	10%	4%	5%	3%
CED _T	54%	14%	16%	1%	5%	3%	4%	4%
CED _R	96%	1%	1%	0%	0%	0%	0%	2%
CED _{NR}	30%	22%	25%	2%	8%	5%	6%	2%
Total weight ^a	33%	28%	14%	6%	5%	2%	0%	10%

^a Diaper + packaging.

Although absolute results and contributions vary among products depending on the technical and geographical characteristics of the specific system evaluated, the results generally highlight the importance of materials in the design of disposable baby diapers.

3.2. Historical analysis of disposable baby diapers in Europe and trends

As described in Section 2.3.1, the average weight and composition of disposable baby diapers in Europe has changed significantly as a consequence of modifications to the design of products on the market. Based on the information gathered, it has been possible to calculate approximately how impacts due to the production and consumption of an average unit of product have changed from 1987, set as the reference year for this historical analysis, to 2011. The results are illustrated in Table 5. As introduced in the previous section on materials and methods, because of the assumptions made during the modelling of the analysed product systems, the actual variation of impacts could be different, and probably more significant, than that resulting from this streamlined assessment.

According to the LCA, a progressive decrease in the potential environmental impacts of an average unit of product is registered over time.

From 1987 to 1995, the magnitude of impacts decreased by 16–36%, depending on the indicator considered. This improvement could be explained with the greater use of SAP (+629%) in place of fluff pulp (−29%), which contributed to a reduction in the average product weight of 14%.

From 1995 to 2005, the magnitude of impacts decreased by 7–61%. The average product weight decreased by 27% mainly thanks to a further reduction in the use of fluff pulp (−62%), compensated by an increased use of SAP (+159%). This could explain the significant reduction of impacts achieved in indicators which see a dominant contribution of fluff pulp, namely PED_R (−61%), AP (−45%) and EP (−45%).

The results from 1987 to 2005 are in accordance with the summary indications reported in EDANA (2008), although not all assumptions of the assessment are detailed there.

In more recent years, from 2005 to 2011, a further decrease in the potential environmental impacts results: 7–51%. The weight of an average product decreased by 12% in this time period and this was achieved through the reduction of almost all materials used in the product, especially elastics (−41%) and adhesives (−83%).

Under the simplified assumption that the production of disposable baby diapers in Europe remained constant between 2005 and 2011 and that it was equal to that of 2009, i.e. 22 000 million units per year (EDANA, 2011), it could be possible to roughly estimate the average improvements achieved in 2011 in comparison with 2005:

Table 5

Relative magnitude of impacts of an average unit of disposable baby diapers in Europe in 1987 (reference), 1995, 2005 and 2011.

Indicator	1987	1995	2005	2011
ADP elements	100%	64%	59%	29%
AP	100%	75%	42%	36%
EP	100%	75%	42%	38%
GWP	100%	84%	78%	62%
POP	100%	76%	49%	38%
CED _T	100%	75%	47%	38%
CED _R	100%	71%	28%	26%
CED _{NR}	100%	81%	69%	52%
Average weight				
Diaper with packaging	100%	96%	70%	62%
Diaper without packaging	100%	86%	63%	55%

- Savings of 140 000 tonnes of materials per year, equivalent to 1590 kg of antimony equivalents (calculated as ADP according to CML 2001);
- Prevention of the emission of 2020 tonnes of SO₂ equivalents per year, 301 tonnes of PO₄^{3−} equivalents per year, 382 tonnes of C₂H₄ equivalents per year (calculated as AP, EP and POP, respectively, according to CML 2001);
- Prevention of the emission of 738 000 tonnes of CO₂ equivalents per year (calculated as GWP according to CML 2001);
- Savings of 22 400 TJ of primary energy per year, 90% of which are from sources that are not renewable (calculated according to the CED method).

The results show an apparent correlation of the environmental impacts of disposable baby diapers with the amount of materials used in the product.

According to a personal communication from a manufacturer interviewed during this study, 70% of products on the market nowadays may have a weight between 30 and 38 g and the remaining 20% and 10% may be heavier by 20% and 60%, respectively. It is thus likely that there is additional environmental improvement potential which could be achieved by acting on product design, resource efficiency and material selection. It is therefore possible that future trends may see the further replacement of fluff pulp with SAP or other alternative materials and the further reduction of the product weight. A practical example of how the market is moving towards this direction is given by Weisbrod and Van Hoof (2012). However, it should be kept in mind that the environmental performance of specific products on the market differs depending on the technical and geographical characteristics of the product system.

3.3. Technical indications for the potential reduction of the impacts of diapers

Based on the results presented and on the analysis of sectorial literature and initiatives, a series of technical indications for the potential reduction of the impacts of disposable baby diapers are discussed. However, the key role of the LCA as the tool for assessing the effectiveness of any improvement options under a holistic approach should be noted.

Although the LCA study presented depends on a set of assumptions and background data used to describe general trends for average products, results reveal the importance of materials in the design of disposable baby diapers. Most of the environmental impacts of disposable baby diapers can be seen as a function of the product weight, material composition and environmental profile of the individual materials. It is thus apparent that actions in this area may lead to a significantly varied overall environmental performance of the product. The first measure to decrease the environmental impacts of the product should therefore focus on the reduction of the product weight and on the increase of the resource efficiency and on the parallel selection of low impact materials following an LCA approach. Trends seem to indicate a general tendency of the market towards lighter products. However, there are physical and functional constraints to the extent to which weight can be reduced and material selected by manufacturers since it is fundamental that the technical performance of the product is not compromised. Malfunctioning of products may indeed require their premature substitution, with a consequent increase in consumption of product units and related impacts.

Actions on materials are particularly important for key components of diapers such as fluff pulp and SAP, for which it would be important to select from producers and suppliers the alternatives that are functional, free of health risks and with lower

environmental impacts. A general conclusion of the analysis is that the substitution of fluff pulp with SAP has contributed to reduce the weight and environmental impacts of products, which is also supported by practical examples from industry (Weisbrod and Van Hoof, 2012). However, due to the product variety on the market, it cannot be denied that specific conditions exist under which this general rule is not valid.

Environmental burdens due to pulp production could be decreased through the application of techniques for increasing the material and energy efficiency of production processes and reducing the related polluting emissions (European Commission's Joint Research Centre – Institute for Prospective Technological Studies – European IPPC Bureau, 2013). The sustainability of fluff pulp could be further improved through the use of wood produced from sustainable forestry management (Lippke et al., 2011; PEFC, 2013), although the assessment of impacts of certification schemes and its integration in the LCA is an issue which needs further development.

With respect to polymers and plastic materials, there is an increasing effort in industry and research to identify alternatives and practices to reduce the environmental burdens due to their production (European Commission's Joint Research Centre – Institute for Prospective Technological Studies – European IPPC Bureau, 2007; Lithner et al., 2011; Plastics Europe, 2011; Tabone et al., 2010). One aspect that is still controversial however is instead related to the feedstock used. Materials based on biomass are in principle considered to save fossil fuel resources because of their renewability. However, embracing a system perspective may in some cases result in environmental trade-offs, for instance due to the additional demand for land, water, energy and chemicals for the production of biomass. Spatial and technical differences between different production chains can result in a complex range of environmental performances (Börjesson and Tufvesson, 2011; Buchholz et al., 2009; Cordella, 2010; Cordella et al., 2013; Fiorentino et al., 2014). The selection of materials based on biomass may be supported in the future by standards and sustainability criteria currently under development (European Committee for Standardization, 2011).

A secondary element of environmental significance along the life cycle of disposable baby diapers is represented by the disposal of the product. Possibilities of influencing disposal practices are however limited since the product is normally mixed with conventional municipal solid waste (MSW) after use and treated in accordance with the practices set by local authorities. Disposable baby diapers are estimated to constitute up to 2–3% of municipal solid waste (MSW) in Europe (EDANA, 2008; Weisbrod and Van Hoof, 2012). Special forms of treatment could require significant investments and structural modifications in waste management systems. The typical disposal scenario for the product is either incineration or landfilling, which do not allow the potential biodegradability of materials to be exploited. Landfilling of biodegradable materials also requires control and management of the disposal conditions which can for instance result in significant emissions of greenhouse gases such as methane (Rossi et al., 2015). Some experimental recycling systems have been tested (European Commission's Eco-innovation Projects; Fater) but this option seems unlikely at present due to the low quality of the recovered materials, which can end up in fertilizers and low-value plastic products. Further problems may be associated to product composting. Colon et al. (2011) analysed the composting of diapers with the organic fraction of MSW. Even if the stability, maturity and phytotoxicity of the compost were not affected, an increased zinc content was found which could limit the possibility of composting the product in large amounts. Another drawback is related to the long degradation time of SAPs and to their difficult separation from organic materials which could contaminate the compost.

Less environmental concerns seem associated to other life cycle stages. However, product manufacturing has a direct influence on the amount of material and energy resources used and on the amount of waste generated. It is thus possible that additional environmental improvement can be achieved through the implementation of appropriate systems for optimising the management of resources and waste (Weiss et al., 2013).

4. Conclusions

General indications of key areas for improving the environmental impacts of disposable baby diapers in Europe have been provided through the LCA of an average diaper in the year 2011 coupled with an environmental analysis of how the product has evolved over time and further analysis of the technical literature.

A metric of key environmental indicators has been selected for the assessment based on the analysis of Type III Environmental Declaration programmes and available studies for this product. The overall contribution of materials to the life cycle impacts of the average product has been assessed to be dominant in 2011 and to vary between 63% and 99%, depending on the indicator considered. Fluff pulp was both the most used material in 2011 and that generating the highest contribution to the environmental impacts. SAP was the second most significant contributor in most of the impact categories while impacts of packaging have appeared negligible. Under the assumptions made in the assessment, smaller contributions have been registered for other life cycle stages although the end of life may be relatively more important for some impact categories (e.g. eutrophication, global warming, photochemical oxidation). The historical analysis of average products between 1987 and 2011 has moreover shown that the introduction of SAP and progressive decrease in use of materials have led to lighter products over time and to apparent environmental benefits. Results, which refer to generic products, are aligned with the outcomes of other studies using a different scope and methodological approach, in particular with respect to time and market representativeness and impact assessment methods.

Based on the elements collected during the study, effective measures for decreasing the environmental impacts of disposable baby diapers should be supported by an LCA and focus on product design, especially for optimising the use of materials with which to fulfil the expected functional and performance requirements. With respect to the end of life stage, incineration seems the best available option for this product group while alternative forms of treatment oriented to material recovery and recycling could require significant structural changes to the waste management system.

The study could be used for addressing the design and potential environmental labelling of disposable baby diapers, to be coupled with the further consideration of legislative, technical and market elements. This study has also revealed an apparent lack of statistically representative data on products. Enhancing data sharing would be fundamental for defining sustainable production and consumption practices and environmental benchmarks. Moreover, it must be pointed out that, besides the purely technological side, interactions between users and product also play a key role in the determination of the environmental impacts of products and that this could be an interesting topic to consider in further investigations.

Disclaimer

The opinions expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

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