Comparison of the environmental impact of disposable diapers vs. cloth diapers

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Abstract

This study compares the environmental and economic impacts of disposable and cloth diapers using Life Cycle Assessment (LCA) and Life Cycle Costing (LCC). The focus is on key sustainability indicators such as global warming potential, water consumption, resource depletion, and their associated costs across the full product lifecycle. The results indicate that disposable diapers have a higher environmental impact in terms of global warming, primarily due to the distribution processes. Cloth diapers, though requiring significant water for washing, show a lower global warming potential. This LCC analysis results conclude that reusable cloth diapers are more economically favorable and moreover, have a less important initial investment than for disposable diapers. The integration of LCA and LCC into business models highlights the opportunity for companies to optimize both environmental performance and economic efficiency. This study offers valuable insights for stakeholders aiming to adopt more sustainable practices in the diaper industry, while also providing a business framework for developing economically viable and environmentally responsible diapering systems.

Keywords: ***Life Cycle Assessment (LCA), Life Cycle Costing (LCC), Sustainability, Cloth Diapers, Disposable Diapers, Global Warming Potential, Water Consumption, Human Health, Ecosystem Quality, Resource Depletion, Environmental Impact***

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1 Introduction

This study is driven by the growing global concern regarding environmental challenges, such as waste generation, energy consumption, and resource depletion. Disposable diapers, which constitute a significant portion of non-biodegradable waste, have long been a focal point of environmental debates, particularly when compared to reusable cloth diapers. The primary objective of this research is to evaluate the environmental impact of both diaper types, with a specific focus on carbon footprint, water consumption, and their overall lifecycle impact(Ng et al., 2013; Cordella et al., 2015). [1][2]

Recent global initiatives aimed at decarbonization and resource efficiency underscore the urgency of adopting sustainable practices (Hoffman et al., 2019). Governments and industries worldwide are increasingly implementing measures to mitigate environmental degradation, placing a heightened emphasis on sustainability. While disposable diapers contribute extensively to landfill waste, reusable diapers, despite their potential to reduce solid waste, necessitate considerable energy and water for laundering (Meseldzija et al., 2013). Thus, a comprehensive Life Cycle Assessment (LCA) of these products is essential to make informed, sustainable choices. [3][4]

This project employs a cradle-to-grave LCA approach, encompassing all stages of the product lifecycle—from raw material extraction to final disposal (O'Brien et al., 2009). By examining multiple scenarios, including diverse laundering practices for reusable diapers and innovative eco-designs for disposable diapers, this study aims to elucidate the trade-offs and identify more sustainable alternatives. [5]

Building on the findings from previous deliverables, this final report incorporates enhanced modeling techniques, literature comparisons, and expert recommendations to refine the analysis. Furthermore, it integrates a section on business models applied to the circular economy, providing actionable insights for stakeholders. This comprehensive approach aims to guide the development of eco-efficient diapering systems that minimize environmental impacts while addressing functional and economic requirements.

1.1 Motivation and background

The environmental debate surrounding disposable diapers versus reusable cloth diapers has gained increasing attention due to their significant impact on waste generation and resource consumption. Disposable diapers contribute substantially to solid waste and landfill overflow, while reusable cloth diapers, although reducing waste, require significant water and energy consumption due to frequent laundering. This project aims to determine which diapering method has the least overall environmental impact through a comprehensive Life Cycle Assessment (LCA).

1.2 State of the art

A range of Life Cycle Assessment studies have examined the environmental impacts of disposable versus reusable diapers. These studies employ distinct product systems, functional units, and impact categories—both at the midpoint and endpoint levels. This review synthesizes prominent studies by comparing the methodologies, defined product systems, and findings for various impact categories, ultimately offering a comprehensive understanding of the environmental implications of diaper usage.

1.2.1 Product Systems and Functional Units

Each study uses specific product systems and functional units, defining the scope and focus of the analysis.

Cordella et al. (2015) analyzed only disposable diapers, focusing on a generic, average disposable diaper available in Europe. The functional unit was “one disposable diaper,” and the study followed a cradle-to-grave model from raw material extraction through to disposal. This approach enabled a close examination of each diaper’s lifecycle in Europe between 1987 and 2011. [2]

Hoffmann et al. (2019) compared four different product systems: a disposable diaper, a cloth diaper in a diaper-as-product model with home laundering, a cloth diaper in a simple diaper-as-service model with on-premise laundry, and a cloth diaper in an optimized diaper-as-service model using industrial laundering. The functional unit was defined as “one toilet-trained child,” covering all diapering needs over the child’s diapering years, thereby enabling a comparable view of environmental impacts across systems. The study is conducted based on data from Brazil. [3]

Meseldzija et al. (2013) presented a general overview of disposable and reusable diaper impacts without specifying distinct laundering models. The study contrasted petroleum-based disposable diapers with cloth diapers made from natural fibers like cotton, bamboo, and hemp. No single functional unit was specified, as the study focused on general resource consumption, waste generation, and pollution impacts. [4]

O’Brien et al. (2009) conducted an Australian-based study comparing three diaper systems: disposable diapers, home-washed reusable diapers, and commercially washed reusable diapers. The functional unit was “diaper use over 2.5 years,” representing the typical diapering period for one child in Australia and providing a broad lifecycle assessment. [5]

Holdway et al. (2023) included both disposable and reusable diapers used over the first 2.5 years of a child’s life, which was taken as the average diapering duration. The study included several types of diapers available in the United Kingdom, focusing on the material composition and the complete lifecycle of each diaper type. The functional unit here was “diaper use over 2.5 years.” [6]

Mirabella et al. (2013) focused on bio-based disposable diapers, comparing them to petroleum-based disposable diapers. The functional unit was “one bio-based disposable diaper,” centered around examining the impacts of renewable versus fossil-derived materials.[7]

Mendoza et al. (2019) explore a unique product system within disposable diapers by examining an eco-designed "glueless" diaper that minimizes the use of adhesives and incorporates a thermo-mechanical and ultrasonic bonding technique. This approach is intended to improve the environmental footprint by reducing material weight, particularly superabsorbent polymers (SAP) and fluff pulp. The functional unit in this study is “the manufacture of 1000 disposable baby diapers” on a P10 production platform, offering a standardized assessment of the production efficiency across a single production line, industrial scale, and European context. This focus on eco-design extends traditional disposable diaper LCAs by introducing bonding innovations and material optimizations, making it a relevant addition to comparing standard disposable diaper models.[8]

Weisbrod et al. (2012) examined Pampers diapers by Procter & Gamble, tracking changes in design from 1992 to 2010 to evaluate improvements in environmental efficiency. The functional unit was “one Pampers disposable diaper,” with a cradle-to-grave lifecycle approach assessing the impacts of design changes on environmental outcomes. [9]

1.2.2 Methodologies

Each study employed specific software, data sources, and impact assessment categories, allowing for a detailed examination of diaper impacts.

Cordella et al. (2015) used the GaBi 5 software, with data sourced from EDANA, the European nonwovens industry association, representing over 85 percent of the market. The study assessed midpoint impact categories such as Abiotic Depletion Potential for mineral resources, Eutrophication Potential, Global Warming Potential, and Photochemical Oxidation Potential. No endpoint categories were included. This study’s regional focus was Europe, examining key lifecycle stages to identify significant environmental contributors in disposable diapers. [2]

Hoffmann et al. (2019) utilized the Ecoinvent 3.5 database with the ReCiPe impact assessment model, providing both midpoint and endpoint assessments. Midpoint categories included climate change, freshwater eutrophication, terrestrial acidification, and water depletion, while endpoint categories grouped impacts under damage to ecosystems, human health, and resource depletion. Data for Hoffmann et al.’s study were sourced from Ecoinvent, scientific literature, and manufacturer data, creating a comprehensive basis for analysis within a European context. [3]

Meseldzija et al. (2013) synthesized national reports, LCA studies, and literature sources for data without specific LCA software. The study did not differentiate between midpoint and endpoint categories but examined resource consumption, water and energy usage, air pollution, and waste management, providing a general analysis of diaper impacts. As a Canada-based study, it focused on the environmental trade-offs between petroleum-based disposable and natural-fiber reusable diapers. [4]

O’Brien et al. (2009) used Australian data from manufacturers, suppliers, and literature sources. Four midpoint impact indicators were assessed: water depletion, non-renewable energy depletion, solid waste, and land area for resource production. No endpoint categories were applied. By examining these indicators over a functional unit of 2.5 years, the study aimed to provide insight into the typical diaper impacts experienced by Australian households. [5]

Holdway et al. (2023) adhered to ISO 14040 and ISO 14044 standards, incorporating primary data from manufacturers and industry sources, such as the Association of Manufacturers of Hygiene Products. Midpoint categories included Global Warming Potential, Ozone Depletion Potential, Ionizing Radiation Potential, Particulate Matter Formation Potential, Terrestrial Acidification Potential, Freshwater and Marine Eutrophication Potential, and Water Consumption Potential. No endpoint categories were included, and the study used data relevant to the United Kingdom market. [6]

Mirabella et al. (2013) assessed bio-based disposable diapers using the Work In Progress tracking system for material flows. Midpoint categories included global warming potential, water use, and land use. This cradle-to-grave study provided a focused comparison of bio-based versus traditional petroleum-based disposable diapers. [7]

Mendoza et al. (2019) employed GaBi software to perform the LCA, following ISO 14040 and ISO 14044 standards. Data were derived from production trials, literature, and the Ecoinvent 2.2 database, with a particular focus on the environmental impacts of material sourcing, production, and end-of-life waste management for both standard and glueless diaper designs. Their analysis covered key midpoint impact categories such as global warming potential, primary energy demand, eutrophication potential, ozone depletion, and human toxicity potential. Unlike some prior studies that concentrate on usage and disposal phases, Mendoza's study limits the scope to production and end-of-life, specifically excluding usage since consumer usage does not differ significantly between standard and glueless models. [8]

Weisbrod et al. (2012) employed Monte Carlo simulations to model Pampers disposable diapers, assessing midpoint categories including land occupation, non-renewable energy use, global warming potential, and respiratory impacts. No endpoint categories were defined, and the study relied on regional data from the United States, highlighting the impact of Pampers diaper design changes. [9]

1.2.3 Comparative Outcomes of the Studies

Each study provides unique insights into the environmental impacts of diaper use, with results differing based on midpoint and endpoint impact categories, product systems, and regional variations. Global Warming Potential emerged as a key midpoint impact category across studies, with disposable diapers generally showing higher impacts due to resource-intensive material production, particularly of fluff pulp and superabsorbent polymers. Cordella et al. (2015) found that material production contributed between 63 and 99 percent of the lifecycle impacts of disposable diapers in Europe. Similarly, Hoffmann et al. (2019) and the United Kingdom Department for Environment, Food and Rural Affairs study identified high emissions in the production phase for disposable diapers, contributing substantially to their global warming potential. Mendoza et al. (2019) added to this understanding by comparing standard disposable diapers with an eco-designed “glueless” version, finding that the glueless design achieved a 10 percent reduction in global warming potential due to reductions in material requirements and the elimination of adhesives. By contrast, reusable diapers showed a more variable global warming potential based on laundering practices. Hoffmann et al. found that the industrial diaper-as-service model using continuous batch washers achieved the lowest global warming potential due to optimized water and energy use. O'Brien et al. (2009) also noted that home-washed reusable diapers could reach low global warming potential levels if washed in cold water, using efficient front-loading machines, and line-dried. [2][3][5][8]

Water Depletion was significant in reusable diaper systems, especially in studies like Meseldzija et al. (2013) and O'Brien et al. (2009) that identified high water usage in household laundering of reusable diapers. Cordella et al. (2015) found that disposable diapers generally had lower water depletion impacts since water was primarily used in the production phase, not in ongoing laundering. Hoffmann et al. (2019) highlighted that industrial laundering in diaper-as-service models offered efficiency benefits, reducing the water footprint of reusable diapers. Mendoza et al. (2019) noted that eco-design efforts, such as reduced material use in glueless diapers, led to decreased water depletion, contributing to improved environmental performance. [2][3][4][5][8]

Eutrophication and Acidification impacts were highest in disposable diapers across studies, largely due to end-of-life disposal and pollutants from production processes. Cordella et al. (2015) and

Meseldzija et al. (2013) both found that emissions from plastic and fluff pulp production contributed to eutrophication and acidification. The presence of nutrients and chemicals in these materials, especially in unsanitary landfills, exacerbates these impacts. In reusable diapers, eutrophication impacts were minor and were linked to detergent use in laundering. Studies like Hoffmann et al. (2019) indicated that using phosphate-free detergents in laundering could mitigate this impact. Mendoza et al. (2019) further demonstrated that glueless diapers achieved over a 50 percent reduction in eutrophication and acidification impacts compared to conventional disposable diapers, highlighting the potential of eco-design in mitigating these environmental harms. [2][3][4][8]

Land Use impacts were found to be higher for disposable diapers due to the demand for softwood for fluff pulp, particularly in O'Brien et al. (2009) and Weisbrod et al. (2012), which documented substantial land requirements for disposables. Mirabella et al. (2013) showed that while bio-based disposables reduce fossil fuel use, they increase land use due to agricultural demands for biopolymers. Conversely, reusable diapers used less land due to fewer materials needed over a child's diapering period, with cotton and recycled materials requiring lower land area per unit. Mendoza et al. (2019) confirmed that material efficiency in glueless diapers resulted in a 23 percent reduction in material demands, helping to alleviate land use impacts associated with disposable diapers. [5][7][8][9]

Endpoint categories were only used by Hoffmann et al. (2019) and included damage to ecosystems, human health, and resource depletion. Reusable diapers, particularly in the industrial laundering system, showed lower impacts across these endpoint categories, primarily due to reduced water and energy demands in optimized laundering practices. Disposable diapers, with high impacts in material production and end-of-life disposal, performed worse in endpoint categories for human health and ecosystem damage. The study of Mendoza et al. (2019) supports this by indicating that glueless disposable diapers present a significant improvement in eco-efficiency, reducing environmental burdens across several categories while maintaining functionality. [3][8]

1.2.4 Limitations and gaps

While current studies provide valuable insights, several limitations and gaps remain. Many studies rely on data and waste management practices specific to certain regions, such as Europe, Brazil, or Australia, limiting the applicability of findings to other areas with different waste infrastructure or energy profiles. Methodological inconsistencies also complicate comparisons, as studies use varied functional units and assessment methods, introducing variability that can influence conclusions.

Eco-designed disposables and alternative materials, though promising, receive limited attention in the literature, with few studies fully exploring their environmental potential or the trade-offs they introduce. For instance, Mendoza et al. (2019) provides insights into glueless designs but acknowledges that this innovation alone may not achieve full circularity, emphasizing a need for further research into recyclable and biodegradable materials. Additionally, impacts of reusable diapers vary widely due to user behavior, particularly in laundering practices, and few studies comprehensively examine the effects of washing frequency, temperature, and drying methods. These gaps leave questions about optimal laundering practices to minimize environmental impacts. [8]

Finally, while industrial laundering shows environmental benefits, the scalability of diaper-as-service models in regions without such facilities remains uncertain. Further research on infrastructure requirements and feasibility across diverse contexts could enhance understanding of this model's practicality and broaden sustainable options for diapering.

1.2.5 Conclusion

The reviewed studies illustrate that reusable diapers generally demonstrate lower environmental impacts in water depletion, global warming potential, and land use when optimized laundering practices are employed. Disposable diapers, despite design improvements over time, exhibit high impacts in resource-intensive production and end-of-life disposal, particularly in eutrophication and acidification. Each diaper system's environmental footprint is heavily influenced by regional waste management practices, consumer habits, and laundering efficiencies, underscoring the need for a tailored approach to sustainable diaper use. Despite the gaps in the literature, which are mentioned above, the literature review forms a good basis for this study.

1.3 Objective

This project aims to assess the environmental impact of both disposable and reusable diapers, comparing key indicators like global warming potential (carbon footprint), water use, eutrophication, and land use. The goal is to identify the most sustainable diapering option over a child's diapering years (typically 2.5 years) by evaluating different lifecycle stages: production, use (washing for cloth diapers), and disposal. Other sensitivity analysis will be done for completeness of the comparison.

Additionally, a life cycle costing will be executed to compare the financial costs. There will also be some attention devoted to the development of a business model to create a comprehensive deliverable with extra information.

2 Methods

This study conducts a Life Cycle Assessment (LCA) to evaluate the environmental impacts of disposable and reusable diapers, examining the key stages of production, use, and disposal. All methodological choices, including functional units, impact categories, and system boundaries, are informed by insights from the literature review and aligned with the study objectives. OpenLCA software with the Ecoinvent 3.7.1 database is used to ensure comprehensive and consistent data across each diaper type and lifecycle phase. A cradle-to-grave approach examines each diaper system from raw material extraction through to end-of-life scenarios.

The functional unit is defined as "diaper use over 2.5 years," representing the average diapering duration for a single child. This allows for a lifecycle comparison of both disposable and reusable systems, and the usage rates are derived from literature sources (Hoffman et al., 2019; O'Brien et al., 2009). For disposable diapers, an estimated total of 5005 diapers is used over 2.5 years, while 6370 uses of reusable diapers are estimated for the same period. This quantity reflects total usage rather than the actual number of reusable diapers needed, as cloth diapers are laundered and reused. An estimated 30 reusable diapers, accounting for wear and tear, should suffice, with two different diaper sizes incorporated to reflect realistic lifecycle use patterns. [3][5]

System boundaries include raw material sourcing, manufacturing, usage (including laundering for reusable diapers), and disposal options, such as landfilling, composting, and incineration. Transportation between lifecycle stages is included in the boundaries to ensure a thorough cradle-to-grave analysis.

Three general product systems are analyzed: a disposable diaper model, a diaper-as-product model representing cloth diapers laundered domestically, and a diaper-as-service model, which involves laundering at a small facility or using industrial laundering with continuous batch washing. To perform a sensitivity analysis and provide a thorough comparison, additional scenarios will include:

- Disposable Diaper Systems: Sanitary landfill disposal, unsanitary landfill disposal, open dump disposal, and incineration with energy recovery.
- Home-Washed Cloth Diaper Systems: Cold wash with line drying, cold wash with machine drying, warm/hot wash with line drying, and warm/hot wash with machine drying.
- On-Site Facility Laundered Cloth Diaper Systems: Warm wash with line drying, warm wash with machine drying, hot wash with line drying, and hot wash with machine drying.
- Industrial Laundered Cloth Diaper System: Optimized hot wash with industrial machine drying.

Additionally, the eco-designed “glueless” diaper from Mendoza et al. (2019) could be analyzed for its production phase only, following a cradle-to-gate approach, which assumes the same use and disposal phases as a standard disposable diaper. This would involve fewer product systems while still assessing the environmental impact of eco-design innovations. [8]

The baseline scenario will be the disposable diaper system with sanitary landfill disposal and the substitution scenario will be the industrial laundered cloth diaper system. Additional sensitivity analyses are done as well, but most of the attention will be devoted to the comparison of these two scenarios.

The ReCiPe impact assessment methodology in OpenLCA is applied, using the hierarchical version with a 100-year timeframe. This method includes both midpoint and endpoint categories, offering insights into specific environmental impacts as well as overall damage to ecosystems, human health, and resource depletion.

Data collection relies primarily on Ecoinvent 3.7.1 for material, energy, and water inputs. Secondary data from recent scientific literature and industry reports supplement information on laundering practices and disposal scenarios. Standard assumptions are applied to energy and water use in laundering, with scenarios modeling cold versus hot washing and line drying versus machine drying. For inventory analysis, data from Mendoza et al. (2019) and Hoffman et al. (2019) are also used, providing recent and relevant inputs, including detergent use, on-premise laundering, and industrial laundering details. Additionally, primary data from Professor Eva Gallego Piñol are used to validate literature data regarding the weight and use of reusable diapers, ensuring realistic benchmarks for comparison. [3][8]

This methodology enables a thorough comparison of the environmental impacts associated with each diaper type, emphasizing how design, material choices, and user practices influence sustainability across each diaper’s lifecycle.

2.1 Inventory analysis and Life Cycle Assessment (LCA)

2.1.1 Baseline Scenario

The baseline scenario is considered to be the disposable diaper with sanitary landfill.

For the baseline scenario, the production, distribution, use, and waste treatment phases must be considered. Before implementing this scenario in the OpenLCA software, the system boundaries and the functional unit need to be defined. The baseline scenario includes three product systems, as shown in Figure 1. The process system from Hoffman et al. (2019) was selected due to its clarity and because it is the most recent source. Although transportation is not depicted in the process system, it will also be included in the LCA modeling. [3]

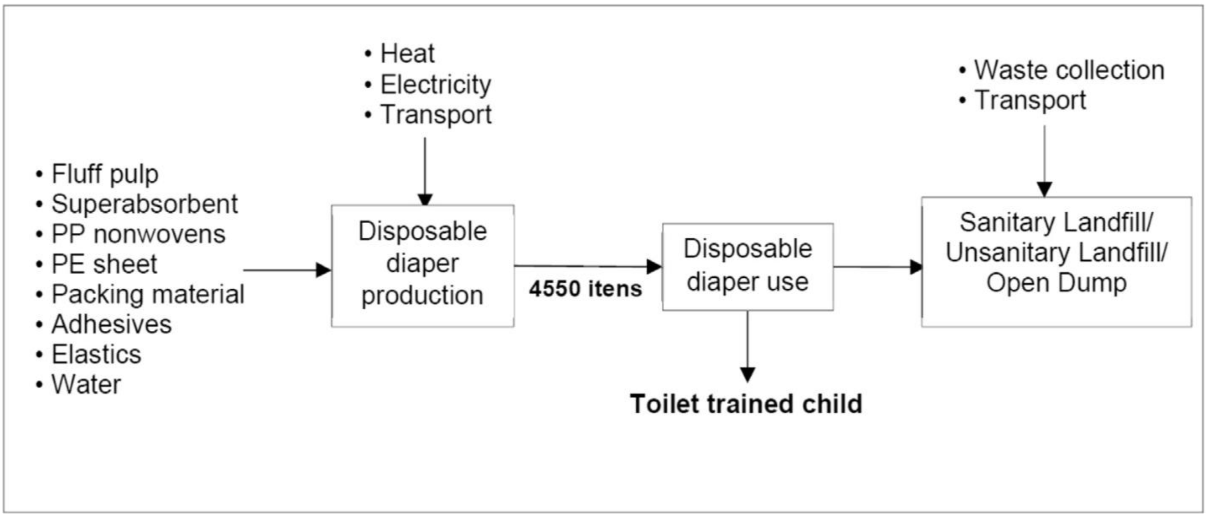


Figure 1: Simplified process system for disposable diapers with

As stated previously, the functional unit is 5005 diapers. This figure is derived from the research of O’Brien et al. (2009), which calculates the daily diaper usage for moderate impact (5.5 diapers) and multiplies it by the average diaper training time of 2.5 years per child. Hoffman et al. (2019) also use this source to determine the functional unit, but they assume an average of 5 diapers per day, which explains the difference in Figure 1. [5]

Main material inputs for disposable diapers in g/diaper.

	Cordella (36.0 g/diaper)	Mendoza (33.0 g/diaper)
Fluff pulp	13.2	12.7
Superabsorbent polymers (SAP)	11.1	15.2
Polypropylene nonwovens	5.8	7.5
Back sheet (polyethylene LD)	2.2	1.9

Source: based on data from Cordella et al. (2015) and Mendoza et al. (2019).

Table 1: Material inputs for one diaper. [3]

Table 1 illustrates the main material inputs for the production of disposable diapers. The table shows a simplified summary of the most important material inputs for diaper production to prevent excessive detail and complexity. The four materials presented in table 1 contribute to approximately 90% of the total material requirements, indicating their importance. When modeling in the OpenLCA software, extra material requirements should be taken into account, like the carton box for packaging, electricity, water etc.

Therefore, the inventory analysis presented in Table 2 is used.

Firstly, the fluff pulp production is added in the OpenLCA software. Since there were already many existing processes in the OpenLCA software, no production processes or inventory analyses were required. However, there were many sources for the production of fluff pulp like softwood or hardwood. According to Ismaeilimoghadam et al. (2022), pulp production sources are mostly based on the availability of resources. Eucalyptus is the most common source in Spain according to Gonzàlez-Garcìa et al. (2009). Therefore, the final choice of the production process for fluff pulp is “sulfate pulp production, from eucalyptus, bleached | electricity, high voltage | Cutoff, U - ROW”.

There was no location of Spain or Europe available. After copy-pasting the inputs and outputs, the provider is changed to try to adapt as accurately as possible to Spain. [10] [11]

Table 2: Inputs for the Manufacture of One Disposable Diaper

Inputs for the manufacture of 1 disposable diaper.

Inputs	Value
Sulfate pulp for fluff pulp	15.0 g
Superabsorbent polymers (SAP)	13.0 g
Acrylonitrile-butadiene-styrene copolymer for adhesives	0.1 g
PP granulate with extrusion and thermoforming for acquisition and distribution layer, Top layer and other nonwovens	7.5 g
PE granulate with extrusion for back sheet	2.0 g
Polyurethane for elastics	1.0 g
Electricity	52.8 Wh
Heat from natural gas	20.0 kJ
Water, deionized	2.0 g
Carton box for packaging	3.6 g
EUR-flat pallet for packaging	0.7%
Packaging film	0.5 g

Source: Based on data from Cordella et al. (2015) and Mendoza et al. (2019).

Table 2: Inventory analysis for the production of 1 diaper [1]

Hoffman et al. (2019) described a SAP (sodium polyacrylate) production process, since there was not one available in the Ecoinvent database. After checking to confirm the lack of an existing process, the inventory analysis described by Hoffman et al. (2019) is implemented. This is shown in Table 3. This inventory is added in OpenLCA to implement the production of SAP. [3]

Inputs for the production of 1 kg of sodium acrylate.

Input	Value
Sulfuric acid	0.006 kg
Ammoniumm sulfate	0.002 kg
Acrylic acid	0.780 kg
Sodium hydroxide	0.460 kg
Water	1.700 kg
Wastewater	- 1.900 l
Electricity, high voltage	2.187 kWh

Source: Adapted from Gontia and Janssen (2016).

Table 3: Inputs for the production of 1 kg of sodium acrylate [3]

Continuing from the inventory list depicted in Table 2, the acrylonitrile-butadiene-styrene copolymer production is modeled in the software. There was only one choice of production process available in OpenLCA with RER, RoW and GLO. Therefore, the inputs and outputs for “acrylonitrile-butadiene-styrene copolymer production | acrylonitrile-butadiene-styrene copolymer | Cutoff, U-RER” were copied and providers were adapted again to Spain.

For the polypropylene production, there was again only one suitable process available. However, for the polyethylene, distinctions between high-density, linear-low-density and low-density polyethylene are made. LDPE is usually chosen (Chabowska et al. (2023)) and this is also confirmed by the density range in the ethylene-polymers produced by ExxonMobil. [12] [13]

Next, the polyurethane is modeled. Hoffman et al. (2019) used the existing flexible polyurethane foam production in their research. Therefore, the same existing process is applied in OpenLCA in this case. [3]

Mendoza et al. (2018) mention that the motors in the diaper manufacturing process require high voltage electricity. This is modeled in OpenLCA. The provider still needs to be chosen as accurately as possible. Figure 2 shows the different sources of electricity in Spain, which shows that there is no dominant electricity source. Therefore, a production mix is chosen and as reference location Spain. [8]

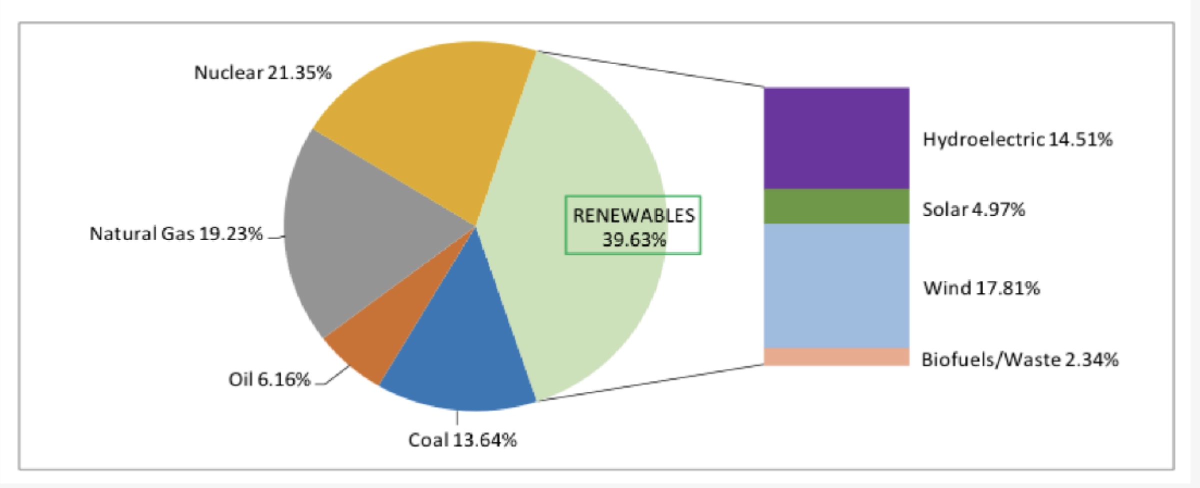


Figure 2: Sources of electricity generation in Spain, year 2016

The heat from natural gas is modeled in OpenLCA. Since Spain does not have natural gas reserves, it relies on import. Therefore, the market provider for Europe without Switzerland is selected in the OpenLCA software.[15]

The deionized water is assumed to be produced in Spain, since it is a big supplier for India for example. Therefore, the production for Europe without Switzerland is assumed as the provider. [16]

For the production of the cardboard boxes, Cordella et al. (2015) implemented the existing process in OpenLCA for corrugated board box production. The location of RER is implemented and all providers are changed to match Spain as closely as possible. The pallet production process for “EUR-flat pallet production” is implemented, following the calculations of Hoffman et al. (2019). The packaging film is a low-density polyethylene film (Cordella et al., 2015) and there already exists a production process in OpenLCA. RER is chosen again between GLO, RoW and RER. Inputs and outputs are again copied and providers are changed. [2][3]

Now everything required for the production process of 1 diaper is put in OpenLCA. The value of 0.7% in Table 2 for the pallet is replaced by 0.2 g. This value comes from Cordella et al. (2015) and is easier to implement. [2]

Figure 3 shows the list of inputs and outputs, with respective specifications, for the disposable diaper production process in OpenLCA.

Inputs/Outputs – disposable diaper production – ES

Inputs

Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided waste	Provider	Data quality entry	Location	Description
Acrylonitrile-butadiene-styrene	DIAPERS DISPOSABLE	1.0E-4*5005	kg		none		acrylonitrile-b			
cardboard box produced	DIAPERS DISPOSABLE	0.0035*5005	kg		none		cardboard pro			
electricity, high voltage	D:Electricity, gas, steam and air co	52.8*5005	Wh		none		electricity, hig			
fluff pulp produced	DIAPERS DISPOSABLE	0.015*5005	kg		none		fluff pulp proc			
heat, district or industrial, natu	D:Electricity, gas, steam and air co	20.0*5005	kJ		none		market for hea			
pallet produced	DIAPERS DISPOSABLE	2.0E-4*5005	kg		none		wooden pallet			
plastic film produced	DIAPERS DISPOSABLE	5.0E-4*5005	kg		none		packaging film			
polyethylene granulate produce	DIAPERS DISPOSABLE	0.002*5005	kg		none		polyethylene g			
polypropylene granulate produ	DIAPERS DISPOSABLE	0.0075*5005	kg		none		polypropylene			
polyurethane produced	DIAPERS DISPOSABLE	0.001*5005	kg		none		polyurethane			
SAP produced	DIAPERS DISPOSABLE	0.013*5005	kg		none		SAP productic			
water, deionised	E:Water supply; sewerage, waste n	0.002*5005	kg		none		water product			

Outputs

Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided product	Provider	Data quality entry	Location	Description
disposable diaper produced	**DIAPERS DISPOSABLE**	**1.0*5005**	**Item(s)**		**none**					

Figure 3: Inputs and outputs for disposable diapers production

Next in the process system, the diapers have to be distributed. Hoffman et al. (2019) used data from Cordella et al. (2015) and this data is suitable for a European context. Table 4 shows the transportation distances and weight inputs for the distribution of the diapers after production and also for the waste treatment phase. The same transportation information is used as Cordella et al. (2015), namely: EURO3 truck for 1000 km, with a capacity of 27.4 tonnes. This leads to the transport choice of: transport, freight, lorry 16-32 metric ton, EURO3. [2][3]

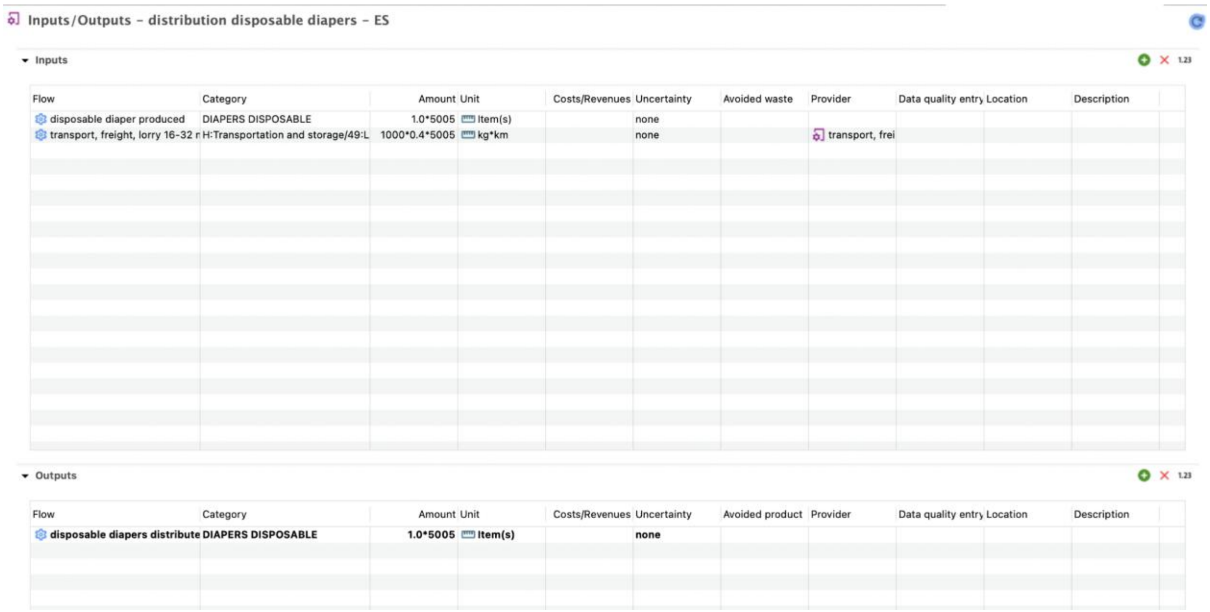
Inputs for distribution and waste treatment.

Inputs	Values
Transport for distribution and sale	0.04 kg × 1000 km
Municipal waste collection service	0.34 kg × 10 km
Waste transport	0.34 kg × 80 km
Waste treatment (sanitary landfill, unsanitary landfill, open dump)	0.34 kg

Table 4: Inputs for distribution and waste treatment. [3]

The use of the diapers does not require any water or electricity and therefore will not be considered in the life cycle assessment. The end-of-life cycle however, is critical and needs to be modeled in the software. Inputs are shown in Table 4. These inputs are considered to be applicable for Brazil. The distribution distance comes from Cordella et al. (2015) and can be applied in this research as well. The same is assumed for the other transport distances. Diapers are usually mixed with the municipal solid waste fraction. However, the municipal waste handling part in Spain can be significantly different from Brazil. Cordella et al. (2015) state that composting and recycling of diapers is not a common practice and use this distribution: 63% landfill, 25% incineration with energy recovery, and 12% incineration without energy recovery. However, as stated earlier, the baseline scenario only considered sanitary landfill as waste disposal. For the transport: the same lorry has been chosen. [2]

Inputs and outputs for the disposable diapers distribution process are shown in Figure 4, while Figure 5 lists inputs and outputs for the diaper waste collection process.



Inputs/Outputs – distribution disposable diapers – ES

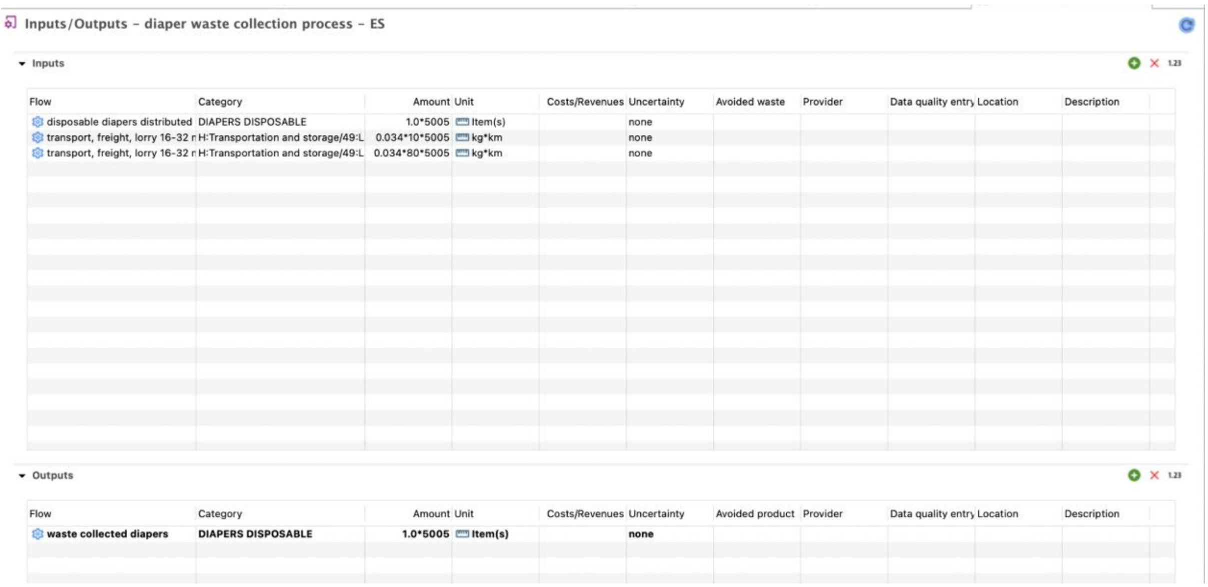
Inputs

Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided waste	Provider	Data quality entry	Location	Description
disposable diaper produced	DIAPERS DISPOSABLE	1.0*5005	Item(s)		none					
transport, freight, lorry 16-32 r	H:Transportation and storage/49:L	1000*0.4*5005	kg*km		none		transport, frei			

Outputs

Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided product	Provider	Data quality entry	Location	Description
disposable diapers distribute	**DIAPERS DISPOSABLE**	**1.0*5005**	**Item(s)**		**none**					

Figure 4: Inputs and outputs for disposable diapers distribution



Inputs/Outputs – diaper waste collection process – ES

Inputs

Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided waste	Provider	Data quality entry	Location	Description
disposable diapers distributed	DIAPERS DISPOSABLE	1.0*5005	Item(s)		none					
transport, freight, lorry 16-32 r	H:Transportation and storage/49:L	0.034*10*5005	kg*km		none					
transport, freight, lorry 16-32 r	H:Transportation and storage/49:L	0.034*80*5005	kg*km		none					

Outputs

Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided product	Provider	Data quality entry	Location	Description
waste collected diapers	**DIAPERS DISPOSABLE**	**1.0*5005**	**Item(s)**		**none**					

Figure 5: Inputs and outputs for diaper waste collection process

Sanitary landfill is chosen since no clear sources were found about the landfill habits of disposable diapers and choosing sanitary landfill in both the baseline scenario and the substitution scenario allows better comparison than to choose one landfill habit for the baseline scenario and another one for the substitution scenario. The product system implemented on OpenLCA for the disposable diapers is shown in Figure 6.

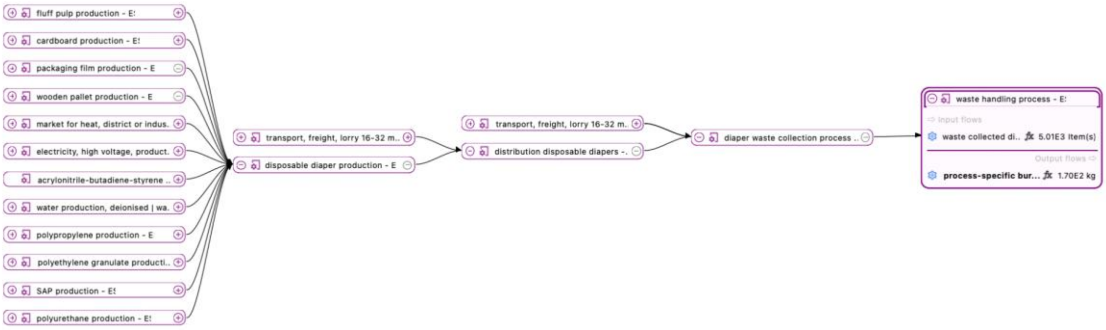


Figure 6: Product system for disposable diapers

2.1.2 Substitution Scenario

For the substitution scenario, there are a lot of possibilities mentioned in the previous section. However, the focus will lie on the comparison of the regular disposable diaper with the scenario of industrial washing for the cloth diapers and working with a collection system. The entire product system is as depicted in Figure 7.

The diaper consists of an absorbent and a cover, to minimize washing cycles. The production inputs for a cloth diaper is depicted in Table 5 in a simplified way. The simplification is allowed due to the assumption that the cloth diaper production does not have a dominant environmental impact compared to other parts in the entire product system. [3]

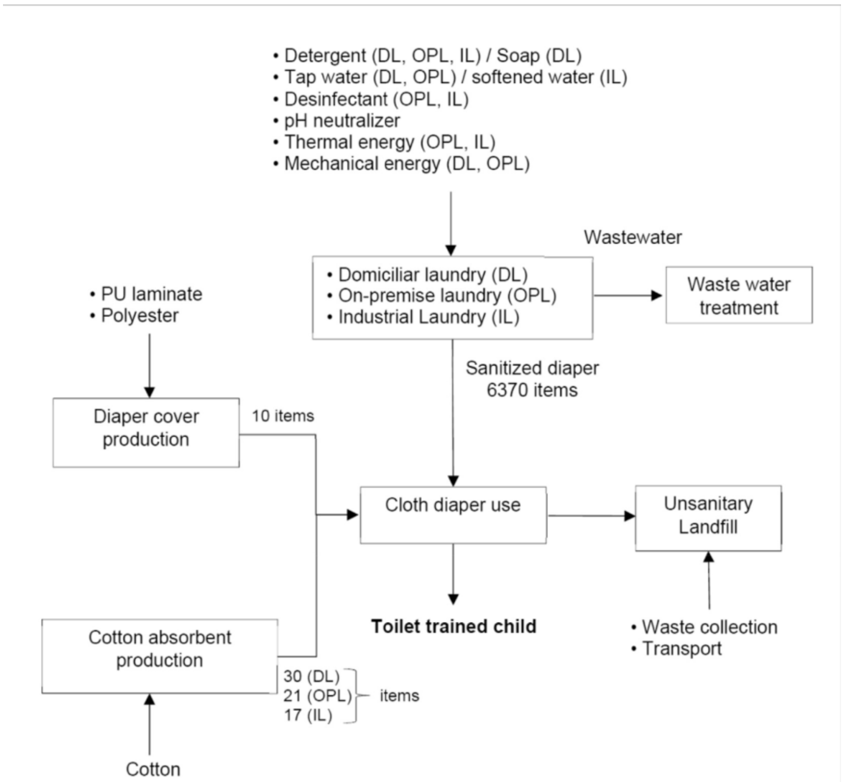


Figure 7: Simplified process system for cloth diapers with

Inputs for the production of 1 cloth diaper.

Material	Value	Reference
Polyurethane for PUL	10.0 g	Estimated
Waste PET for polyester knit	10.0 g	Estimated
Electricity for polyester fiber production	10.0 Wh	van der Velden et al., 2014
Natural gas for polyester fibre production	19.0 J	van der Velden et al., 2014
Cotton	150.0 g	O'Brian et al. (2009)

Table 5: Inputs for the production of one cloth diaper. [3]

With the information from Table 5, the cloth diaper can be estimated in the software. Polyurethane flexible foam is chosen as in the section above. Waste PET is added and low voltage electricity is used (Van de Velde et al. 2014). The woven cotton is chosen as in the paper described from Mendoza et al. (2019). The woven textile cotton is an existing flow in the OpenLCA software and according to Spain Cotton Industry Outlook 2022-2026, the import is more dominant than the production, leading to the choice of provider as "market for textile, woven cotton | textile, woven cotton | Cutoff, U - GLO". [8][17][18]

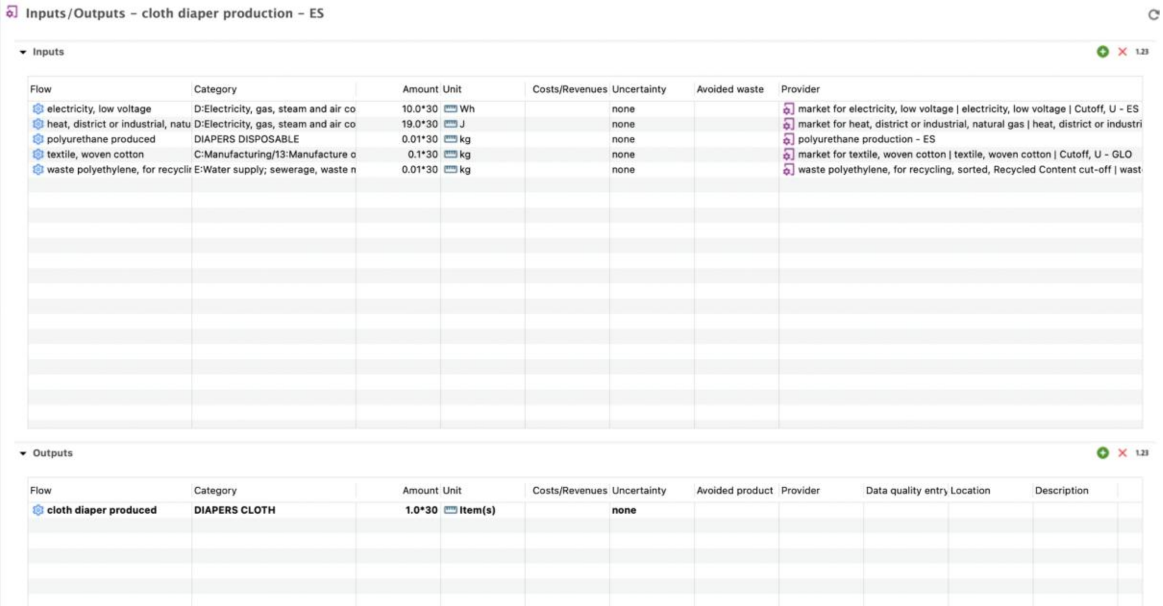
Inputs for the production of 1 kg of detergent.

Inputs	Value
Sodium alkyl sulphonate	0.04 kg
Sodium alkyl benzene sulphonate	0.19 kg
Sodium alcohol ethoxylate	0.03 kg
Polyethylene glycol NW4000 spray on binder	0.02 kg
Sodium perborate	0.05 kg
Sodium carbonate	0.24 kg
Sodium polyacrylate (45%)	0.03 kg
Sodium silicate (1:6 ration NaO/SiO2), 46%	0.02 kg
Sodium sulfate	0.12 kg
Zeolite A	0.26 kg

Source: Based on data from St Laurent et al. (2007).bib_St_Laurent_et_al_2007

Table 6:Inputs for the production of 1 kg of detergent. [3]

Figure 8 shows the list of inputs and outputs, with respective specifications, for the cloth diaper production process in OpenLCA.



Inputs/Outputs – cloth diaper production – ES

Inputs

Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided waste	Provider
electricity, low voltage	D:Electricity, gas, steam and air co	10.0*30	Wh		none		market for electricity, low voltage | electricity, low voltage | Cutoff, U - ES
heat, district or industrial, natu	D:Electricity, gas, steam and air co	19.0*30	J		none		market for heat, district or industrial, natural gas | heat, district or industri
polyurethane produced	DIAPERS DISPOSABLE	0.01*30	kg		none		polyurethane production - ES
textile, woven cotton	C:Manufacturing/13:Manufacture o	0.1*30	kg		none		market for textile, woven cotton | textile, woven cotton | Cutoff, U - GLO
waste polyethylene, for recyclir	E:Water supply; sewerage, waste n	0.01*30	kg		none		waste polyethylene, for recycling, sorted, Recycled Content cut-off | wast

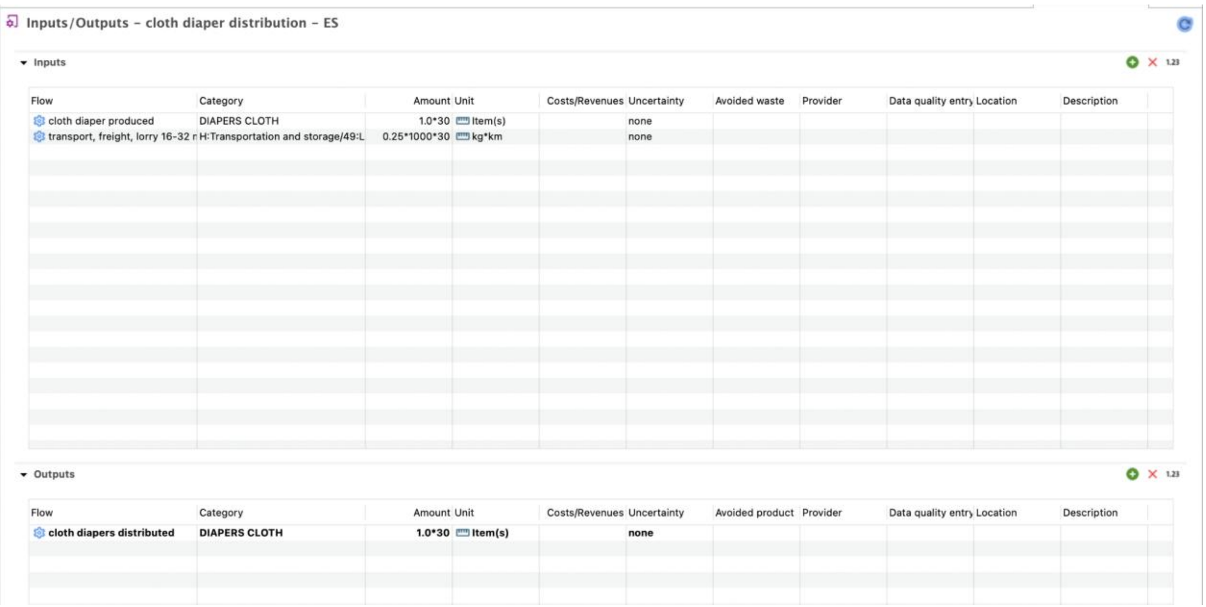
Outputs

Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided product	Provider	Data quality entry	Location	Description
cloth diaper produced	**DIAPERS CLOTH**	**1.0*30**	**Item(s)**		**none**					

Figure 8: Inputs and outputs for cloth diapers production process

The detergent inventory analysis is not applied in this research, due to the lack of existing flows for the inputs. Instead, the existing product "soap" is used, which was available in the ecoinvent database. Industrial laundering usually works with softened water and medium voltage. Since with industrial laundering, a diaper-as-service model is applied, transport during the usage stage has to be considered. It is assumed that with the diaper-as-service model, dirty diapers are picked up and clean diapers are dropped off. This is included in the 0.5 kg, assuming 250 g for one diaper, and the 60 km is a good estimation for the distance between middle and high class residences and industrial sites (Hoffman et al., 2019). For the distribution of the diapers, the same values as for the disposable ones are assumed. [3]

Inputs and outputs for the transportation stage are listed in Figure 9. Same distances and transport inputs are chosen as the baseline scenario. A distance of 1000 km is assumed.



Inputs/Outputs – cloth diaper distribution – ES

Inputs

Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided waste	Provider	Data quality entry	Location	Description
cloth diaper produced	DIAPERS CLOTH	1.0*30	Item(s)		none					
transport, freight, lorry 16-32 r	H:Transportation and storage/49:L	0.25*1000*30	kg*km		none					

Outputs

Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided product	Provider	Data quality entry	Location	Description
cloth diapers distributed	**DIAPERS CLOTH**	**1.0*30**	**Item(s)**		**none**					

Figure 9: Inputs and outputs for cloth diapers distribution process

After modeling the transport, the usage stage can be modeled using the inputs in the table below (Tab.7).

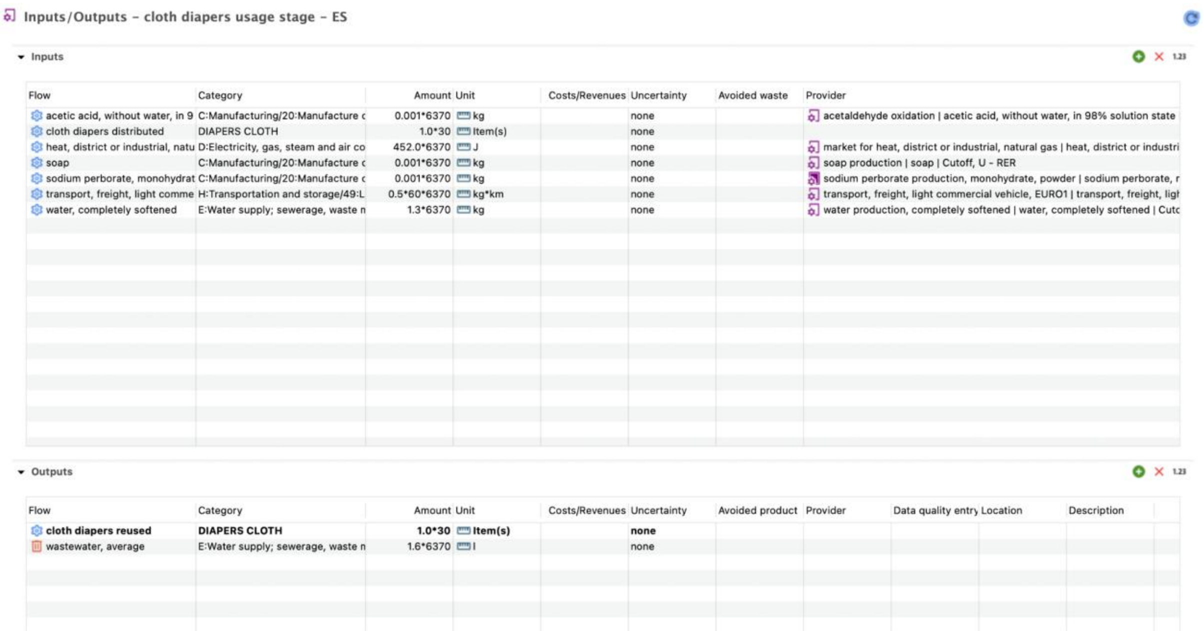
Inputs for industrial laundering for 1 cloth diaper.

Input per diaper	Value	Reference
Softened water	1.3 l	G.A. Braun, Inc, n.d.
Wastewater	1.6 l	
Gas for water heating	272.0 J	G.A. Braun, Inc, n.d.
Gas for tumble drying	180.0 J	International Energy Agency (2012)
Detergent	1.0 g	Fijan et al. (2008)
Bleach	1.0 g	US Chemical (2016)
Sour (acetic acid)	1.0 g	Estimated
Transport	60 km × 0.5 kg	Estimated

Table 7: Inputs for laundering 1 cloth diaper [3]

The gas for water heating and tumble drying is added up and a total of 452 Joule is modeled in the software. As previously mentioned, natural gas is not available in ground reserves of Spain. Therefore, the market for Europe without Switzerland is implemented as the provider. For detergent, bleach and sour, existing products in the database are chosen. Firstly, detergent is modeled as soap. Then, sodium perborate is chosen as a bleaching agent (because it was used as a bleaching agent in the detergent inventory analysis) and acetic acid as sour. For the providers, soap production and sodium perborate production in the RER are chosen. However, there were multiple processes to choose with the production of acetic acid. The final choice is the oxidation of acetaldehyde, because it is one of the most common processes to produce it. [19]

Figure 10 specifies inputs and outputs for industrial laundering.


Inputs/Outputs – cloth diapers usage stage – ES

Inputs

Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided waste	Provider
acetic acid, without water, in 9	C:Manufacturing/20:Manufacture c	0.001*6370	kg		none		acetaldehyde oxidation | acetic acid, without water, in 98% solution state
cloth diapers distributed	DIAPERS CLOTH	1.0*30	Item(s)		none		
heat, district or industrial, natu	D:Electricity, gas, steam and air co	452.0*6370	J		none		market for heat, district or industrial, natural gas | heat, district or industri
soap	C:Manufacturing/20:Manufacture c	0.001*6370	kg		none		soap production | soap | Cutoff, U - RER
sodium perborate, monohydrat	C:Manufacturing/20:Manufacture c	0.001*6370	kg		none		sodium perborate production, monohydrate, powder | sodium perborate, r
transport, freight, light comme	H:Transportation and storage/49:L	0.5*60*6370	kg*km		none		transport, freight, light commercial vehicle, EURO1 | transport, freight, ligl
water, completely softened	E:Water supply; sewerage, waste n	1.3*6370	kg		none		water production, completely softened | water, completely softened | Cutc

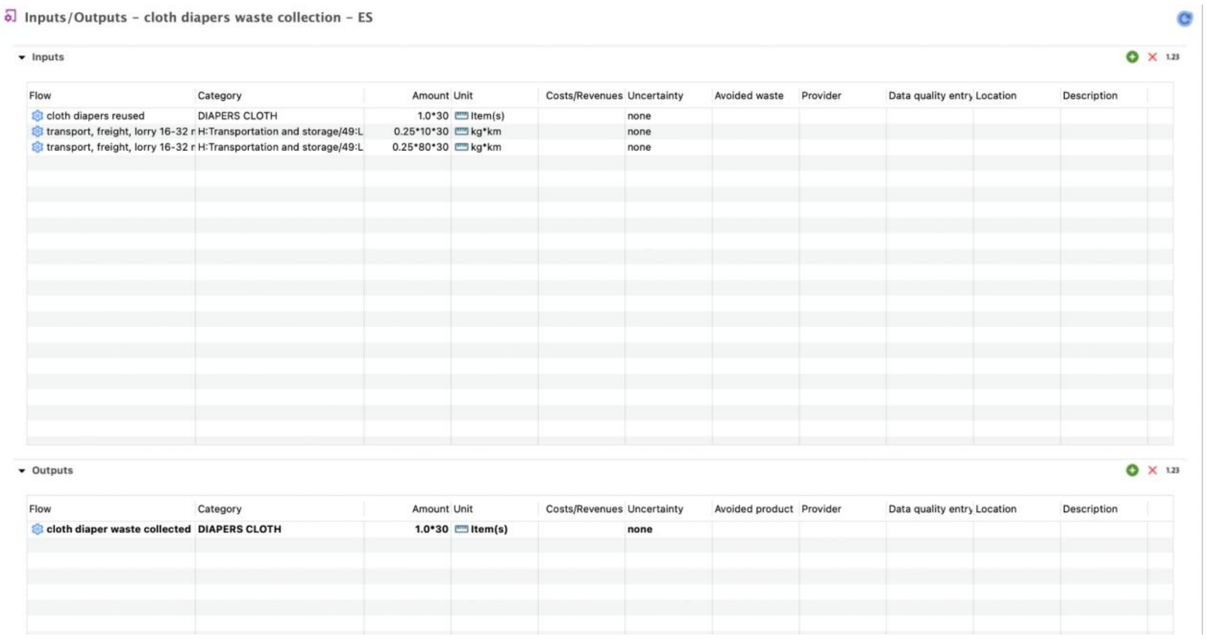
Outputs

Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided product	Provider	Data quality entry	Location	Description
cloth diapers reused	**DIAPERS CLOTH**	**1.0*30**	**Item(s)**		**none**					
wastewater, average	E:Water supply; sewerage, waste n	1.6*6370	l		none					

Figure 10: Inputs and outputs for cloth diapers usage stage

For the 60 km transport during the usage stage, a light commercial vehicle is assumed that suffices European standards, leading to the choice of “Light commercial vehicle, EURO 1| transport, freight, light commercial vehicle, EURO1| Cutoff, U - ZA” in OpenLCA. This seems to be more realistic for these small distances and for the diaper-as-service transport van. Inputs and outputs of this stage are shown in Figure 11.

For the waste collection, the same trucks and distances are applied as for the baseline scenario (both go with municipal solid waste) and then the mass is adapted to 0.025 kg.



Inputs/Outputs – cloth diapers waste collection – ES

Inputs

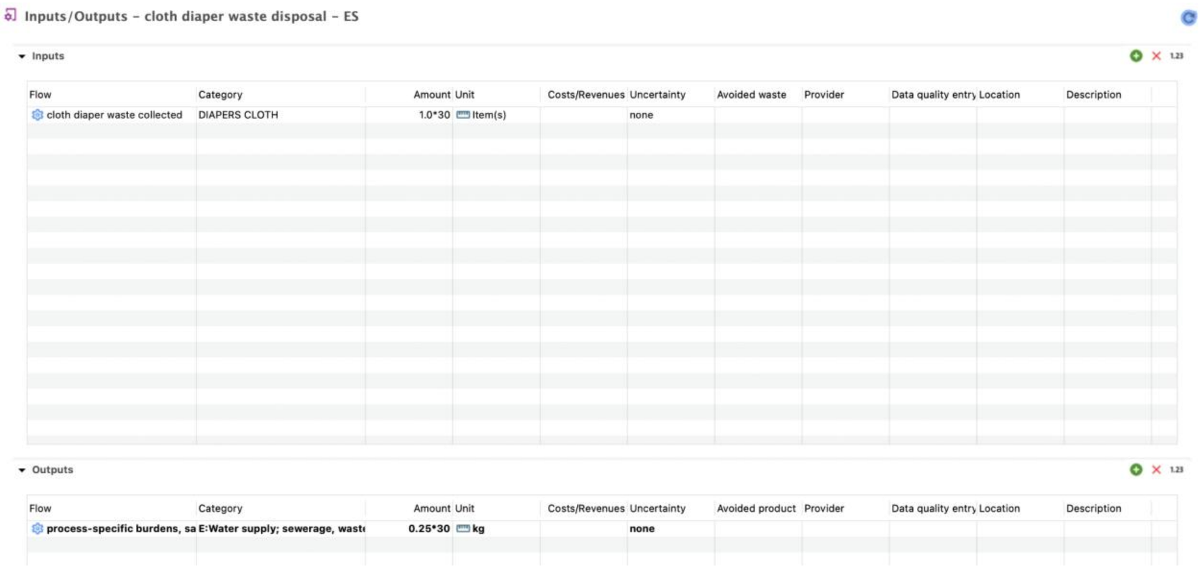
Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided waste	Provider	Data quality entry	Location	Description
cloth diapers reused	DIAPERS CLOTH	1.0*30	Item(s)		none					
transport, freight, lorry 16-32 r	H:Transportation and storage/49:L	0.25*10*30	kg*km		none					
transport, freight, lorry 16-32 r	H:Transportation and storage/49:L	0.25*80*30	kg*km		none					

Outputs

Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided product	Provider	Data quality entry	Location	Description
cloth diaper waste collected	**DIAPERS CLOTH**	**1.0*30**	**Item(s)**		**none**					

Figure 11: Inputs and outputs for cloth diapers waste collection

As mentioned above, sanitary landfill is chosen also for the substitutional scenario in order to allow a better comparison between the two scenarios. Inputs and outputs of the waste disposal process are presented in Figure 12.



Inputs/Outputs – cloth diaper waste disposal – ES

Inputs

Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided waste	Provider	Data quality entry	Location	Description
cloth diaper waste collected	DIAPERS CLOTH	1.0*30	Item(s)		none					

Outputs

Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided product	Provider	Data quality entry	Location	Description
process-specific burdens, sa	**E:Water supply; sewerage, wast**	**0.25*30**	**kg**		**none**					

Figure 12: Inputs and outputs for cloth diapers waste disposal

The product system implemented on OpenLCA for the disposable diapers is shown in Figure 13.

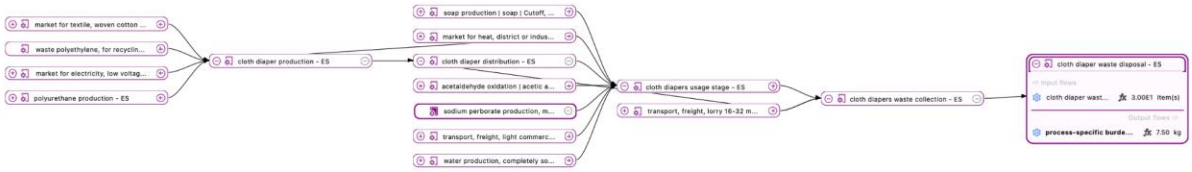


Figure 13: Product system for cloth diapers

2.2 Life Cycle Costing (LCC)

The objective is to calculate the total costs associated with both disposable and reusable diapers throughout their entire life cycle, encompassing production, use (including washing cycles for cloth diapers), and disposal.

For disposable diapers, the life cycle cost (LCC) will cover production, packaging, transportation, and disposal costs, including landfill or incineration. In the case of reusable cloth diapers, the LCC will factor in the initial purchase price, washing cycles, detergent, water, energy consumption, and the disposal of damaged diapers.

The LCC analysis will be based on existing data regarding production and disposal costs for diapers, as well as typical consumer costs related to washing and maintenance. The relevant cost categories will be broken down by each phase of the product's life cycle: production, use, and disposal.

The expected outcome of this analysis is to provide a comparison of the cost-effectiveness of both diapering systems. This will offer valuable insights into which option is more economical over its lifecycle, while also considering the environmental impact of each choice.

To do the Life Cycle Costing (LCC) analysis about these two different kinds of diapers, the main objective is to compare the NPV values obtained for each diaper and therefore understand which one is the most economically favorable.

To carry out this comparison, the calculation of NPV is made through the following formula :

$$\mathrm{NPV} = \sum_{n=0}^{T} \frac{Cn}{(1+i)^{n}}$$

with the Cn the different costs involved in the processes, i the discount rate and n the year.

A child is wearing diapers for an average lifecycle time of 2,5 years which represents 30 months. This will be the time used for a single child in the following costs data and calculations.

According to the literature with the UK Environment Agency Report **:** **"**Life Cycle Assessment of Disposable and Reusable Nappies in the UK" (2023) [20], the UNEP Report on Disposable and Reusable Diapers (2021) [21], Hoffmann et al. (2019) [23], Jason Rector et al. (2024) [24] but also the article from Norasnursery.com – Understanding Laundry Costs for Cloth Diapers [22] , the following data is obtained :

	Disposable diapers	Reusable cloth diapers
Initial purchase costs ($)	0,25 per diaper and 6000 diapers per child so 1500	400 (20-30 diapers in a set)
Washing cycles and maintenance costs ($)	/	- Detergent costs : 0,50 per load (2-3 loads per week) - electricity for washing and drying : 0,40 per load - monthly utility increase : 2-5 depending on local rates and machine efficiency
Disposal of damages diapers costs ($)	50-70 per ton and 1 ton of diaper waste for a child so 50-70 for disposal per child	Negligible disposal costs
Production costs ($)	- material costs : 0,05-0,10 per diaper - environmental costs : a child generates 15-20 kg of CO2 equivalent	- costs of manufacturing per diaper : 8-20 - environmental costs : 3000-4000 liters of water per diaper for cotton-based products
Packaging and transportation costs ($)	- packaging : 0,01-0,03 per diaper - transportation : 0,01-0,02 per diaper	- packaging : 0,01-0,02 per diaper - transportation : 0,01-0,03 per diaper
End-of-Life disposal costs ($)	- landfill disposal costs : 50-100 per child - incineration costs : 70-120 per child	- repurposing and recycling costs : 0,10-0,30 per kg - landfill disposal costs : negligible

Table 8 : literature data about disposable and reusable cloth diverse costs for LCC analysis

An estimation of 6000 diapers is made for the number of disposable diapers used for a single child in a lifespan of 2,5 years, which represents approximately 200 diapers per month. For the reusable cloth

diapers, it is a 30 diapers set bought for a single child for a lifespan of 2,5 years, which represents approximately an average of 1 cloth diaper per month.
A reusable cloth diaper weighs approximately 0,15 kg, which will be useful to do an approximation of the end-of-life disposal costs of these cloth diapers, in order to do the LCC analysis. For repurposing and recycling costs, it is 0,20 $ for 1 kg of diaper. And one cloth diaper weighs approximately 0,15 kg as mentioned just before. So it represents 0,03 $ for a cloth diaper and therefore 0,03 $ per month because the approximation was to say that an average of 1 cloth diaper is used for one month.

For a reusable cloth diaper, a set of approximately 30 diapers is bought at the beginning for 400 $, for the 2,5 years when the baby is still not toilet-trained. So it represents approximately an average of 1 cloth diaper per month. For this kind of diaper, according to the data collected, an estimation of 3 loads per week is made, which represents 12 loads per month. For these cloth diapers, there are monthly utility costs that increase by 2 $ each month. This will be used for the calculation of the costs involved in the process of cloth diapers each month, through this LCC analysis.
For the calculation of NPV, for the process costs Cn, the average value of the ranges of data found in the literature and that are present in the table above is chosen to make calculations easier.

A discount rate of i = 4% is chosen, which is an average and convenient value when the study is a case of a consumer-focused analysis and especially in a LCC analysis about disposable and cloth diapers.

For the calculation of the NPV, the different costs involved in the process of use of the disposable diapers and reusable cloth diapers are needed to calculate the term Cn in the formula of NPV :

- For disposable diapers : the costs of initial investment, disposal of damaged diapers costs, production costs with material costs, packaging and transportation costs and end-of-life disposal by landfill disposal or incineration costs are necessary to calculate the NPV and are put in the formula for each month during these 2,5 years. For disposable diapers, there are no washing cycles and maintenance costs because each diaper is thrown away after use.
- For reusable cloth diapers : costs of initial investments, washing cycle and maintenance costs with detergent costs, electricity costs for washing and drying and the utility costs raising by 2 $ each month, the production costs with manufacturing costs of these kinds of diapers, the packaging and transportation costs, and the end-of-life disposal costs with repurposing and recycling costs. For cloth diapers, there are negligible disposal costs compared to the ones for disposable diapers and also negligible landfill disposal costs.

In terms of time, the unity is the year and as the diaper use lifespan chosen in this case is 2,5 years, the calculation of NPV factor is repeated for each month of this cycle. So from month 0 to month 30 with each time, 1 month = $\frac{1}{12}$ year = 0,083 year, 2 months = $\frac{2}{12}$ = 0,167 year, etc…, until 30 months = 2,5 years. So the n in the formula of NPV corresponds to the number of months converted in years : n = 0, n = 0,083, n = 0,167, ….., n= 2,5.

<u>Calculation of NPV for disposable diapers :</u>

For n=0, the only process costs is the initial investment of 1500 $, so according to the formula, NPV (n=0) = 1500 $

For n=1, the process costs involved are as follows : Cn = costs of disposal of damaged diapers per month + number of diapers used per month * material costs + number of diapers used per month * packaging costs + number of diapers used per month * transportation costs + 6000 disposable diapers used for a child in a 2,5 years lifespan landfill disposal costs / the total number of months that is 30 + 6000 disposable diapers used for a child in a 2,5 years lifespan incineration costs / the total number of months that is 30
So Cn = (60/30) + (6000/30)*0,075 + (6000/30) * 0,02 + (6000/30) * 0,015 + (75/30) + (95/30) = 29,666667 $
This is the same value of Cn for n=1 until n=30.

This makes it possible to calculate the corresponding NPV with the discount rate of i = 0,04 and finally the sum of all the NPV for each n is made and enables to obtain the final NPV value for disposable diapers.

<u>Calculation of NPV for reusable cloth diapers :</u>

For n=0, the only process costs is the initial investment of 400 $, so according to the formula, NPV (n=0) = 400 $

For n=1, the process costs involved are as follows : Cn = monthly utility costs increase of 2 $ + washing cycles and maintenance costs + number of diapers used per month * manufacturing costs + number of diapers used per month * packaging costs + number of diapers used per month * transportation costs + repurposing and recycling costs
So Cn = 2 + (detergent costs + electricity costs for washing and drying) + 14* 1 + 0,015*1 + 0,02*1 + 0,03
So Cn = 2 + (0,50 * 3 * 4 + 0,40 * 3 *4) + 14* 1 + 0,015*1 + 0,02*1 + 0,03 = 2 + 6 + 4,8 + 14 + 0,015 + 0,02 + 0,03
So Cn = 26,77 $
For the following values of NPV, for n=2, the calculation is the same except that the utility costs increase of 2 $ has to be taken into account, so the NPV value for n=2 is increased by 2 $ and same again for n=3, …., until n=30.

This makes it possible to calculate the corresponding NPV with the discount rate of i = 0,04 and finally the sum of all the NPV for each n is made and enables to obtain the final NPV value for disposable diapers.

2.3 Business model approach

The business model encompasses three key components: a value creation ecosystem that maps the interconnected relationships among stakeholders, a business model canvas that outlines the operational and strategic framework, including market opportunities and sizing, and a strategy canvas that highlights competitive positioning against market leaders.

The analysis of the Value Creation Ecosystem employs a systemic approach to map the interconnections between stakeholders in the industrial laundering of reusable diapers. Key stakeholders include parents, logistics providers, laundering facilities, and diaper manufacturers. The methodology incorporates stakeholder mapping and value flow analysis to illustrate the exchange of resources, services, and payments within the ecosystem.

The business model was structured using the Business Model Canvas framework, integrating nine key components: value propositions, customer segments, channels, customer relationships, revenue streams, key resources, key activities, key partnerships, and cost structure. This framework was adapted to reflect the service of industrial laundering for reusable diapers, focusing on eco-conscious families. The market opportunity and potential market size for the reusable diaper laundering service have been estimated for the city of Barcelona in Spain.

The business opportunity concerns a diaper laundry service in Spain, catering to families who use reusable diapers but find washing them inconvenient. As reusable diapers gain popularity due to environmental and cost-saving benefits, one of the main barriers to adoption is the time and effort required for regular cleaning. A professional laundry service would solve this problem by offering a convenient, hygienic, and eco-friendly solution for parents. This service would target eco-conscious families, working parents, and urban households where time constraints and practicality are major concerns. By emphasizing sustainability and leveraging Spain's growing awareness of waste reduction, the business can position itself as both a practical and green alternative. The service could also include subscription models, offering pickup, washing, and delivery for added convenience, making it an attractive option in a growing niche market.

An estimation of the market size for the municipality of Barcelona can be derived by multiplying the following factors: annual births, target market penetration rate, price per month, and duration in months, as shown in the following formula.

$$Market\ size = Annual\ births \times\ Penetration\ rate \times\ Price\ per\ month \times\ Duration\ in\ months$$

In 2024, there were 8,269 newborns in Barcelona, according to official statistics of the municipality of Barcelona. For this estimation, the market penetration rate assumed is 10%, reflecting the proportion of eco-conscious families or those interested in sustainability who are likely to adopt reusable diapers and laundry services. This assumption is based on general trends, as precise data on this topic is not readily available.

The cost structure is based on the assumption that each child uses approximately 200 diapers per month, with a washing service priced at 10.5 € per month (10.8 $), and an additional 3.8 € (4 $) for transportation. Therefore, the total monthly cost for the service, which includes collection, laundry, and delivery of the diapers, is estimated to be 14.3 €. Parents are assumed to use this service for about 30 months, which corresponds to approximately 2.5 years. [26]

The comparative strategy canvas was developed by benchmarking Pampers (disposable diapers) against Superbottoms (reusable diapers). Criteria included price, advertising, brand recognition, availability, status, environmental impact, convenience, durability, health and safety, and product range. Each criterion was scored qualitatively (low, medium, high) based on secondary data, consumer feedback, and market trends. This comparative analysis enabled identification of strategic gaps and competitive opportunities for reusable diaper services, focusing on sustainability and eco-conscious consumer preferences.

This methodology ensures a comprehensive and actionable business analysis.

3 Results & Discussion

3.1 Life Cycle Assessment (LCA)

This section includes the discussion of the results of the LCA modelling in the Open LCA software. Attention will be devoted to different endpoint and midpoint categories and results between the baseline and substitution scenario are discussed.

3.1.1 Midpoint Categories

Figure 14 shows the result of the midpoint category analysis conducted through ReCiPe 2016 Midpoint (H) method for disposable diapers and Figure 15 shows its global warming contribution tree.

The midpoint category analysis covers various environmental impact indicators related to the production and use of disposable diapers. The "Global warming" indicator is the highest, with 797.47 kg CO_2 eq, related to the use of plastic materials and industrial production. Other predominant indicators include "Fossil resource scarcity" with a value of 321.51 kg oil eq, indicating a high dependence on fossil resources, and "Human carcinogenic toxicity," 44.56 kg 1,4-DCB eq, suggesting a significant impact on human health due to chemicals used in the production processes.

"Marine ecotoxicity" and "Freshwater ecotoxicity" are also relevant, showing values of 77.68 kg 1,4-DCB eq and 18.72 kg 1,4-DCB eq, respectively, indicating significant effects on aquatic environments. "Terrestrial acidification" and "Ozone formation (Human health)" present more contained impacts, but they are not negligible.
The "Water consumption" indicator records 8.05 m^3, indicating a moderate contribution to water consumption, but still relevant considering the industrial scale of diaper production.

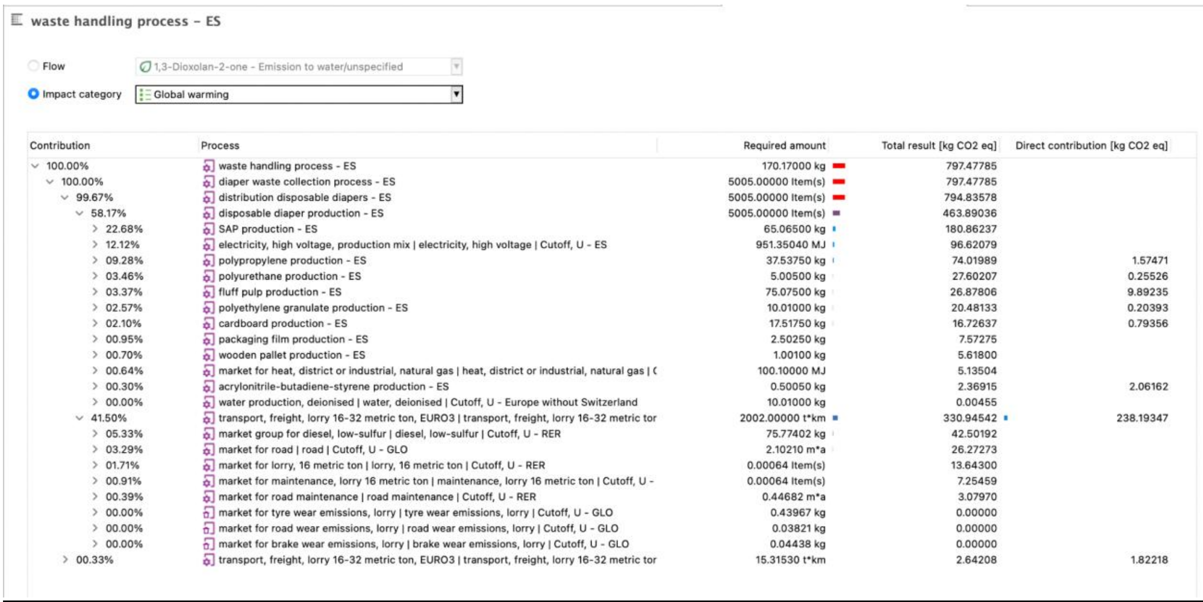
waste handling process – ES

Impact analysis - ReCiPe 2016 Midpoint (H)

Sub-group by Flows Processes | Don't show < 1 %

Name	Category	Inventory result	Characterization factor	Impact assessment result
Fine particulate matter formation	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			1.42733 kg PM2.5 eq
Fossil resource scarcity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			321.50889 kg oil eq
Freshwater ecotoxicity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			18.72051 kg 1,4-DCB
Freshwater eutrophication	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			0.15702 kg P eq
Global warming	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			797.47785 kg CO2 eq
Human carcinogenic toxicity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			44.55855 kg 1,4-DCB
Human non-carcinogenic toxicity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			531.28917 kg 1,4-DCB
Ionizing radiation	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			108.38902 kBq Co-60 eq
Land use	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			77.68748 m2a crop eq
Marine ecotoxicity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			27.86868 kg 1,4-DCB
Marine eutrophication	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			0.03578 kg N eq
Mineral resource scarcity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			1.39564 kg Cu eq
Ozone formation, Human health	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			3.44841 kg NOx eq
Ozone formation, Terrestrial ecosystems	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			3.52568 kg NOx eq
Stratospheric ozone depletion	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			0.00026 kg CFC11 eq
Terrestrial acidification	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			2.92323 kg SO2 eq
Terrestrial ecotoxicity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			6246.11605 kg 1,4-DCB
Water consumption	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			8.05416 m3

Figure 14: Disposable diaper midpoint category analysis



waste handling process - ES

Flow: 1,3-Dioxolan-2-one - Emission to water/unspecified

Impact category: Global warming

Contribution	Process	Required amount	Total result [kg CO2 eq]	Direct contribution [kg CO2 eq]
100.00%	waste handling process - ES	170.17000 kg	797.47785	
100.00%	diaper waste collection process - ES	5005.00000 Item(s)	797.47785	
99.67%	distribution disposable diapers - ES	5005.00000 Item(s)	794.83578	
58.17%	disposable diaper production - ES	5005.00000 Item(s)	463.89036	
22.68%	SAP production - ES	65.06500 kg	180.86237	
12.12%	electricity, high voltage, production mix | electricity, high voltage | Cutoff, U - ES	951.35040 MJ	96.62079	
09.28%	polypropylene production - ES	37.53750 kg	74.01989	1.57471
03.46%	polyurethane production - ES	5.00500 kg	27.60207	0.25526
03.37%	fluff pulp production - ES	75.07500 kg	26.87806	9.89235
02.57%	polyethylene granulate production - ES	10.01000 kg	20.48133	0.20393
02.10%	cardboard production - ES	17.51750 kg	16.72637	0.79356
00.95%	packaging film production - ES	2.50250 kg	7.57275	
00.70%	wooden pallet production - ES	1.00100 kg	5.61800	
00.64%	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | (	100.10000 MJ	5.13504	
00.30%	acrylonitrile-butadiene-styrene production - ES	0.50050 kg	2.36915	2.06162
00.00%	water production, deionised | water, deionised | Cutoff, U - Europe without Switzerland	10.01000 kg	0.00455	
41.50%	transport, freight, lorry 16-32 metric ton, EURO3 | transport, freight, lorry 16-32 metric tor	2002.00000 t*km	330.94542	238.19347
05.33%	market group for diesel, low-sulfur | diesel, low-sulfur | Cutoff, U - RER	75.77402 kg	42.50192	
03.29%	market for road | road | Cutoff, U - GLO	2.10210 m*a	26.27273	
01.71%	market for lorry, 16 metric ton | lorry, 16 metric ton | Cutoff, U - RER	0.00064 Item(s)	13.64300	
00.91%	market for maintenance, lorry 16 metric ton | maintenance, lorry 16 metric ton | Cutoff, U -	0.00064 Item(s)	7.25459	
00.39%	market for road maintenance | road maintenance | Cutoff, U - RER	0.44682 m*a	3.07970	
00.00%	market for tyre wear emissions, lorry | tyre wear emissions, lorry | Cutoff, U - GLO	0.43967 kg	0.00000	
00.00%	market for road wear emissions, lorry | road wear emissions, lorry | Cutoff, U - GLO	0.03821 kg	0.00000	
00.00%	market for brake wear emissions, lorry | brake wear emissions, lorry | Cutoff, U - GLO	0.04438 kg	0.00000	
00.33%	transport, freight, lorry 16-32 metric ton, EURO3 | transport, freight, lorry 16-32 metric tor	15.31530 t*km	2.64208	1.82218

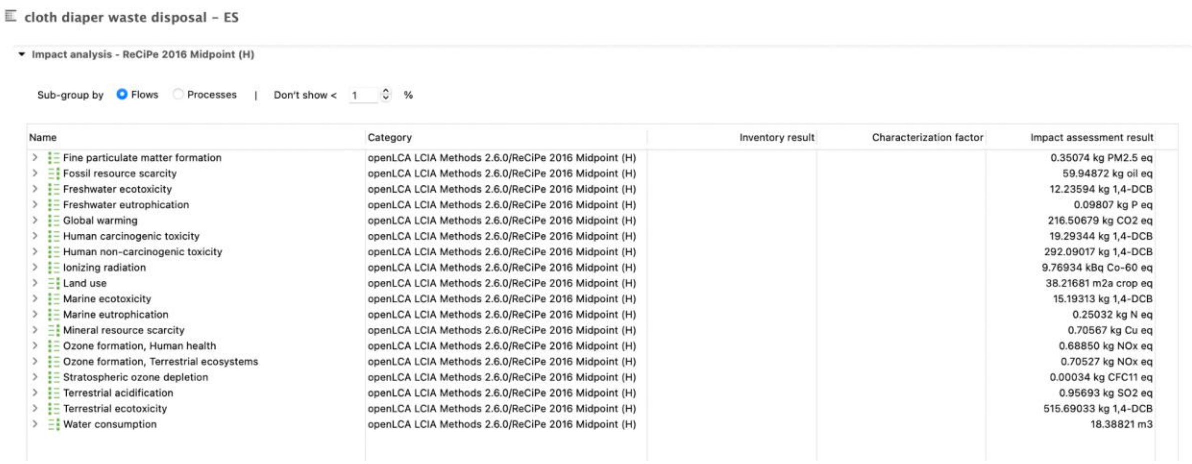
Figure 15: Disposable diaper global warming contribution tree

The Global Warming Contribution Tree provides a detailed overview of greenhouse gas emissions contributions, measured in kg CO_2 eq, during the production, use and final disposal of disposable diapers.

The "waste handling process" has the highest contribution with 797.47 kg CO_2 eq. The "disposable diaper production" has a significant weight on the total (463.89 kg CO_2 eq). This highlights that also the production process is a critical factor, mainly due to energy consumption and the materials used. Associated processes, such as "polypropylene production" (37.54 kg CO_2 eq) and "SAP production" (65.07 kg CO_2 eq), also make significant contributions. The "electricity, high voltage" category adds 96.62 kg CO_2 eq, clearly indicating the importance of energy sources used in production and the high energy consumption during this phase. Additionally, the transportation of diapers and materials has a substantial impact, contributing 330.95 kg CO_2 equivalent.

The results for the substitution scenario are shown in Figure 16. Among the impact categories, “Global Warming” stands out with a value of 216.51 kg CO_2 eq. The “Water Consumption” is also high, reaching 18.39 m³, due to the significant water required not only during the production phase but also for washing cloth diapers. The use of fossil resources remains considerable (59.95 kg oil eq for “Fossil Resource Scarcity”), suggesting that the energy used primarily comes from non-renewable sources, such as oil or gas.

Values like 292.09 kg 1,4-DCB for “Human Non-Carcinogenic Toxicity” and 19.29 kg 1,4-DCB for “Carcinogenic Toxicity” indicate significant effects on human health caused by toxic substances released during the product's life cycle. Additionally, “Freshwater Ecotoxicity” (12.24 kg 1,4-DCB) and “Marine Ecotoxicity” (15.19 kg 1,4-DCB) highlight the sensitivity of aquatic ecosystems to the production and disposal processes of cloth diapers.



cloth diaper waste disposal – ES

Impact analysis - ReCiPe 2016 Midpoint (H)

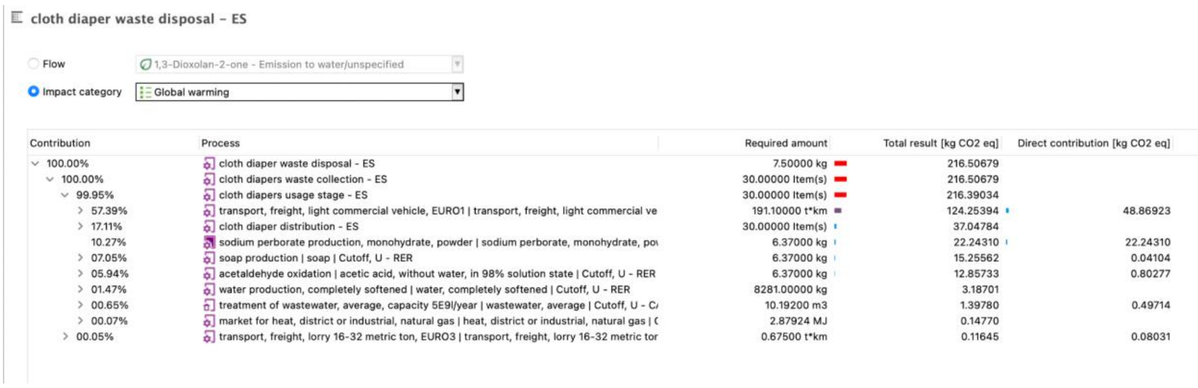
Sub-group by Flows Processes | Don't show < 1 %

Name	Category	Inventory result	Characterization factor	Impact assessment result
Fine particulate matter formation	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			0.35074 kg PM2.5 eq
Fossil resource scarcity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			59.94872 kg oil eq
Freshwater ecotoxicity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			12.23594 kg 1,4-DCB
Freshwater eutrophication	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			0.09807 kg P eq
Global warming	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			216.50679 kg CO2 eq
Human carcinogenic toxicity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			19.29344 kg 1,4-DCB
Human non-carcinogenic toxicity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			292.09017 kg 1,4-DCB
Ionizing radiation	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			9.76934 kBq Co-60 eq
Land use	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			38.21681 m2a crop eq
Marine ecotoxicity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			15.19313 kg 1,4-DCB
Marine eutrophication	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			0.25032 kg N eq
Mineral resource scarcity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			0.70567 kg Cu eq
Ozone formation, Human health	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			0.68850 kg NOx eq
Ozone formation, Terrestrial ecosystems	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			0.70527 kg NOx eq
Stratospheric ozone depletion	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			0.00034 kg CFC11 eq
Terrestrial acidification	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			0.95693 kg SO2 eq
Terrestrial ecotoxicity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			515.69033 kg 1,4-DCB
Water consumption	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Midpoint (H)			18.38821 m3

Figure 16: Cloth diaper midpoint category analysis

Figure 17 illustrates the corresponding global warming contribution tree. The disposal of cloth diapers shows a very high value, amounting to 216.51 kg CO_2 eq. Regarding the usage stage, the percentage of impact related to transportation is 57.33% (124.25 kg CO_2 eq), while the distribution of diapers accounts for 37.05 kg CO_2 eq (17.11%), highlighting how logistics and transportation significantly contribute to the total impact.

Certain processes related to the production of sodium percarbonate (22.24 kg CO_2 eq) and soap (15.25 kg CO_2 eq) represent significant impacts. This reflects the importance of the materials used for washing cloth diapers, which require chemicals with high energy consumption during their production. The energy used during the washing phase has smaller but still non-negligible impacts (1.4 kg CO_2 eq and 1.39 kg CO_2 eq, respectively).



cloth diaper waste disposal – ES

Flow: 1,3-Dioxolan-2-one - Emission to water/unspecified

Impact category: Global warming

Contribution	Process	Required amount	Total result [kg CO2 eq]	Direct contribution [kg CO2 eq]
100.00%	cloth diaper waste disposal - ES	7.50000 kg	216.50679	
100.00%	cloth diapers waste collection - ES	30.00000 Item(s)	216.50679	
99.95%	cloth diapers usage stage - ES	30.00000 Item(s)	216.39034	
57.39%	transport, freight, light commercial vehicle, EURO1 | transport, freight, light commercial ve	191.10000 t*km	124.25394	48.86923
17.11%	cloth diaper distribution - ES	30.00000 Item(s)	37.04784	
10.27%	sodium perborate production, monohydrate, powder | sodium perborate, monohydrate, pov	6.37000 kg	22.24310	22.24310
07.05%	soap production | soap | Cutoff, U - RER	6.37000 kg	15.25562	0.04104
05.94%	acetaldehyde oxidation | acetic acid, without water, in 98% solution state | Cutoff, U - RER	6.37000 kg	12.85733	0.80277
01.47%	water production, completely softened | water, completely softened | Cutoff, U - RER	8281.00000 kg	3.18701	
00.65%	treatment of wastewater, average, capacity 5E9l/year | wastewater, average | Cutoff, U - C/	10.19200 m3	1.39780	0.49714
00.07%	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | (	2.87924 MJ	0.14770	
00.05%	transport, freight, lorry 16-32 metric ton, EURO3 | transport, freight, lorry 16-32 metric tor	0.67500 t*km	0.11645	0.08031

Figure 17: Cloth diaper global warming contribution tree

The comparison between cloth diapers and disposable diapers highlights significant differences in their environmental impacts, particularly regarding Global Warming Potential (GWP), Fossil Resource Scarcity, and Water Consumption. Disposable diapers have a GWP nearly four times higher than cloth diapers, with values of 797.47 kg CO_2 eq compared to 216.51 kg CO_2 eq. This substantial impact is primarily caused by the large-scale industrial production of disposable diapers and the use of fossil-based plastic materials. In contrast, cloth diapers, despite requiring energy and water during their usage phase for washing and drying, achieve a much lower GWP due to their prolonged reusability over time.

When considering Fossil Resource Scarcity, disposable diapers also show a far greater impact, reaching 321.51 kg oil eq, compared to 59.95 kg oil eq for cloth diapers. This difference is largely attributed to the production of plastic materials derived from petroleum, which are integral to disposable diapers. For cloth diapers, the consumption of fossil resources is mainly related to transportation and the production of washing products, such as detergents and sodium percarbonate.

A notable difference also emerges in Water Consumption. Cloth diapers consume 18.39 m^3 of water, a significantly higher value compared to the 8.05 m^3 required for disposable diapers. The washing cycles during the usage stage use a lot of water, but this water can be recovered with the adequate wastewater treatment. Most of the water consumption is required for the distribution in the usage stage. This can be seen in the following figure. It would be interesting to find alternative ways to distribute the diapers in order to reduce its water consumption requirements.

Figure 18: Water Consumption Contributions for Cloth Diaper

3.1.2 Endpoint categories

Additionally, endpoint categories can be discussed and compared. These results are calculated with the Endpoint (H) method in the Open LCA software. Figures 19 and 20 show the impact analysis for endpoint categories. In the Table below, the values are added up to calculate the total impact for damage on ecosystem quality, human healt and resources.

In terms of Ecosystem Quality, disposable diapers cause a biodiversity loss of 4.30*10^{-6} species*year, which is more than double the impact of cloth diapers at 1.57*10^{-6} species*year. This difference is largely due to the higher environmental costs associated with the production of disposable diapers, particularly the extraction of raw materials like petroleum for plastics, which has a severe impact on ecosystems. Cloth diapers, although still contributing to ecosystem degradation, are reusable, which reduces their need for constant new production and results in a lower overall impact.

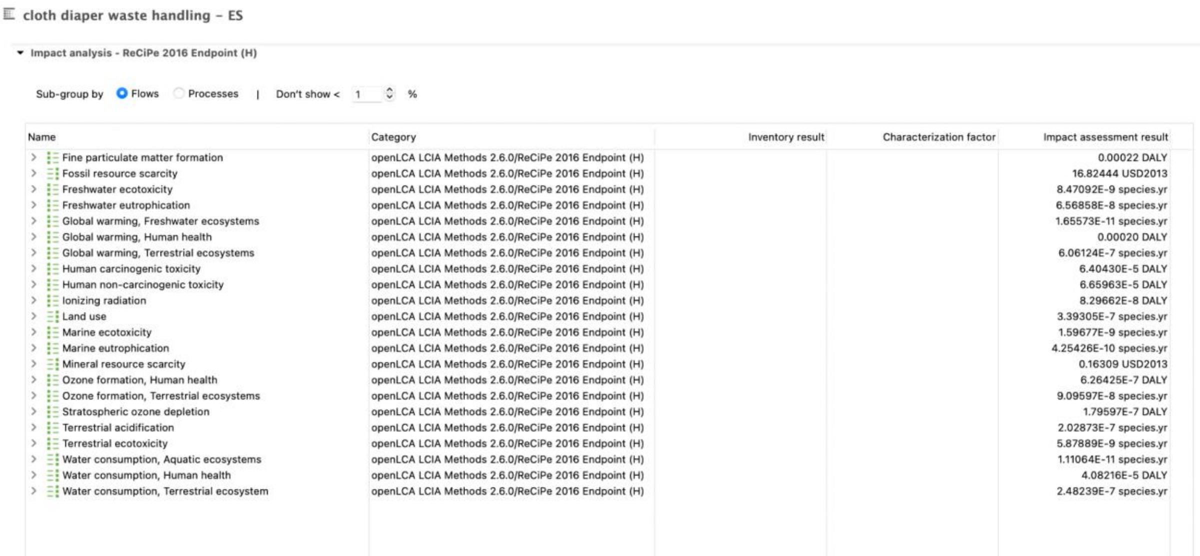
When it comes to Human Health, disposable diapers have a significantly higher impact with a value of 1.93*10^{-3} DALY compared to cloth diapers at 5.92*10^{-4} DALY. The higher impact for disposable diapers can be attributed to the chemicals used in their production, including fragrances and absorbents, as well as transportation emissions. These emissions, particularly from fossil-fuel-powered transport, contribute to air pollution and health risks such as respiratory and cardiovascular diseases. Cloth diapers require less transport because the largest transport distances are in the distribution phase, while the usage stage requires shorter distances. This explains the difference in impact on human health.

In terms of Resources, the difference is even more pronounced. Disposable diapers have a much higher resource depletion, with a total cost of 123.50 USD surplus, compared to cloth diapers at only 16.99 USD surplus. This stark contrast is mainly due to the significant resource requirements in producing disposable diapers, particularly the energy-intensive process of creating plastics and the continuous need for new products. Cloth diapers, while requiring water, detergent, and energy for washing, are more efficient in the long run due to their reusability, leading to a much lower overall resource impact.

Looking at the processes contributing to these impacts, we can see that for disposable diapers, the highest impacts come from the production of petroleum-based materials and the extraction of crude oil. These processes are not only resource-intensive but also contribute significantly to environmental degradation and human health risks due to the toxic chemicals used. In contrast, the major processes for cloth diapers include raw cotton production, which still has an environmental impact, but the reusability of the diapers significantly mitigates their overall effect.

In conclusion, while cloth diapers do have some environmental and resource impacts, they are overall more sustainable than disposable diapers. Disposable diapers cause greater harm to ecosystems, human health, and resources due to their reliance on petrochemicals, high resource consumption, and one-time use. Cloth diapers, by being reusable, result in a smaller overall environmental footprint, making them a more sustainable choice in the long term.

	Ecosystem Quality (species*year)	Human Health (DALY)	Resources ($ surplus)
Disposable Diapers	$4.30*10^{-6}$	$1.93*10^{-3}$	123.50
Cloth Diapers	$1.57*10^{-6}$	$5.92*10^{-4}$	16.99



cloth diaper waste handling – ES

Impact analysis - ReCiPe 2016 Endpoint (H)

Sub-group by Flows Processes | Don't show < 1 %

Name	Category	Inventory result	Characterization factor	Impact assessment result
Fine particulate matter formation	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			0.00022 DALY
Fossil resource scarcity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			16.82444 USD2013
Freshwater ecotoxicity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			8.47092E-9 species.yr
Freshwater eutrophication	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			6.56858E-8 species.yr
Global warming, Freshwater ecosystems	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			1.65573E-11 species.yr
Global warming, Human health	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			0.00020 DALY
Global warming, Terrestrial ecosystems	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			6.06124E-7 species.yr
Human carcinogenic toxicity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			6.40430E-5 DALY
Human non-carcinogenic toxicity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			6.65963E-5 DALY
Ionizing radiation	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			8.29662E-8 DALY
Land use	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			3.39305E-7 species.yr
Marine ecotoxicity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			1.59677E-9 species.yr
Marine eutrophication	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			4.25426E-10 species.yr
Mineral resource scarcity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			0.16309 USD2013
Ozone formation, Human health	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			6.26425E-7 DALY
Ozone formation, Terrestrial ecosystems	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			9.09597E-8 species.yr
Stratospheric ozone depletion	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			1.79597E-7 DALY
Terrestrial acidification	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			2.02873E-7 species.yr
Terrestrial ecotoxicity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			5.87889E-9 species.yr
Water consumption, Aquatic ecosystems	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			1.11064E-11 species.yr
Water consumption, Human health	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			4.08216E-5 DALY
Water consumption, Terrestrial ecosystem	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			2.48239E-7 species.yr

Figure 19: Endpoint categories cloth diapers

disposable diaper waste handling – ES

Impact analysis - ReCiPe 2016 Endpoint (H)

Sub-group by Flows Processes | Don't show < 1 %

Name	Category	Inventory result	Characterization factor	Impact assessment result
Fine particulate matter formation	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			0.00090 DALY
Fossil resource scarcity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			123.17636 USD2013
Freshwater ecotoxicity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			1.29586E-8 species.yr
Freshwater eutrophication	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			1.05160E-7 species.yr
Global warming, Freshwater ecosystems	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			6.09997E-11 species.yr
Global warming, Human health	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			0.00074 DALY
Global warming, Terrestrial ecosystems	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			2.23329E-6 species.yr
Human carcinogenic toxicity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			0.00015 DALY
Human non-carcinogenic toxicity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			0.00012 DALY
Ionizing radiation	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			9.19600E-7 DALY
Land use	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			6.89008E-7 species.yr
Marine ecotoxicity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			2.92831E-9 species.yr
Marine eutrophication	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			6.08267E-11 species.yr
Mineral resource scarcity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			0.32260 USD2013
Ozone formation, Human health	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			3.13817E-6 DALY
Ozone formation, Terrestrial ecosystems	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			4.54806E-7 species.yr
Stratospheric ozone depletion	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			1.35587E-7 DALY
Terrestrial acidification	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			6.19670E-7 species.yr
Terrestrial ecotoxicity	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			7.11930E-8 species.yr
Water consumption, Aquatic ecosystems	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			4.88716E-12 species.yr
Water consumption, Human health	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			1.79123E-5 DALY
Water consumption, Terrestrial ecosystem	openLCA LCIA Methods 2.6.0/ReCiPe 2016 Endpoint (H)			1.07742E-7 species.yr

Figure 20: Endpoint categories Disposable diapers

3.2 Literature comparison

3.2.1 Endpoint categories

In order to validate the results of the Life Cycle Assessments, the results are compared to those of literature. First, the results for the endpoint categories are compared. Only one study was found that clearly stated the impact for endpoint categories: the results of Hoffman et al. (2019) are shown in the Table below. This study's outcome has a lower impact on Human Healt and Ecosystem Quality compared to Hoffman et al. (2019). [3]

	Ecosystem Quality (species*year)	Human Health (DALY)	Resources ($ surplus)
Disposable Diapers (Hoffman et al., 2019)	~ 10^{-4}	~ 10^{-4}	~ 3.5
Cloth Diapers (Hoffman et al., 2019)	~ 10^{-5}	~ 10^{-3}	~ 1.8
Disposable Diapers (this study)	4.30*10^{-6}	1.93*10^{-3}	123.50
Cloth Diapers (this study)	1.57*10^{-6}	5.92*10^{-4}	16.99

Table 9: Comparison of Endpoint Categories Between This Study

Human health impacts are of similar magnitude. Although, this study contradicts the study of Hoffman et al. (2019), where they found that disposable diapers with sanitary landfill have a lower impact on human health. In the other categories, this study agrees with Hoffman et al. (2019) and validate the lower impact of cloth diapers with industrial laundering compared to disposable diapers. The difference in magnitudes however, is quite pronounced. While this study mostly found impacts due to the production and distribution phase, the study of Hoffman et al. (2019) found the end-of-life stage (sanitary landfill) to be the most impactful. This could be due to differences in modelling the LCA. [3]

3.2.2 Midpoint categories

First, the most important midpoint category, namely Global Warming impact, is compared to literature. However, literature mostly discusses results of disposable diapers and not cloth diapers, which makes it hard to validate these values of the study.

The literature comparison, particularly with Hoffman et al. (2019), reveals both alignment and discrepancies. Hoffman et al. (2019) report a range of global warming impacts for disposable diapers between 358 and 774 kg CO_2 eq, which aligns closely with our findings of 797.47 kg CO_2 eq. However, they identify a much higher contribution from end-of-life processes for disposable diapers, particularly in the case of disposal in sanitary landfills, which accounts for 75% of the impact in our study. This contrasts with Aumônier et al. (2008), where only 15% of the overall impact was attributed to disposal. This discrepancy is significant and points to the necessity of more detailed life-cycle inventories for landfill scenarios. [3][26]

Additionally, studies such as Cordella et al. (2015) report a CO_2 eq of 592 kg for disposable diapers, with 29% of the impact coming from end-of-life processes, which include landfill and incineration. Similarly, Mendoza et al. (2019) report 412 kg CO_2 eq, with around 30% of the emissions originating from the end-of-life stage. These studies align more closely with the findings in Aumônier et al. (2008), where landfill scenarios are modeled with less emphasis on end-of-life emissions. The significant difference in results across studies suggests that further investigation is needed, particularly regarding the impacts of different waste management strategies, to refine global warming impact calculations for disposable diapers. However, it can be concluded that results from this study have realistic values. The difference in contributions of phases to the global warming is an interesting subject for further research. [2][8][26]

The second midpoint category which is compared to literature is Water Depletion or Consumption. In Hoffman et al. (2019), the water depletion for disposable diapers amounted to over 300 m^3 for the production of 4550 diapers, with more than 80% of this water depletion attributed to the diaper production phase. A significant portion of this impact, over 50%, is caused by the production of Super Absorbent Polymers (SAP). Cloth diapers, depending on the laundry method, exhibit higher water depletion. When washed with synthetic detergents, the water depletion for cloth diapers exceeds 450 m^3, while for natural soap, the depletion rises to over 500 m^3. However, when industrial laundering (IL) is used, the water depletion for cloth diapers is reduced to under 300 m^3, which is comparable to the water depletion of disposable diapers. [3]

In contrast, this study reports that cloth diapers consume 18.39 m^3 of water, significantly higher than the 8.05 m^3 required for disposable diapers. These values are much lower than the values of the study of Hoffman et. al (2019). The impact of the production phase and the SAP production is much less impactful in this study. Further research in the difference in Water Consumption can be useful to find explanations for this difference. [3]

The table below shows an overview of the comparison of the midpoint categories with literature.

Study	Global Warming Potential (kg CO_2 eq.)	Water Consumption (m^3)
This Study (Cloth)	216.51	18.39
This Study (Disposable)	797.47	8.05
Hoffman et al. 2019 (cloth)	358 - 774	< 300 (Industrial laundering) > 450 (Other Washing Methods)
Hoffman et al. 2019 (Disposable)	358 - 774	> 300
Cordella et al. 2015 (Disposable)	592	/
Mendoza et al. 2019 (Disposable)	412	/
Aumônier et al. 2008 (Disposable)	550	/

Table 10: Comparison of Global Warming Potential and Water

3.3 Life Cycle Costing results

The following results are found :

NPV (disposable diapers) = 2346,37 $
NPV (reusable cloth diapers) = 1979,83 $

So **NPV (reusable cloth diapers) < NPV (disposable diapers)**

This LCC analysis and NPV results make it possible to conclude that reusable cloth diapers are more economically favorable and moreover, have a less important initial investment than for disposable diapers. So economically speaking, cloth diapers are the best solution for all the new parents who want to be economically responsible and do some savings, while considering environmental issues.

3.4 Business model results

3.4.1 Ecosystem of stakeholders

The Value Creation Ecosystem focuses on the industrial washing process of reusable diapers, combined with a home pick-up and delivery service. This model offers a sustainable and user-friendly solution for parents while fostering a coordinated network among various stakeholders.

In this system, parents play a central role by providing dirty diapers and receiving sanitized, high-quality ones. Logistics providers manage the pick-up of used diapers from households and deliver clean ones back to parents. The industrial laundering facility ensures that the diapers are thoroughly cleaned and sanitized, maintaining high hygiene standards. Additionally, new reusable diapers are supplied by manufacturers who provide parents with high-quality products in exchange for payment.

The flow of value within the ecosystem is dynamic and interconnected. Parents pay logistics providers for the pick-up and delivery service, and industrial laundering facilities for the sanitizing process. In addition to these cash flows, families pay for new diapers to manufacturers.

The accompanying diagram (Fig.21) visually represents this ecosystem. It depicts the key stakeholders (parents, logistics providers, the industrial laundering facility, diaper manufacturers) connected through arrows that illustrate the flow of value and operational processes. This visualization highlights the efficiency and sustainability of the ecosystem, which aims to reduce waste while offering a convenient and reliable service for families.

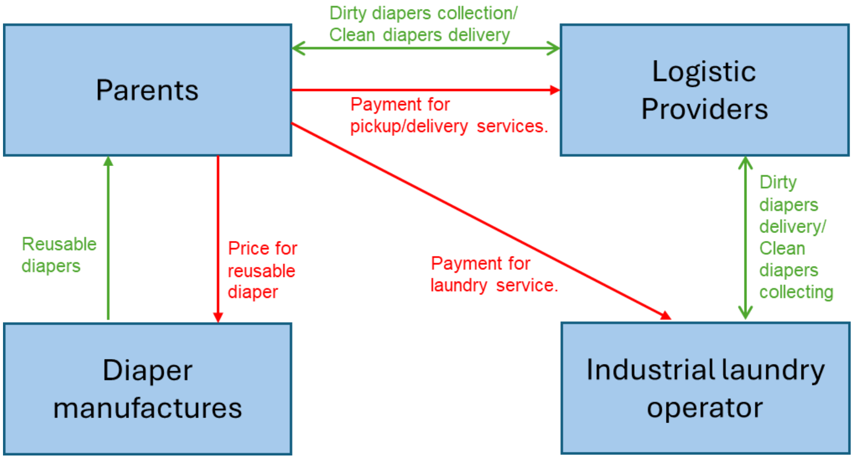


Figure 21: Value creation ecosystem

3.4.2 Business analysis

The following business canvas (Fig.22) is drafted for the scenario described above, so in the case of an industrial laundering process for cloth diapers, with home pick-up and delivery service.

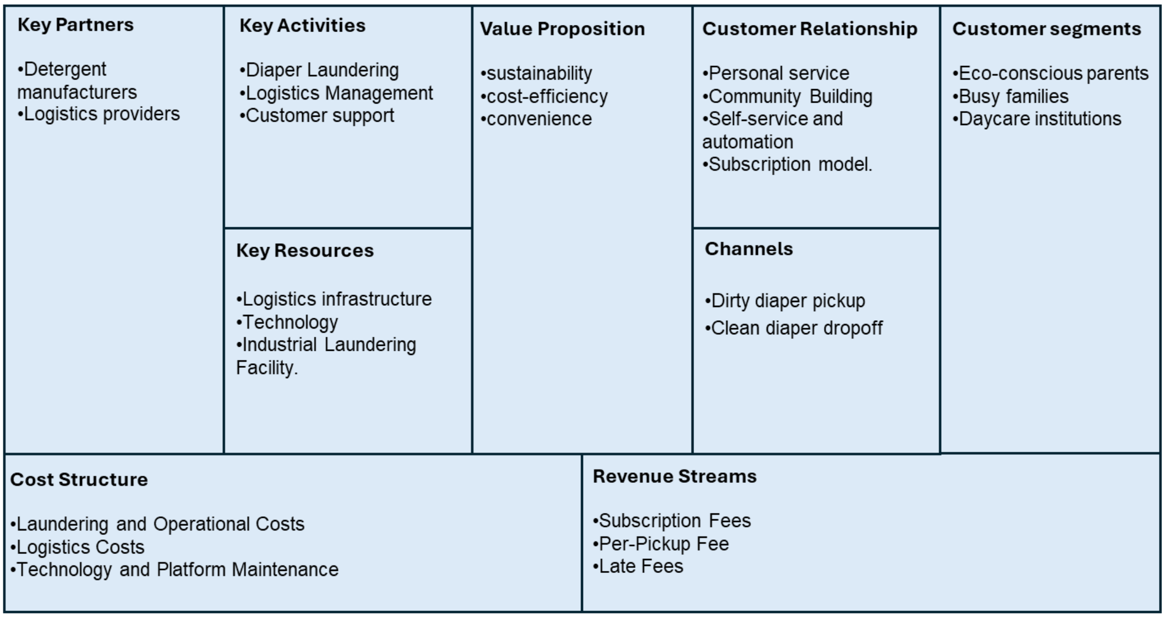


Figure 22: Business Model canvas

The business model canvas outlines a comprehensive strategy for a reusable diaper service, focusing on sustainability, cost-efficiency, and convenience. The value proposition is built on these pillars, aiming to meet the needs of eco-conscious parents, busy families, and eventually daycare institutions who prioritize environmentally friendly and practical solutions for diapering.

Customers can access the service through two primary channels: a convenient pick-up of dirty diapers and home delivery of clean ones. Relationships with customers are cultivated through personalized services, such as flexible pick-up options, and a subscription model that ensures regular diaper deliveries and laundering services. In addition, the business fosters a sense of community among parents by offering forums, newsletters, and social media platforms where they can share tips and promote sustainable practices. Self-service and automation also play a role, allowing parents to request pick-ups or drop off diapers at their convenience.

Revenue is generated through multiple streams, including subscription fees for regular services, per-pickup fees for on-demand options, and late fees for missed service windows. This diversified approach caters to a variety of customer preferences, ensuring both flexibility and steady income.
The business relies on key resources such as a robust logistics infrastructure for efficient delivery and collection, and a centralized industrial laundering facility equipped with advanced washing systems. Technology is another critical resource, supporting subscription management, customer interactions, and order tracking while also providing educational content about sustainability.

Key activities include the laundering process, which ensures the professional washing, sanitizing, and quality control of diapers to maintain hygiene and durability, as well as logistics management to coordinate pick-up and delivery schedules efficiently. Customer support is integral to maintaining satisfaction and retention.

Partnerships with detergent manufacturers and eco-friendly logistics providers strengthen the business's operations, ensuring that all aspects of the service align with its sustainability goals. The cost structure reflects the primary expenses of laundering and logistics operations, technology and platform maintenance, and the management of the industrial laundering facility.

Using the parameters specific above, the estimated market opportunity for the reusable diaper laundering service in Barcelona is approximately 354,740 € over the considered period, as shown below.

$$8{,}269\ babies \times 0.1 \times 14.3\ \frac{€}{Month \times Baby} \times 30\ Months = 354{,}740€$$

Several factors could impact the market size for a reusable diaper laundering service. One of the key elements is the penetration rate; if more families choose to adopt reusable diapers, the market size could expand significantly. The willingness of parents to embrace eco-friendly alternatives, especially as sustainability awareness grows, will play a crucial role in determining the potential customer base. Another important factor is pricing. If the cost of the service is adjusted, either higher or lower, it will directly influence the market opportunity. A lower price could attract a larger customer base, but it might also affect profitability, while a higher price could reduce demand. Additionally, competition and substitutes pose significant risks to the market size. The presence of alternative solutions, self-laundering, could limit the adoption of the industrial laundering service. As these factors evolve, they will either expand or contract the potential market, requiring continuous monitoring and adaptation of the business strategy.

There are several key barriers and risks that must be considered when capturing the market opportunity for a reusable diaper laundering service.

- Customer Adoption: The primary barrier is convincing parents to switch from disposable to reusable diapers, particularly when the latter requires additional effort for cleaning and storage. Despite growing environmental awareness, the initial inconvenience of reusable diapers may deter some potential customers.

- Operational Costs: Running an industrial laundry facility involves substantial operational costs, including energy, water, and detergent. The process of collecting, washing, and delivering diapers requires efficient logistics, and any inefficiencies could lead to increased costs and lower profitability.

- Logistical Complexity: Coordinating the collection and delivery of diapers at scale is a logistical challenge, especially in urban areas with dense populations like Barcelona. Delays or service failures could undermine customer trust and satisfaction.

- Regulatory Compliance: The business must adhere to strict hygiene and health regulations related to handling, washing, and sanitizing diapers. Non-compliance with these standards could result in legal risks and reputational damage.

- Market Penetration: Achieving the estimated 10% market penetration may prove difficult if consumer interest does not meet expectations. Misjudging demand could result in underutilized capacity, leading to inefficiencies.

- Sustainability Concerns: While the business focuses on sustainability, it must ensure that its operations (such as energy use and transportation) are environmentally friendly to avoid criticism for not aligning with its eco-conscious value proposition.

3.4.3 Strategy canvas

Here is a comparative table (Tab. 11) in the form of a Strategy Canvas, created to compare two of the most popular global brands in their respective categories: Pampers (disposable diapers) and Superbottoms (cloth diapers).

Category	Pampers (disposable)	Superbottoms (Cloth)
Price	High	Low
Number of commercials	High	Low
Strong Brand	High	Medium
Symbol of status	High	Low
Environmental impact	Low	High
Convenience	High	Medium
Durability	Low	High
Healt and safety	Low	High
Product range	High	Medium

Table 11: Strategy canvas. High: Indicates an area in which the company excels. Medium: Indicates an area in which the

Pampers and Superbottoms differ significantly in several key aspects, as illustrated in this comparison. Pampers ranks high in price due to its convenience and widespread availability, although its long-term cost is higher since disposable diapers are single-use. In contrast, Superbottoms, while having a higher upfront cost, saves money over time because they are reusable and can be used for multiple children.

In terms of advertising, Pampers benefits from a substantial marketing budget, with frequent commercials across TV, online, and print media, reinforcing its brand presence globally. Superbottoms, as a smaller and more niche brand, relies on organic and community-driven marketing, such as word of mouth, social media, and educational campaigns. Pampers is globally recognized and associated with convenience and quality, giving it strong brand equity, whereas Superbottoms, though growing in popularity, appeals primarily to eco-conscious families and is not yet as established. It is well known that disposable diapers are widely available in most supermarkets, pharmacies, and baby stores. In contrast, reusable diapers are typically found in specialized shops, eco-friendly boutiques, or through e-commerce platforms.

Pampers often carries a sense of status due to its premium positioning and extensive market penetration. In contrast, Superbottoms has a lower perceived status, though it is valued among sustainability-oriented consumers. From an environmental perspective, Pampers scores poorly due to its single-use nature, contributing significantly to landfill waste. Superbottoms, on the other hand, scores highly for its reusability and eco-friendly focus, including sustainable production and packaging.

Convenience is another area where Pampers excels, offering a disposable option that requires no maintenance. Superbottoms is less convenient due to the need for regular washing and sanitizing, although its long-term benefits appeal to certain families. Regarding durability, Pampers is designed for single-use, making it less sustainable and cost-effective, whereas Superbottoms’ cloth diapers are built for long-term use and can serve multiple children.

In health and safety, Superbottoms stands out for its natural, chemical-free materials, which minimize the risk of skin irritation. Pampers, while trusted by many, faces concerns about chemicals in disposable diapers that could potentially harm sensitive baby skin. In terms of product range, Pampers offers a wide variety of diapers and related products, whereas Superbottoms focuses primarily on reusable diapers and accessories, catering to a more niche market.

The comparison highlights Pampers' dominance in brand recognition, convenience, and perceived status, making it the preferred choice for many families. However, Superbottoms appeals to a growing segment of environmentally conscious parents, offering a sustainable, cost-effective, and health-conscious alternative. As sustainability continues to gain importance among consumers, Superbottoms is well-positioned to capture a larger market share in the coming years, particularly as families shift toward eco-friendly, long-term solutions over convenience-driven choices.

In conclusion, Superbottoms can improve its competitive position by focusing on brand visibility, convenience, and product variety while maintaining its commitment to sustainability and consumer education. By addressing these areas, the brand can attract a broader audience, including those currently hesitant to switch to cloth diapers. This balanced approach can help Superbottoms grow its market share and reinforce its status as a leader in the sustainable parenting market.

4 Conclusion

This study demonstrates that cloth diapers, despite their higher water consumption during the usage phase, present a more sustainable alternative to disposable diapers in terms of global warming potential, resource depletion, impact on human health and ecosystems and long-term economic benefits. The Life Cycle Assessment reveals that disposable diapers have significantly higher impacts across several categories, particularly in global warming and resource use, due to the heavy reliance on petroleum-based materials, single-use design and larger transport contributions. Conversely, cloth diapers, through their reusability, lower the overall environmental footprint, especially in global warming potential.

From a Life Cycle Costing (LCC) perspective, cloth diapers prove to be more cost-effective over time due to their reusability, lower resource consumption, and minimal disposal costs. In contrast, disposable diapers incur continuous costs related to production, use, and disposal, making them more expensive in the long term. Additionally, the initial investment of cloth diapers is lower than those of disposable ones. This analysis underscores the importance of considering both environmental and financial aspects when assessing diaper systems.

Incorporating the business model approach, this study highlights how businesses in the diaper industry can optimize their operations to align with sustainable practices. The findings of this study provide crucial insights for stakeholders in the diaper industry seeking to implement more sustainable practices. It also offers a comprehensive business framework that supports the development of diapering systems that are both economically viable and environmentally responsible, encouraging businesses to integrate sustainability into their core strategies for long-term success.

In conclusion, this study emphasizes that a shift towards cloth diapers, supported by innovative business models and improved laundering technologies, can contribute to significant environmental and economic benefits. Companies that embrace sustainability in their strategies will not only benefit the environment but also enhance their market position by offering responsible and long-term solutions to diapering needs.

References

[1] Ng, F. S.F., Muthu, S. S., Li, Y., & Hui, P. C.L. (2013). A Critical Review on Life Cycle Assessment Studies of Diapers. Critical Reviews in Environmental Science and Technology, 43(16), 1795-1822. http://dx.doi.org/10.1080/10643389.2012.671746

[2] Cordella, M., Bauer, I., Lehmann, A., Schulz, M., & Wolf, O. (2015). Evolution of disposable baby diapers in Europe: Life cycle assessment of environmental impacts and identification of key areas of improvement. Journal of Cleaner Production, 95, 322-331. https://doi.org/10.1016/j.jclepro.2015.02.040

[3] Hoffmann, B. S., Morais, J. de S., & Teodoro, P. F. (2019). Life cycle assessment of innovative circular business models for modern cloth diapers. Journal of Cleaner Production, 249, 119364. https://doi.org/10.1016/j.jclepro.2019.119364

[4] O'Brien, K., Olive, R., Hsu, Y.-C., Morris, L., Bell, R., & Kendall, N. (2009). Life cycle assessment: Reusable and disposable nappies in Australia. Environmental Engineering, School of Engineering, The University of Queensland, Brisbane.

[5] Ismaeilimoghadam, S., Sheikh, M., Taheri, P., Maleki, S., Resalati, H., Jonoobi, M., Azimi, B., & Danti, S. (2022). Manufacturing of fluff pulp using different pulp sources and bentonite on an industrial scale for absorbent hygienic products. Molecules, 27(15), 5022. https://doi.org/10.3390/molecules27155022

[6] González-García, S., Hospido, A., Moreira, M. T., Romero, J., & Feijoo, G. (2009). Environmental impact assessment of total chlorine free pulp from Eucalyptus globulus in Spain. Journal of Cleaner Production, 17(14), 1331–1339. https://doi.org/10.1016/j.jclepro.2009.02.002

[7] Mendoza, J. M. F., D'Aponte, F., Gualtieri, D., & Azapagic, A. (2019). Disposable baby diapers: Life cycle costs, eco-efficiency, and circular economy. Journal of Cleaner Production, 211, 455–467. https://doi.org/10.1016/j.jclepro.2018.11.146

[8] González Lorente, Á., Hernández López, M., Martín Álvarez, F.J., & Mendoza Jiménez, J. (2020). Differences in Electricity Generation from Renewable Sources from Similar Environmental Conditions: The Cases of Spain and Cuba. Sustainability 12, 5190. https://doi.org/10.3390/su12125190

[9] ExxonMobil. (2024). Innovate new levels of comfort, fit, and barrier performance with our hygiene solutions [Factsheet]. ExxonMobil. Retrieved from https://exxonmobilchemical.com

[10] Ismaeilimoghadam, S., Sheikh, M., Taheri, P., Maleki, S., Resalati, H., Jonoobi, M., Azimi, B., & Danti, S. (2022). Manufacturing of fluff pulp using different pulp sources and bentonite on an industrial scale for absorbent hygienic products. Molecules, 27(15), 5022. https://doi.org/10.3390/molecules27155022

[11] González-García, S., Hospido, A., Moreira, M. T., Romero, J., & Feijoo, G. (2009). Environmental impact assessment of total chlorine free pulp from Eucalyptus globulus in Spain. Journal of Cleaner Production, 17(14), 1331–1339. https://doi.org/10.1016/j.jclepro.2009.02.002

[12] Aneta Chabowska, Natalia Jatkowska, Paweł Kubica, Justyna Płotka-Wasylka. (2023). Exposure scenario and risk assessment of infants and newborns to bisphenols and their derivatives from diapers. Ecotoxicology and Environmental Safety, 262, 115351. https://doi.org/10.1016/j.ecoenv.2023.115351

[13] ExxonMobil. (2024). Innovate new levels of comfort, fit, and barrier performance with our hygiene solutions. [Factsheet]. Retrieved from https://exxonmobilchemical.com

[14] González Lorente, Á.; Hernández López, M.; Martín Álvarez, F.J.; Mendoza Jiménez, J. (2020). Differences in Electricity Generation from Renewable Sources from Similar Environmental Conditions: The Cases of Spain and Cuba. Sustainability 12, 5190. https://doi.org/10.3390/su12125190

[15] RBAC. (n.d.). Spain's role as a natural gas importer and re-exporter. Retrieved December 17, 2024, from https://rbac.com/spains-role-as-a-natural-gas-importer-and-re-exporter/

[16] Zauba. Import analysis of deionized water under HS code 84219900. Retrieved June 17, 2024, from https://www.zauba.com/importanalysis-deionized+water/hs-code-84219900-report.html

[17] Van der Velden, N. M., Patel, M. K., & Vogtländer, J. G. (2014). LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane. International Journal of Life Cycle Assessment, 19(2), 331–356. https://doi.org/10.1007/s11367-013-0626-9

[18] ReportLinker. Country reports: Deionized water market. Retrieved June 17, 2024, from https://www.reportlinker.com/clp/country/15690/726363

[19] Deshmukh, G., & Manyar, H. (2021). Production pathways of acetic acid and versatile applications in the food industry. In T. P. Basso, T. O. Basso, & L. C. Basso (Eds.), Biotechnological applications of biomass. InTechOpen. https://doi.org/10.5772/intechopen.92289

[20] Defra - Department for Environment, Food and Rural Affairs, Giraffe Innovation Ltd (UK) Professor Robert Holdway FRSA FIEMA, Mark Dowling (Technical Director), EV0493. (2023). Life Cycle Assessment (LCA) of Disposable and Reusable Nappies in the UK. 15724_EV0493_NAPPY_LCA_REPORT_FINAL.pdf

[21] UNEP Report on Disposable and Reusable Diapers. (2021).

[22] Norasnursery.com. Understanding Laundry Costs for Cloth Diapers. Retrieved from https://norasnursery.com/blogs/how-to/making-cents-of-washing-cloth-diapers-understanding-laundry-cost-per-load

[23] Bettina Susanne Hoffmann. (2019). Life Cycle Assessment of innovative circular business models for modern cloth diapers. Journal of Cleaner Production, 249(1525–1539):119364. https://www.researchgate.net/publication/337376527_Life_Cycle_Assessment_of_innovative_circular_business_models_for_modern_cloth_diapers

[24] Jason Rector. (2024). The Cost Comparison of Cloth Diapers vs. Disposable. Retrieved from https://babeegreens.com/blogs/blog/the-cost-comparison-of-cloth-diapers-vs-disposable#:~:text=Disposable%20diapers%20are%20convenient%20but%20can%20cost%20a,diapers%20that%20will%20last%20you%20about%20a%20week

[25] Aumônier, S., Collins, M., Garrett, P. (2008). An Updated Lifecycle Assessment Study for Disposable and Reusable Nappies. Environment Agency, Bristol, Great Britain

[26]Ajuntament de Barcelona. (n.d.). *Statistics* - *Population data portal*. Retrieved January 11, 2025, from https://portaldades.ajuntament.barcelona.cat/en/statistics/9xd7sbumfo