Comparative Life Cycle Assessment of Disposable and Reusable Absorbent Mats

Paving the way for product redesign and informed decision-making to promote sustainable healthcare practices

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By

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Preface

This master's thesis delves into the environmental impact of absorbent mats, those often overlooked yet indispensable products employed in hospitals. These absorbent mats, whether disposable or reusable, serve the essential purpose of absorbing patients' bodily fluids, thus, playing a pivotal role in maintaining the standards of hygiene and cleanliness that are paramount in hospitals. This thesis undertakes a comprehensive examination, not only to determine the environmental impact of disposable and reusable absorbent mats, but also to investigate possibilities for absorbent mat redesign enhancements aimed at improving their environmental impact. This research was conducted in response to a request from the Leiden University Medical Centre, which sought to make informed decisions regarding the use of reusable and disposable absorbent mats.

I embarked on this research project fuelled by my enthusiasm for medical devices and sustainability, with a personal aim to broaden my knowledge and delve into areas extending beyond mere technical problem-solving. Despite my initial limited knowledge of methodologies for assessing the environmental impact of products, I take pride in presenting my findings, which have the potential to promote sustainable healthcare practices in the Netherlands and beyond its borders.

I would like to thank my supervisors Jenny Dankelman, Anne van der Eijk, and Kim van Nieuwenhuizen for their excellent guidance and all the support and help I needed during the process of writing my master thesis. I would like to extend special appreciation to Kim for consistently providing me with valuable advice, fresh perspectives, and for her guidance during my time at the Leiden University Medical Center. Also, I want to offer great thanks to Lauran van Oers for advising me on questions regarding Life Cycle Assessment. Lastly, I would like to thank F.W. Jansen and J.C. Diehl for participating in my graduation committee.

In addition, I want to express my gratitude to Luisa Kremer and Claire Millward for supporting me in the writing process of my thesis. Lastly, I want to thank my family and friends who encouraged and supported me throughout the final project of my master's degree.

Moreover, as I reflect on my academic journey at the Delft University of Technology over the past six years, I wish to emphasize that I derived great satisfaction from every moment of my studies. The completion of my master's in Biomedical Engineering may mark the beginning of a further career within academics.

Kind regards,

Bastiaan Alfred Blank

Summary

Absorbent mats, abundantly used in hospitals, are integral to maintaining hygiene and cleanliness by effectively collecting and retaining patient's bodily fluids. Absorbent mats are available as disposable and reusable products. In the Netherlands, predominantly disposable products are used, and approximately 23 million absorbent mats are employed each year. The abundant use contributes to the Dutch healthcare sector’s substantial impact to the country’s greenhouse gas emissions, waste generation, material extraction, water consumption, and land use. Hospitals and policy makers within the healthcare sector striving to implement environmentally sustainable practices, require current data for informed decision-making. Yet, only two studies have determined the environmental impact of absorbent mats; however, critical environmental metrics are lacking and detail on the contributions of life cycle stages are insufficient. This study addresses these issues by conducting a comparative Life Cycle Assessment, examining eighteen environmental metrics of both disposable and reusable absorbent mats. The primary objective is to not only assess the environmental impact across all their life cycle stages but also to facilitate the redesign of these absorbent mats to reduce their environmental impact.

An in-depth cradle-to-grave Life cycle Assessment, utilizing the ReCiPe impact assessment method, was conducted to compare and evaluate the environmental impact of three different disposable absorbent mats and one reusable absorbent mat. The identification of major contributors to their environmental impact, combined with the application of eco-design strategies, facilitated the sustainable absorbent mat redesign. The Life Cycle Assessment findings indicate that reusable absorbent mats are environmentally superior compared to their disposable counterparts, even if the impact of disposable absorbent mats is mitigated by sustainable product redesign. The reusable absorbent mat demonstrates a lower environmental impact score in fifteen out of eighteen environmental metrics when compared to the disposable absorbent mats. The environmental impact of absorbent mats is largest in the use stage for reusable absorbent mats, and in the material production and manufacturing stage for disposable absorbent mats. The redesigned disposable and reusable absorbent mat concepts exhibit a reduced environmental impact, among other factors, attributed to product recycling. Both concepts facilitate recycling by utilizing a single material for the entire absorbent mat, namely wood-derived materials for the disposable redesign and polyethylene terephthalate-derived materials for the reusable redesign.

This study has demonstrated the versatility of Life Cycle Assessment in aiding informed decisions-making and providing valuable insights for sustainable product redesign. The outcomes of the Life Cycle Assessment suggest that hospitals should transition to the use of reusable absorbent mats. Furthermore, the redesign findings offer valuable insights into the environmental benefits achievable through the recycling of medical products.

Contents

Glossary

Acidification: Terrestrial (TAP) - Measures the impact of emissions on terrestrial acidification, primarily from sulfur dioxide emissions (kg SO2-Eq).

Allocation - Method for partitioning the input and/or output of multifunctional unit process to the product system studied.

Background process - Processes or systems that support the product or system under assessment but are not directly measured or analysed; instead, they rely on secondary data sources and databases to estimate their environmental impact.

Burden shifting - The transfer of environmental or social burdens from one life cycle stage, process, or impact category to another within a product system

Characterisation - A phase within the Impact Assessment process where formerly classified environmental flows are quantified by multiplication with a characterisation factor with a common unit.

Classification - A phase within the Impact Assessment process where environmental flows are qualitatively assigned to predetermined impact categories.

Climate Change (GWP) - Assesses the global warming potential of greenhouse gas emissions, particularly carbon dioxide (kg CO2-Eq).

Cradle to grave - A comprehensive scope in life cycle assessment that encompasses the entire life cycle of a product, from its initial extraction of raw materials (cradle) to its ultimate disposal or return to the environment (grave).

Economic flow - The movement of goods, materials, services, energy, or waste from one unit process to another.

Ecotoxicity: Freshwater (FETP) - Evaluates the potential harm to freshwater ecosystems from toxic emissions (kg 1.4-DCB-Eq).

Ecotoxicity: Marine (METP) - Measures the potential harm to marine ecosystems from toxic emissions (kg 1.4-DCB-Eq).

Ecotoxicity: Terrestrial (TETP) - Assesses the potential harm to terrestrial ecosystems from toxic emissions (kg 1.4-DCB-Eq).

Elementary flow - Material or energy that enters or leaves the product system, having been extracted from or discarded into the environment without subsequent human transformation.

Energy Resources: Non-renewable, Fossil (FFP) - Quantifies the consumption of fossil energy resources (kg oil-Eq).

Eutrophication: Freshwater (FEP) - Measures the impact of nutrient release on freshwater eutrophication, particularly phosphorus emissions (kg P-Eq).

Eutrophication: Marine (MEP) - Assesses the impact of nutrient release on marine eutrophication, primarily nitrogen emissions (kg N-Eq).

Foreground process - Specific processes directly related to the product or system under assessment, collected through direct measurements or detailed analysis, and used to determine the product's unique environmental impact.

Functional flow - The material, energy, or waste flows within a unit process in an LCA that represent its intended function or purpose as a product or waste.

Human Toxicity: Carcinogenic (HTPc) - Evaluates the potential carcinogenic effects on human health from toxic emissions (kg 1.4-DCB-Eq).

Human Toxicity: Non-carcinogenic (HTPnc) - Measures the potential non-carcinogenic effects on human health from toxic emissions (kg 1.4-DCB-Eq).

Inventory analysis - The second phase of a Life Cycle Assessment (LCA) in which all the inputs and outputs of the product system under study are collected and quantified.

Impact category - A category that represents an area of environmental concern or issue.

Ionizing Radiation (IRP) - Assesses the impact of ionizing radiation on human health (kg Co-60-Eq).

Land Use (LOP) - Quantifies land use impacts, considering different land types (m2*a crop-Eq).

Life cycle assessment (LCA) - The process of collecting and assessing the inputs, outputs, and potential environmental impact of a product system across its entire life cycle.

Life cycle impact assessment (LCIA) - The phase of life cycle assessment where the potential environmental impact associated with a product system are evaluated based on the compiled data from the inventory analysis

Material Resources: Metals/Minerals (SOP) - Measures the consumption of metal and mineral resources (kg Cu-Eq).

Midpoint method - A characterisation method that offers characterisation impact categories for comparing environmental interventions based on cause-effect chains between emissions.

Multifunctional process - A unit process yielding more than one functional flow.

Normalisation - A step of the LCIA in which the indicator results are expressed relative to well defined reference information.

Ozone Depletion (ODP) - Assesses the impact on ozone layer depletion, primarily from CFC-11 emissions (kg CF-11-Eq).

Particulate Matter Formation (PMFP) - Quantifies the formation of particulate matter and its effects on air quality (kg PM2.5-Eq).

Photochemical Oxidant Formation: Human Health (HOFP) - Measures the impact of photochemical oxidants on human health, particularly nitrogen oxides (kg NOx-Eq).

Photochemical Oxidant Formation: Terrestrial Ecosystems (EOFP) - Assesses the impact of photochemical oxidants on terrestrial ecosystems, primarily nitrogen oxides (kg NOx-Eq).

ReCiPe - A specific life cycle impact assessment method used to evaluate and characterize the potential environmental impact of products or processes across various impact categories.

Reference flow - The quantified unit or function that serves as a basis for comparing different environmental impact in a life cycle assessment study

Unit process - The smallest segment of a product system for which data is gathered.

Water Use (WCP) - Quantifies the consumption of water resources (cubic meter).

1 Introduction

It is undeniable that our climate is changing and that human interventions are driving the current climate crisis [1]. Climate change is impacting everyday life, encompassing extreme weather events, such as hurricanes, destructive wildfires, and heatwaves. Climate change extends beyond ecological concerns to impact socio-economic, geopolitical, and public health domains [1]. In the domain of public health, notable repercussions include an increased incidence of heat-related illnesses, the geographical expansion of diseases like malaria and dengue, and a rise in respiratory and cardiovascular diseases attributed to poor air quality [1]. However, not only does the climate crisis affect the health domain but, paradoxically, the latter also contributes to the climate crisis. The global healthcare sector contributes to 4.4% of the total annual greenhouse gas emission [2]. In Western countries, the healthcare sector's impact can even be higher. For instance, in the Netherlands the healthcare sector contributes to 8% of the respective national greenhouse gas emissions [2], [3]. The impact extends beyond greenhouse gas emissions, for example in the Netherlands, 13% of material extraction, 8% of blue water consumption, 7% of land use and 4% of waste generation originate from the healthcare sector [4]. To enhance sustainability in the Dutch national health sector, the Green Deal Sustainable Care was established in 2015 by the Dutch National Institute of Public Health and the Environment [5]. Within this deal, agreements have been established to enhance sustainability in the healthcare sector, which include the identification of prospects in domains such as food, construction materials, and medical products. In recent decades, there has been a trend towards the use of disposable instead of reusable medical products in hospitals [6]. However, two distinct reviews that investigated the environmental impact of a wide range of disposable and reusable medical products indicate that disposable medical products tend to have a greater environmental impact compared to their reusable counterparts [7], [8].

One such disposable medical product is the absorbent mat, also known as an underpad, disposable sheet, bed sheet, or cellulose mat. For the purpose of this study, it will be consistently referred to as the absorbent mat. The main function of the absorbent mat is to collect and retain body fluids, such as blood, urine and amniotic fluid. The absorbent mat maintains surface dryness beneath the patient, while also ensuring the patient's comfort by keeping the skin dry [9]. Absorbent mats are used abundantly in the healthcare sector. In 2016/2017, the National Health Service of England procured 53 million absorbent mats and for the Netherlands it is estimated that 23 million mats are used annually in Dutch hospitals [10], [11]. Research conducted at the University Medical Centre Groningen and the Leiden University Medical Center (LUMC) indicate that their hospitals use 325,000 and 239,000 mats annually, respectively [12], [13]. Additionally, research conducted by the LUMC in the obstetric ward indicates that, in practice, disposable absorbent mats are frequently misused, such as being used for patient cushioning, or temporarily serving as instrument wrapping paper [14]. Also, when employed for their intended absorption function, these mats are seldomly completely saturated. This, among other factors, contributes to the abundant use of absorbent mats in the Dutch hospitals.

Despite their widespread use within hospitals, the environmental footprint of absorbent mats remains largely unquantified. To date, there have only been two studies conducted that have quantified the environmental impact of disposable and reusable absorbent mats. Both studies suggest that the selection of reusable absorbent mats over disposable absorbent mats reduces the environmental impact [11], [15]. However, one of the studies, a master's thesis, is not publicly available due to an imposed embargo [16]. The second study has solely focussed on six environmental metrics, and furthermore, the absorbent mats under evaluation were considerably smaller in size than the mats used in Dutch hospitals. Unfortunately, detailed data on the environmental impact for each of the life cycle stages of absorbent mats is not publicly accessible. Research on the environmental impact is needed to provide detailed insight into the disposable and reusable absorbent mat's life cycle impacts in order to aid informed decision making within hospital settings, and to facilitate sustainable product design.

The main goal of this study is to determine the environmental impact of disposable and reusable absorbent mats across all stages of their life cycle, and to propose a redesign of those mats with reduced environmental impact. Therefore, this study seeks to address the following research questions:

- What is the environmental impact of reusable absorbent mats compared to disposable absorbent mats?
- What is the environmental impact associated with each of the life cycle stages of reusable and disposable absorbent mats?
- How can the design of reusable and disposable absorbent mats be improved to reduce their environmental impact?

To answer the questions a Life Cycle Assessment (LCA) was conducted on both reusable and disposable absorbent mats, adhering to the ISO standards 14040 and 14044. Additionally, eco-design strategies were applied in the redesign of the absorbent mats. LCA is a standardised methodology that examines a product's environmental impact throughout its life cycle, ideally adopting a 'cradle-to-grave' perspective, which encompasses all life cycle stages from raw material extraction to disposal. This study offers important insights into the life cycle environmental impact of absorbent mats, offering guidance for decision-making in healthcare settings to promote sustainable product selection. The study specifically aims to aid the decision on which absorbent mat to use in the LUMC. Therefore, in addition to other types of disposable and reusable absorbent mats, this study specifically investigates two disposable absorbent mats that are currently being used at the LUMC. Moreover, the subsequent absorbent mat redesign showcases how redesign can mitigate the environmental impact of healthcare products, thus promoting sustainability within the healthcare sector.

The study is organised in the following way: Section 2 describes the typical material composition of absorbent mats; Section 3 describes the methodology followed to perform the LCA analysis, as well as the design methods; Section 4 presents the results obtained from the LCA analysis of the different absorbent mats and their improved design; Section 5 discusses the main outcomes of the LCA analysis and the design process, and presents practical implications for both hospitals and industry. Finally, Section 6 summarizes the conclusions that can be drawn from this study.

2 Background: Typical Material Composition of Absorbent Mats

Absorbent mats are specialised mats designed to soak up and contain liquids, typically used in various settings to manage spills, leaks, and fluids. In healthcare, they are often used to absorb bodily fluids and protect surfaces. These mats can come in disposable or reusable forms, and they play a crucial role in maintaining cleanliness and safety in environments where liquids may be spilled. They belong to the product category 'absorbent hygiene products' (AHP) which also include diapers, menstrual pads, and absorbent bed sheets. They have different shapes and dimensions and can contain additional features such as straps and tapes. However, they all share the same basic functional layers which consist of the top sheet, the acquisition/distribution layer, the soaker, and the bottom sheet, see Figure 2.1 [17]. The layer in direct contact with the outside world, most of the time the skin in healthcare settings, is known as the top sheet. It is typically made of a thin hydrophilic soft sheet that has been designed to rapidly transfer urine and other liquids to the underlying layers. In addition, emollients and antibacterial coatings may be incorporated into the top sheet to protect the skin from irritation and over hydration [18]. The acquisition layer facilitates the transport of liquid away from the skin and evenly distributes it throughout the AHP's soaker. The soaker of AHPs is responsible for initial fast uptake of fluids to prevent leakage and to trap and retain fluids, even under pressure [19]. The soaker of disposable AHPs commonly contains the hydrophilic materials super absorbent polymer (SAP) and wood-derived fluff pulp [19]. SAP is a hydrophilic cross-linked polymer that swells in water to form a gel-like structure able to absorb hundreds of times its own mass [20], [21]. Finally, the bottom sheet is the water-resistant outer layer of AHPs. It is typically made of a plastic sheet that has been laminated onto the bottom of the soaker. Its primary function is to prevent liquid from escaping the AHP [19].

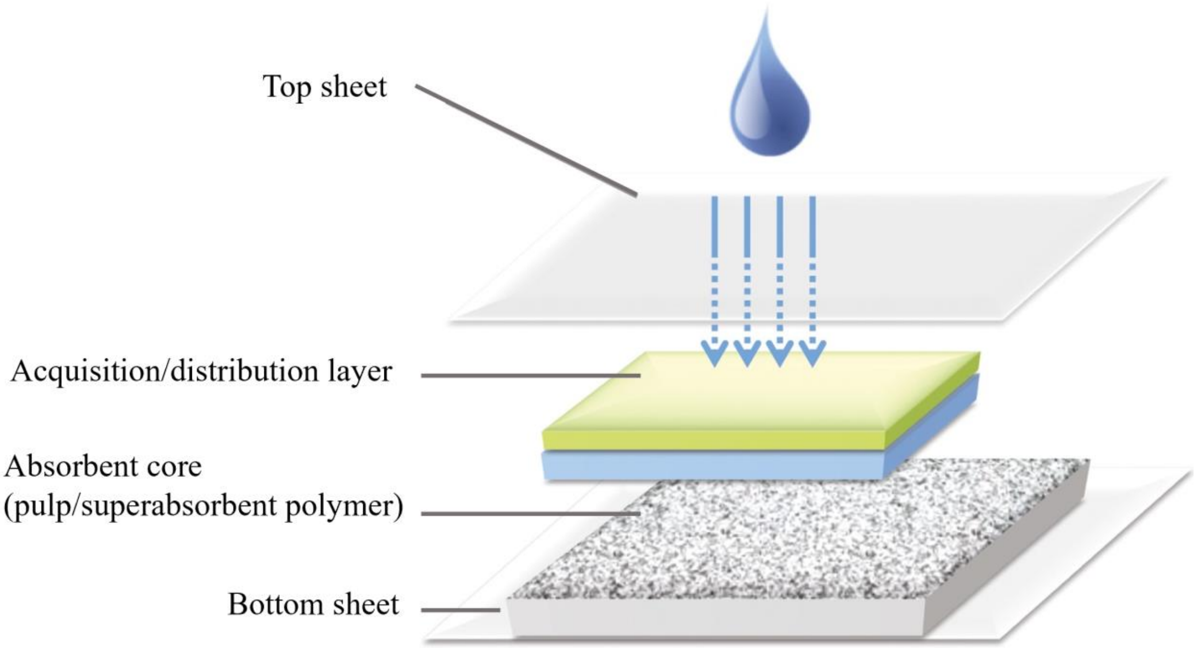

Figure 2.1: Basic functional layers of AHPs, adapted from [22].

3 Methods

The following study was carried out using a methodology that is composed of two distinct stages, namely (1) the LCA of reusable and disposable absorbent mats and (2) the sustainable redesign of the disposable and reusable absorbent mats. This LCA was conducted to compare the environmental impact of disposable and reusable absorbent mats, and to identify hotspots with great environmental impact in both material usage and life cycle stages. Additionally, the results of this LCA were used to aid sustainable product development of the reusable and disposable absorbent mats. The workflow of the study is presented in Figure 3.1.

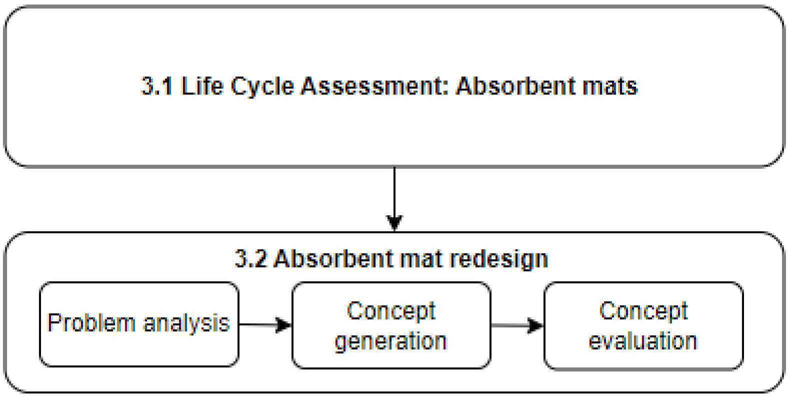

Figure 3.1: Methodology workflow.

3.1 Life Cycle Assessment methods

An LCA was employed as the methodology to quantitatively assess the environmental impact of both reusable and disposable absorbent mats. The LCA was chosen as the most suitable approach for this study due to its ability to compare the environmental impact of products that fulfil the same function, throughout their life cycle, including the extraction of raw materials, manufacturing, transport, use and disposal [23]. By encompassing the entire life cycle of the absorbent mats, LCA avoids the issue of burden shifting [23]. This LCA study followed the established framework of the methodological standards ISO 14040 and ISO 14044, and the Handbook on Life Cycle Assessment [23]–[25]. The systematic and standardised LCA framework comprises four stages: (1) Goal and scope definition, (2) Inventory analysis, (3) Impact assessment, and (4) Interpretation [23], see Figure 3.2.

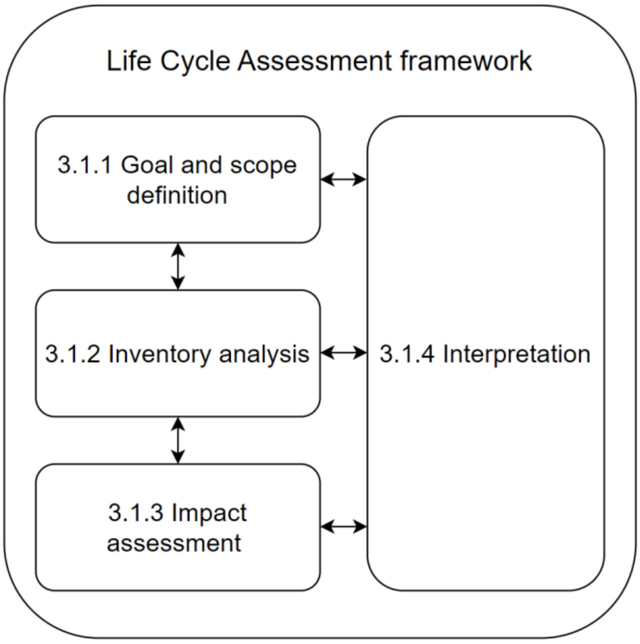

Figure 3.2: Life Cycle Assessment workflow following ISO 14044 and ISO 14040 [24], [25]

3.1.1 Goal and scope LCA methods

The goal of this LCA study was to compare the cradle-to-grave environmental impact of disposable and reusable absorbent mats, and to identify hotspots that had substantial environmental impact, in both material usage and process stages. The intended application of this LCA is to support the decision making on absorbent mat selection in Dutch hospitals and to aid sustainable product development of absorbent mats. The study was conducted by a master's student of Biomedical Engineering (BB, author of this study) from the TU Delft. The commissionaire was the LUMC, and other interested parties were mainly other university medical centres and the suppliers of the absorbent mats. An expert review was not conducted for this study due to limited resources and time constraints.

A simplified LCA was used as the scope of the analysis by conducting a comparative evaluation between disposable and reusable absorbent mats. An attributional approach was adopted which distinguished physical flows to and from the associated product's life cycle in order to identify and quantify the environmental impact. The most recent data for this LCA was collected to represent the present state of technology of absorbent mats and its corresponding processing steps. Regarding the geographical scope of the study, it was assumed that the absorbent mats were used in the LUMC and disposed of in the Netherlands.

To define the functional unit, an evaluation on the practical application of absorbent mats in the LUMC was used. The quantity of absorbent mats employed primarily relies on the subjective judgments of healthcare staff regarding how frequently absorbent mats are required or need to be changed, rather than the absorption of a specific amount of fluid. Absorbent mats are frequently replaced after absorbing as little as 50 grams of fluid, even though they have the capacity to absorb much larger quantities [14]. In order to accurately represent this (mis)use of absorbent mats, the functional unit was defined as the number of absorbent mat uses rather than the absorption of a specific quantity of fluid. For the definition of the functional unit, the clinical performance of the reusable and disposable absorbent mats was assumed to be equal. The function and functional unit were defined as:

- Function: Collect and retain patient's bodily fluids, in order to maintain surface dryness and ensure patient's comfort by keeping the skin dry.

- Functional unit: Utilizing 1000 absorbent mats, each approximately 60x60cm in size, to collect and retain patient's bodily fluids, in order to maintain surface dryness and ensure patient's comfort by keeping the skin dry.

This LCA studied three different disposable absorbent mats and one reusable absorbent mat. The selection of absorbent mats was based on their usage and availability within the network of the LUMC. Within the LUMC, two disposable absorbent mats were in use and easily accessible. The hospital also had access to a reusable absorbent mat through its laundry service provider, as well as a disposable biodegradable mat via 'the green operation room' initiative network. Despite requests, other types of absorbent mats were unavailable. Throughout this study the four different absorbent mats will be referenced to with their anonymised identifiers. Data was made available by industry under the requirement that the provided data could not lead to the identification of the manufacturer, supplier, or brand of the absorbent mat. Therefore, in this study, data leading to the identification was anonymised. The studied absorbent mats together with its anonymised identifiers are listed below in Table 3.1.

Table 3.1: Anonymised identifier and key properties of the studied absorbent mats.

Anonymised identifier	Type	Used in LUMC	Absorption capacity	Dimensions	Biodegradability	Supplier identifier
Disposable A	disposable	yes	570 grams	60x60 cm	non-biodegradable	Supplier A
Disposable B	disposable	yes	330 grams	60x60 cm	non-biodegradable	Supplier A
Disposable C	disposable	no	130 grams	50x48 cm	biodegradable	Supplier B
Reusable A	reusable	no	700 grams	60x60 cm	non-biodegradable	Supplier C

3.1.2 Inventory analysis LCA methods

In this section, the system boundaries, data collection methods, cut-offs, and modelling choices were identified.

System Boundary

This LCA encompassed economic processes across the entire life cycle of the product, commencing from raw material extraction to disposal. The system studied included the (i) Material extraction and production, (ii) Manufacturing, (iii) Use, (iv) End of life, (v) Transport, and (vi) Packaging, see Figure 3.3.

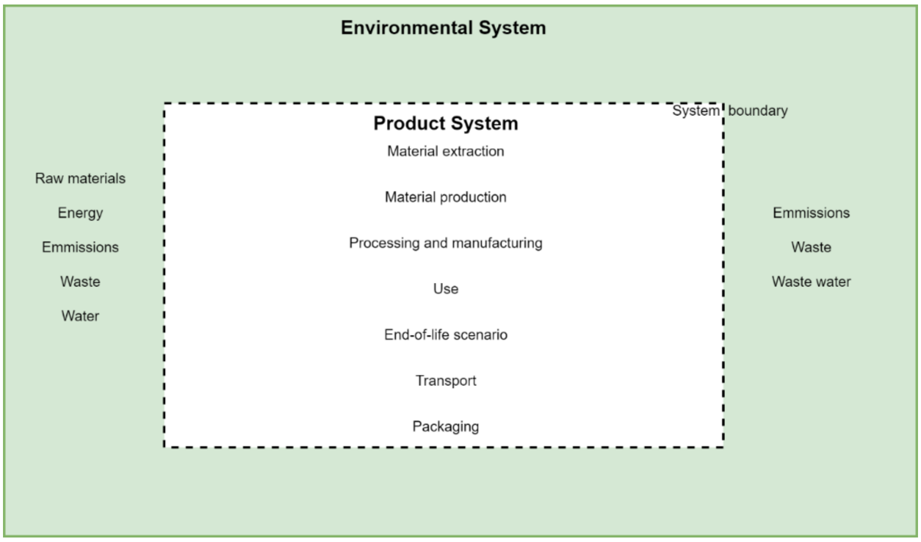

Figure 3.3: Graphical representation of environment-product system boundary.

Flow diagram

For each absorbent mat, a flow diagram was made to provide an outline of the major unit processes including their interrelations with one another. The flow diagrams were made by starting to build the unit processes of the reference flows of each absorbent mat and its adjacent processes. After that, processes producing the main materials and managing the main waste flows followed. To simplify the flow diagrams, several unit processes were merged into one unit process block.

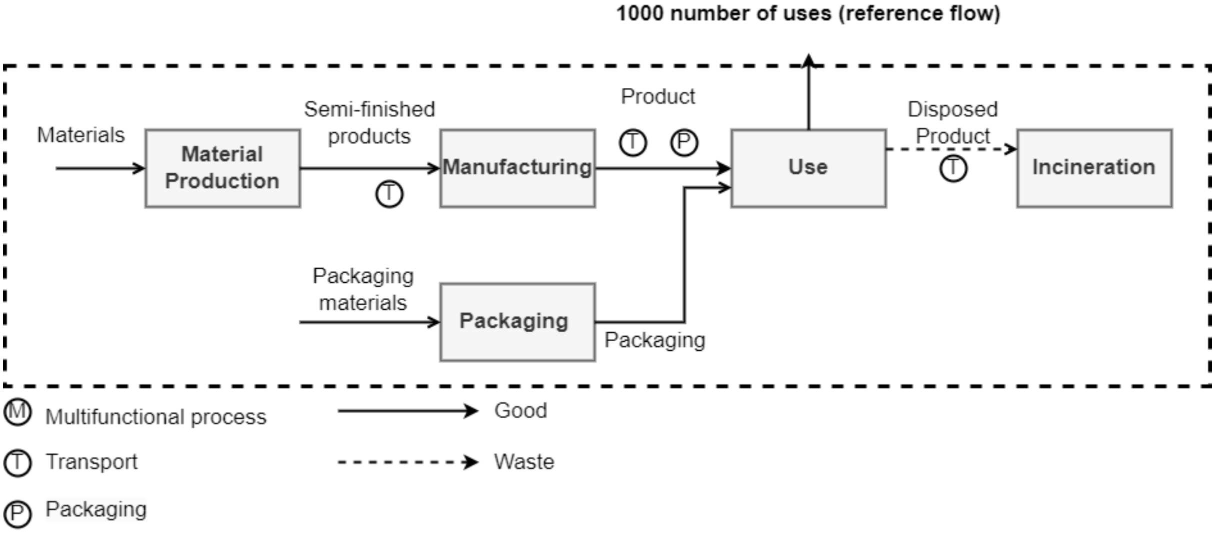

Figure 3.4: Life cycle flow diagram of the Disposable A, Disposable B, and Disposable C.

For the disposable absorbent mats, the uncluttered flow diagrams do not differ from each other, see Figure 3.4. However, the unit process material production includes the unit processes for the production and manufacturing of semi-finished products, such as the top sheet and the soaker, which are specific to the respective absorbent mats. The unit process manufacturing includes the economic flows for the assembly of the semi-finished products into the finished product. The packaging unit process includes the production and manufacturing of the packaging for the finished product that is delivered to the customer. The functional unit for each absorbent mat comes forth from the use unit process. For Reusable A, an additional process 'Washing' is considered, see Figure 3.5. For the end of life, the disposable and reusable absorbent mats are incinerated.

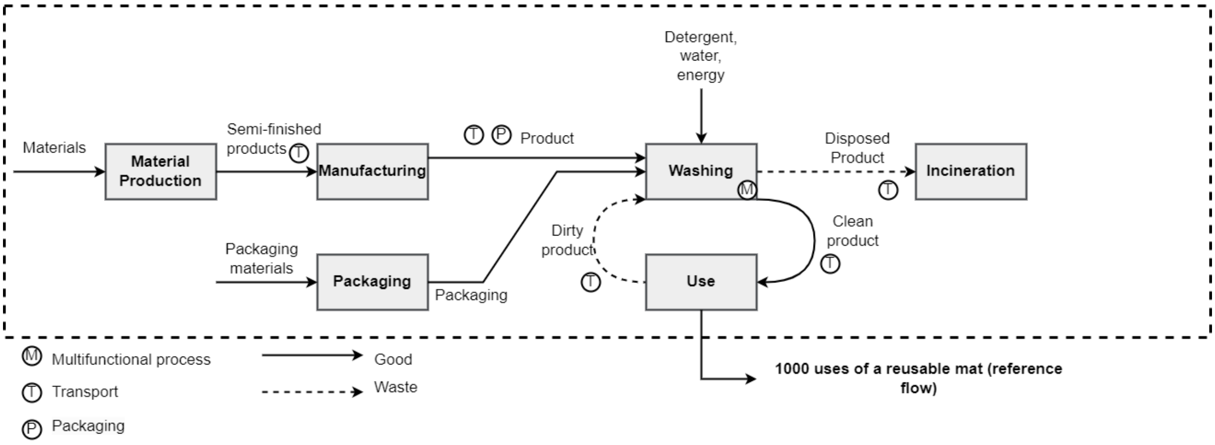

Figure 3.5: Life cycle flow diagram of Reusable A.

Cut-offs and allocation

Cut-offs in LCAs are processes that are considered irrelevant for analysis based on the research goal. These processes were cut off from the product system and their flows were not followed until they become environmental flows. The following unit processes were cut off from the system:

- Capital goods of foreground processes (i.e., machines, process equipment, factory buildings)
- Workforce burdens (i.e., commuting to work)

- Packaging of semi-finished products

Due to the lack of data on capital goods, their use over prolonged periods of time and their use for processes outside the product system, they were excluded. For example, in the case of reusable absorbent pads, washing machines are employed, and their energy consumption during the use stage is approximately 23 times higher as compared to the production stage [26]. It was assumed that machines used within the product system's life cycle have similar outcomes with regards to their environmental impact. Workforce burdens were cut off due to difficulties in allocation, drawing boundaries and obtaining data. Packaging of semi-finished products was also cut-off due to the lack of data. The cut-offs were performed for all absorbent mats and thereby the comparative results will not be noticeably influenced. Allocation for multifunctional processes was avoided by means of modelling choices within the inventory analysis and if allocation could not be avoided, economic allocation based on the value of all resulting functional flows was used [23].

Data collection and data quality

Data gathering for each foreground unit process of the absorbent mats was restricted to economic flows. Data on environmental flows crossing the system boundary were not collected. For following environmental flows that cross the system boundary background processes from the Ecoinvent database, that include environmental flows, were used. Data was gathered from the following sources: (i) Ecoinvent database, allocation, cut-off by classification, version 3.9.1, (ii) Industry data, (iii) Data from measurements, and (iv) Literature data.

For Disposable C, the supplier provided data for the manufacturing (assembly of the semi-finished products), and for Reusable A, data was available for the production of semi-finished products, the manufacturing (assembly of the semi-finished products), and the washing process. For Disposable A and B no industry data was available. To determine the type of material and amount of material of these absorbent mats and to double check the data provided by industry, the author of this study performed multiple material analysis experiments. The type of material was determined through Fourier Transform Infrared Reflectance spectroscopy (FTIR) measurements, which is a technique to determine the chemical composition of materials. The amount of material was determined through mass measurements following a methodology specifically tailored to the absorbent mats under investigation. For details on the performed material analysis experiments see Appendices E and F. To ensure consistency among the gathered data of each absorbent mat, data was collected following a uniform methodology. For the quantification of economic inputs and outputs of unit processes, the following hierarchy was applied ordered from favourable to least favourable: (1) Industry data, (2) Measured or calculated data, (3) Literature data, (4) Estimation based on similar processes, (5) Assumptions, and (6) Missing data.

Because four specific products were investigated, the data were, as far as possible, site-specific, and thus collected from the different suppliers of the products. This was of importance so that the data were representative for the studied absorbent mats. However, where specific data could not be obtained for the unit processes, generic data representing an average of the studied process, were used. To ensure consistency for each common unit process among the products, generic data have been used for all absorbent mats, where specific data could not be obtained for one of the absorbent mats via the above-mentioned hierarchy. All data concerning the production of materials for the semi-finished products and the packaging were non-specific and have been collected from the Ecoinvent database. For manufacturing, specific quantified data, provided by manufacturers and literature on similar processes, was used. For transport, the distance was provided by industry or was calculated from the known locations. For incineration, specific waste treatment processes from the Ecoinvent database were used.

Assumptions data collection

To simplify the modelling, and due to limited time and resources, some assumptions were made throughout the life cycle of the absorbent mats. The soaker and the top sheet of all mats appeared to be of the colour white and therefore bleaching of these materials was assumed. Due to the lack of data on the specific adhesive type used in each absorbent mat, the assumption, based on literature on disposable absorbent hygiene products, was made that polyurethane adhesive was used

[27]. For manufacturing, it was assumed that the energy flows of electricity and gas were high voltage and high pressure to match the industry demand. Additionally, for manufacturing, it was assumed that 4.25% waste was generated for each input material for disposable absorbent mats [27]. For Reusable A, the supplier specified 7% waste generation during manufacturing. It was assumed that the waste was disposed of and that it was not recycled or reused.

The use stage of the disposable absorbent mats did not lead to additional environmental impacts and therefore it was assumed to be negligible [28]. For the use stage of Reusable A, it was assumed that washing was done at full capacity and at standard settings that are also used for hospital linen. Additionally, for all absorbent mats it was assumed that the fluid absorbed by the mat during the use stage in the LUMC had a negligible effect on the overall environmental impact during the life cycle of the absorbent mats.

For packaging, it was assumed that packaging of semi-finished products was negligible and therefore only the packaging of the finished product was included into the life cycle. Furthermore, for the calculation of the total packaging needed for the functional unit, only whole packages were considered. This means that if, for example, 10.33 packages are needed for 1000 disposable absorbent mats, 11 packages are used in the inventory. Based on FTIR material analysis of the plastic packaging of Disposable A it was assumed that all plastic packaging of the absorbent mats was made from the same material.

For transportation, the packaging mass was assumed to be negligible. The transport was incorporated into the separate unit processes. Based on industry data of Reusable A it was assumed that all transport on road was done by a lorry of 7.5-16 metric ton, EURO5. For the production of semi-finished products, it was assumed that they were produced at a different location than the manufacturing location. Transport of the semi-finished products was included in each of the unit processes of the semi-finished products. For the transportation of the finished product, it was assumed that it was directly transported from the manufacturer to the LUMC without a supplier in between. If data on the manufacturing location was absent, the location of the brand's headquarters was used. The transport distance over land was determined with 'Google maps' and over sea with 'Searates' [29], [30]. The longest route was selected for determining the exact kilometres which were rounded to the nearest 10 km.

Based on common practice of waste treatment in the LUMC, it was assumed that disposable absorbent mats were incinerated after one use. Industry partners of Reusable A did not provide data regarding the end of life. Thus, to determine the end of life of Reusable A, literature on textile waste in the European Union (EU) was used. In the EU, 87% of textile waste is incinerated and only 1% of used textile is recycled [31]. Additionally, Reusable A is made from several materials which further hinders recycling. Therefore, it was assumed that Reusable A was also incinerated. For each material of the absorbent mats specific waste treatments for the Netherlands (97% incineration) were used. If no specific treatment of the materials were available generic treatments were used (e.g., plastic mixture instead of polyester).

Furthermore, specific assumptions were made for each of the absorbent mats. The main assumptions are listed in Table 3.2, for detailed assumptions see Appendix B2.

Table 3.2: Main assumptions for each of the absorbent mats.

Absorbent mat	Main assumptions
Disposable A and B	• Economic flows for manufacturing based on LCA literature of disposable diapers.
Disposable C	• Standard viscose from Ecoinvent was used instead of Lenzing viscose[1].
Reusable A	• One reusable mat was disposed of after 100 use cycles. • Washing was done at full capacity and at standard washing settings with standard detergent[2]. • For the transport between the laundry and the LUMC the mass of the rolling container is neglected.

[1]Lenzing viscose is a type of rayon fibre that is produced by Lenzing AG. They claim that their viscose is more sustainable compared to standard viscose [32]. Ecoinvent has no process for Lenzing viscose and no detailed inventory data was available. Thus, standard viscose from Ecoinvent was used.
[2]standard settings refer to settings that are used for hospital (bed)linen. For detailed inputs and outputs of the washing cycle see Appendix A3.

Data modelling

The unit processes of the absorbent mats were modelled in the LCA software Activity-Browser version 2.8.0 [33]. The Activity-browser is an open-source software for LCA that builds on Brightway2. The LCA model, inventory, impact assessment and interpretation were done in Activity-browser. The database 'Allocation, cut-off by classification' version 3.9.1 in the file format 'ecoSpold02' from Ecoinvent version 3.9.1 was imported into the Activity-Browser. Impact categories were imported via the default data available in the Activity-Browser. Products from the Ecoinvent database were used as inputs and outputs of the foreground processes.

To simplify the modelling of the life cycle of the absorbent mats and to avoid allocation a centralised model was selected, see Figure 3.6. With this model, allocation for the washing process of Reusable A was avoided. According to the Handbook on LCA multifunctional processes should be avoided if possible, and modelling should be prioritised whenever feasible as the initial approach for avoiding multifunctionality [23]. Additionally, for all unit processes downstream of the production of semi-finished products, inputs and outputs were adapted to the functional unit of 1000 absorbent mat uses. This means that, for example, for the unit process manufacturing the economic flows were adapted so that the output represented the manufacturing of 1000 absorbent mats. For the unit processes of the semi-finished products the economic flows were adapted so that the output was equal to 1kg of produced semi-finished product.

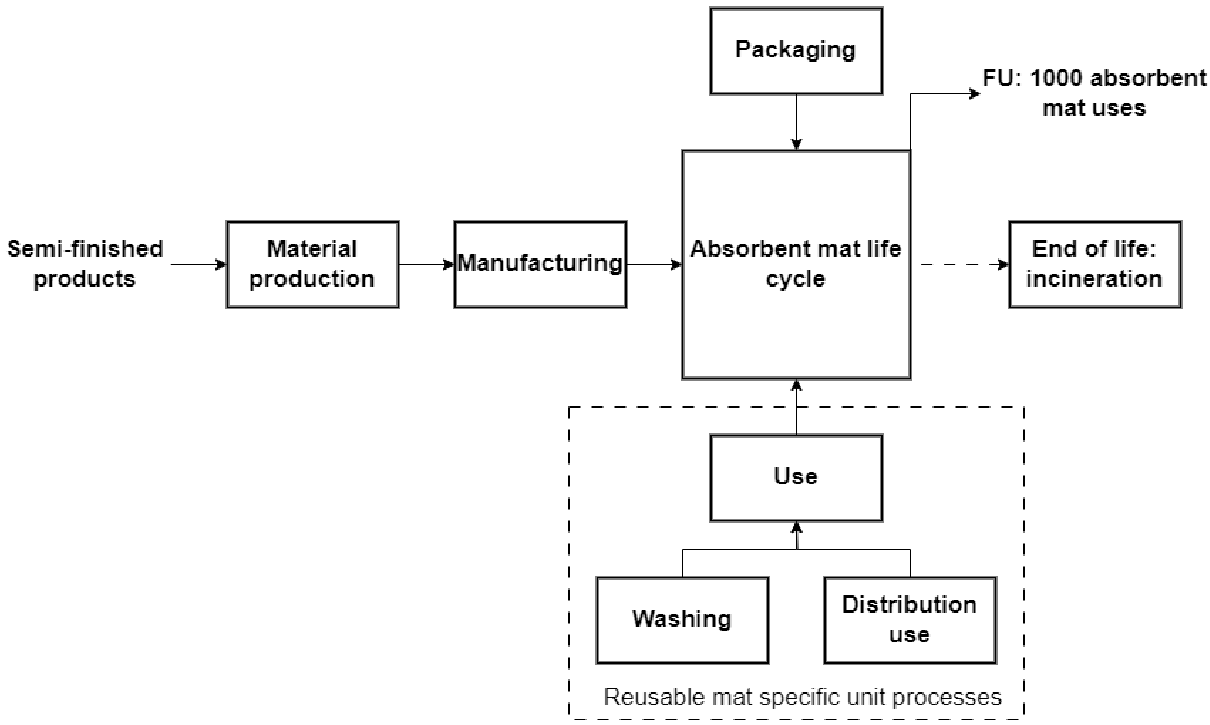

Figure 3.6: Centralised LCA model for the absorbent mats.

3.1.3 Impact Assessment LCA methods

The life cycle impact assessment (LCIA) is the second phase of LCA where the potential environmental impact associated with a product system are evaluated based on the compiled data from the inventory analysis. In order to determine the suitability of an appropriate impact assessment method, the systematic literature review conducted by Keil et al., which examined the environmental impact difference of switching from disposable to reusable healthcare products, was employed as a reference [7]. Most studies about textiles used in healthcare (face masks, scrab suits, protective textiles, and surgical gowns) have used the impact assessment method ReCiPe2016 with midpoint categories [34]–[38]. Healthcare textiles have similar material composition than absorbent mats and are commonly made from polyester, non-woven polypropylene, cotton, and polyethylene. Therefore, in this study the impact assessment method ReCiPe2016 Hierachist with midpoint categories was used, see Figure 3.7 [39].

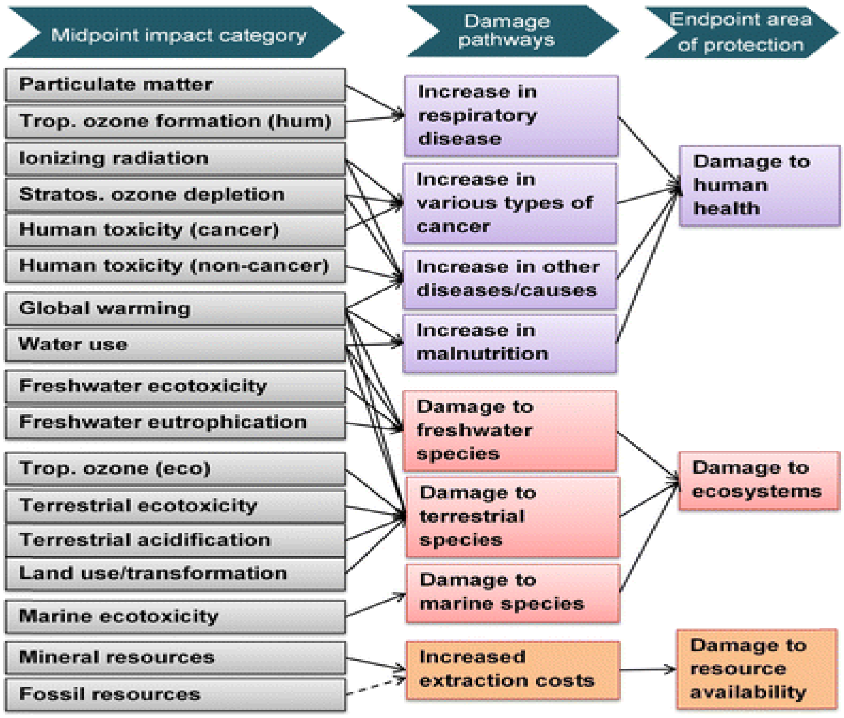

Figure 3.7: Overview of the impact categories of ReCiPe2016 and their relation to areas of protection. Adapted from [39].

The steps classification and characterisation were done in Activity-Browser, and normalisation was conducted manually in an excel spreadsheet with the supplementary data provided in the methodology of ReCiPe2016 [33], [39]. The normalisation is based on the interventions of an average world citizen for the year 2010. For weighting no standard method was provided by ReCiPe2016 and only weighing factors for the endpoint categories are available. Therefore, weighing was omitted from this study [40]. For the presentation of the characterised results, Disposable A was employed as a reference, as it is the standard mat used at the LUMC.

3.1.4 Interpretation LCA methods

The interpretation of the results is the last step of the LCIA. The results were interpreted to assess the soundness and robustness of the assumptions, and the modelling choices that were made in earlier steps. In this study the LCIA results were interpreted through a contribution analysis, sensitivity analysis and a scenario analysis. The sensitivity and scenario analysis were performed at only the characterised midpoint category global warming potential (carbon footprint) measured in CO_2 equivalent. Carbon footprint is commonly used for the sensitivity and scenario analysis of LCAs on healthcare textiles and in several studies, the carbon footprint was the sole impact category measure for analysis [34]–[38]. Additionally, due to limited time and resources only one impact category was chosen. Therefore, in this study's sensitivity and scenario analysis, the carbon footprint was used as sole impact category measure.

Contribution analysis

The contribution analysis identified hotspots and life cycle stages with great environmental impact of the absorbent mats. For the contribution analysis the characterised ReCiPe2016 midpoint impact categories were considered. The contribution analysis was used to identify material and process hotspots. Three levels were considered for the contribution analysis: (i) Level 1 identified life cycle stages with great environmental impact by categorising foreground unit processes into four life cycle stages. The transport to the consuming entity was included in the upstream process, for example, the transport from manufacturer to the hospital was included in the manufacturing stage.

Table 3.3: Life cycle stages and corresponding unit processes for the contribution analysis level 1.

Stage	Unit processes
Material production	Material production, and the processes for production of the semi-finished products
Manufacturing	Manufacturing, and Packaging
Use	Use, Washing, and Distribution use
Disposal	Incineration

(ii) Level 2 analysed the contributions of the background processes to the manufacturing stage of the disposable absorbent mats and to the use stage of the reusable absorbent mat. (iii) Level 3 analysed the contribution of the separate materials to the overall impact of the material production stage.

Sensitivity analysis

Sensitivity analysis was used to determine the robustness of the LCA model by examining how changes in specific input parameters or assumptions influenced the LCIA results of the absorbent mats. For analysis, the baseline carbon footprint of the absorbent mats was compared to the carbon footprint under different sensitivity parameters. For each of the analysed absorbent mats, separate sensitivity parameters were used to evaluate the influence of the main assumptions on the overall carbon footprint.

Disposable A and B

For testing the sensitivity of the main assumptions of Disposable A and B, the quantity (amount) of electricity was chosen as sensitivity parameter. Additionally, the manufacturing inputs and outputs of gas, water, and wastewater were omitted, and the quantitative electricity demand was changed to the value of Disposable C. With this, the main assumption of using disposable diaper manufacturing inputs and outputs can be compared to the manufacturing process of Disposable C. Also, the quality (fossil or renewable) of electricity was changed to test the robustness of the results under different manufacturing conditions and to resemble electricity mixes of different countries. Fossil based electricity and renewable electricity were chosen to be 100% coal and wind energy, respectively. Furthermore, based on measurement inaccuracies, the mass of the materials was increased by 5%. Also, the soaker material was changed to viscose, due to the minimal differences between the FTIR measurements of viscose and softwood.

Disposable C

The main assumption to use standard viscose instead of Lenzing viscose was analysed for sensitivity by decreasing the soaker quantity by two thirds to account for the three times higher environmental impact of standard viscose [32]. This sensitivity analysis should be handled with care as the assumption is made that decreasing the quantity of standard viscose to one third is equal to the manufacturing of Lenzing viscose. Additionally, the soaker material was changed to softwood pulp due to the minimal differences of the FTIR measurements. Furthermore, the quantity (amount) and quality (fossil or renewable) of electricity were chosen as sensitivity parameters.

Reusable A

For testing the sensitivity of the main assumptions of Reusable A, the following parameters were varied: the use cycle of the mat was decreased by 50%, the washing was done at half the capacity, and for transport, the mass of the rolling container was accounted for. For the rolling container, it was assumed that 1000 mats would fit on one rolling container of 60kg [41]. Furthermore, the highest impact inputs for the use cycle were increased by 100%. For the energy demand and for the transport between LUMC and laundry, specific data was used. To apply the results more generally to other hospitals the distance was increased by 100% and set to zero kilometres, respectively. The specific energy inputs are tested by loading the washing machine at half the capacity which is equivalent to doubling the energy inputs.

Scenario analysis

The scenario analysis was used to study the change of the LCA results when multiple inputs were changed at once. The scenario analysis was performed at characterization level and the midpoint category Global Warming Potential (carbon footprint) was selected for analysis. Two scenarios were assessed: (i) Worst- and best-case scenario for each of the absorbent mats, and (ii) Change of characterisation method to CML4.8 (Chain Management Life Cycle Assessment) and EF3.1 (Environmental Footprints). CML and EF are, besides ReCiPe, methods to perform the steps of LCIA.

Worst- and best-case scenario

The scenario analysis was used to compare the carbon footprint of the absorbent mats under a worst- and best-case scenario. These scenarios were used to assess whether the hierarchy between the absorbent mats would change under a particular combination of worst- and/or best-case of the absorbent mats. In this case the hierarchy indicates the quantified carbon footprint of the mats. Table 3.4 specifies the worst- and best-case scenario for each absorbent mat. The choices for the worst- and best-case scenario were based on sensitivity parameters that could be combined and were reasonable applicable to real life scenarios.

Table 3.4: Worst- and best-case scenarios for each of the absorbent mats.

Absorbent mat	Worst-case scenario	Best-case scenario
Disposable A and B	- Electricity manufacturing 100% fossil -Mass of materials increased by 5%	- Electricity manufacturing 100% renewable -Mass of materials decreased by 5%
Disposable C	- Electricity manufacturing 100% fossil	- Electricity manufacturing 100% renewable
Reusable A	- Use cycles decreased by 50% - Washing at half capacity - Electricity washing 100% fossil - Transport distance increased by 100% (240km)	- Electricity washing 100% renewable - Transport distance 0km

Characterisation method scenario

The characterisation method can influence the outcome of the LCA as every method uses different characterisation factors and impact categories. The characterisation method CML4.8 and EF3.1 were used to compare the environmental impact of equivalent impact categories. To compare across impact methods the impact of Disposable B, Disposable C, and Reusable A relative to Disposable A was calculated for each of the impact methods. The relative impacts were compared across impact methods to assess the influence of impact method choice.

3.2 Sustainable redesign methods

The redesign of disposable and reusable absorbent mats was carried out using a methodology composed of three stages: (i) Problem analysis, (ii) Concept generation, and (iii) Concept evaluation, see Figure 3.8. The objective was to improve the design of both disposable and reusable absorbent mats to reduce their environmental impact and to maintain the handling satisfaction of absorbent mats among users. The goal was to present one sustainable disposable absorbent mat concept and one sustainable reusable absorbent mat concept. Throughout the design process, the objective was not to 'reinvent the wheel' but to undertake a redesign of the studied absorbent mats, building upon the existing basic layers, namely the top sheet, the soaker, and the bottom sheet. The redesigned absorbent mats were based on the studied absorbent mats in the LCA. The main optimization measure, regarding the environmental impact, was carbon footprint. The reduction of carbon footprint is in line with the goal of the Green Deal Sustainable Healthcare of the Netherlands [5]. Nonetheless, other environmental impact categories were also assessed during the concept evaluation.

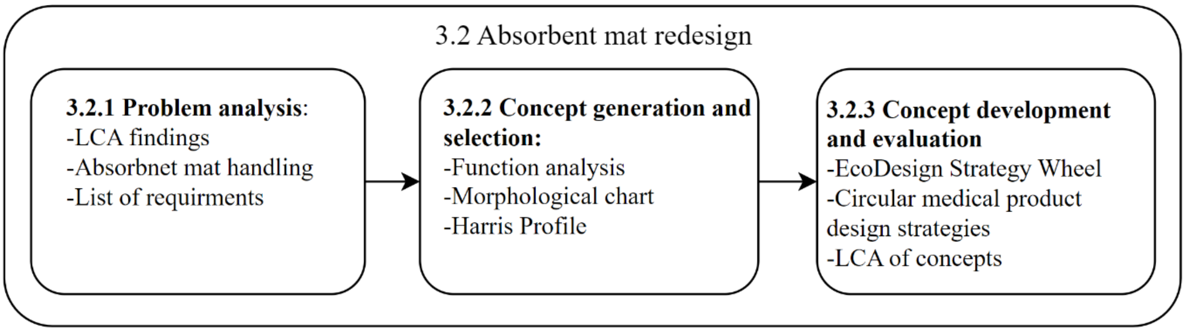

Figure 3.8: Methodological framework for the redesign process.

3.2.1 Problem analysis methods

The objective of the problem analysis stage was to gain a comprehensive understanding of the existing absorbent mat's shortcomings and to identify opportunities for improvement. In the pursuit of comprehending the underlying problem, an examination of the findings from this LCA study was conducted within the broader context of introducing sustainable practices in hospital settings. Additionally, insights from the study of Alam [14] on the handling of absorbent mats within the obstetrics department of the LUMC was analysed, in the pursuit of understanding the problem(s) and advantage(s) of the currently used Disposable A absorbent mat. The information collected during the problem analysis, along with the material investigations of the mats studied in the LCA, was utilised to set up a list of requirements and wishes for the redesign of a sustainable absorbent mat. The material investigation encompasses identifying the types and quantity of materials used and determining the absorption capacity of the mats examined in the LCA. For specific details, please refer to Appendices E through G.

3.2.2 Concept generation and selection methods

The concept generation encompassed a function analysis, a morphological chart, and the generation of concept solutions. The goal of the concept generation was to generate two disposable and two reusable absorbent mat concepts. A function analysis was performed to identify additional functions to the main- and sub-functions of absorbent mats that were already identified in the LCA study, namely:

- Collect and retain patient's bodily fluids, in order to maintain surface dryness and ensure patient's comfort by keeping the skin dry.

The above function describes the main function of the absorbent mat that is inherent to the soaker, and the subfunctions of the absorbent mat that are inherent to the bottom sheet, and top sheet, respectively, see Table 3.5. Additionally, to enhance the handling of absorbent mats by healthcare staff, supporting functions of user tasks were identified. After this a morphological chart was generated. A morphological chart is a method to generate ideas in an analytical and systematic manner [42]. Usually, functions of the product are taken as a starting point and for each function solutions are identified. The solutions serve as possible components for the generation of sustainable absorbent mat concepts. The identified functions from the function analysis served as the parameters and for each parameter solutions were identified. The solutions for the functions inherent to the top sheet, soaker, and bottom sheet were predefined for the sustainable redesign. For these functions, the solution from the studied absorbent mats were taken. Thus, these functions only had one solution, namely that of the studied LCA absorbent mats.

Table 3.5: Function and solution of the top sheet, soaker, and bottom sheet.

Absorbent mat layer	Function	Solution
Top sheet	Ensure patient comfort by keeping the skin dry	Hydrophilic, polar flexible thin sheet
Soaker	Collect and retain body fluids	Absorbent, hydrophilic, polar material
Bottom sheet	Maintain surface dryness beneath the mat	Waterproof, hydrophobic, apolar flexible thin sheet

Following the concept generation stage, two final design concepts were chosen: one for a sustainable disposable absorbent mat and the other for a sustainable reusable absorbent mat. The selection of these concepts was informed with a Harris profile [42]. The qualitative Harris Profile method was selected to intuitively assess the strengths and weaknesses of the design concepts and accelerate the initial stage of the design process. Additionally, quantifying selection criteria proved challenging in the initial stages of the design stage since the concepts were not yet materialised, and their dimensions remained unknown. A Harris profile uses a four-scale scoring system ranging from -2 to +2. A list of criteria was set up to evaluate the design concepts, see Table 3.6. The criteria were classified into three distinct categories, encompassing sustainability, general, and usability. The criteria were ranked from most important to least important from top to bottom. In scoring the concepts, emphasis was laid on the integration of a human-centred approach within the design process. The designer (author of this study) relied on a profound understanding of end-users' needs and expectations, along with their own expertise, to make intuitive design choices.

Table 3.6: Selection criteria to evaluate the sustainable concepts.

	Selection criteria
Sustainability	Reusability
	Quantity of material(s)
	Recyclability
	Separability of components
	Ease to identify the correct disposal method
General	Complexity design
	Complexity manufacturing
	Costs per use cycle
Usability	Comfort for the patient
	Efforts for staff for handling the absorbent mat during the use stage
	Ease to lift the absorbent mat
	Ease to identify the type of collected fluid
	Ease to identify the mass of the absorbent mat

3.2.3 Concept development, and evaluation methods

The absorbent mat design solutions were materialised and further developed. For the materialization of the concepts, disposable and reusable materials for both the top and bottom sheets, as well as the soaker layer of absorbent mats, were identified. Suitable materials were identified using the functions and characteristics of the distinct layers. The materials were determined through an exploratory literature review and an examination of commercial absorbent hygiene products and similar products. Additionally, the literature review on disposable soaker substitute materials for wood derived fluff pulp and/or super absorbent polymer for absorbent hygiene products conducted by Blank (the author of this study) was used [43]. The literature review was conducted as part of the graduation procedure for master’s students of Biomedical Engineering, TU Delft. Solutions of each function were combined to generate two design solutions for a disposable absorbent mat and two design solutions for a reusable absorbent mat.

During the materialization and detailed development, the design strategies of the EcoDesign strategy wheel and the circular medical product design were employed [42], [44]. The EcoDesign strategy wheel encompasses eight design strategies: (1) New concept development, (2) Selection of low-impact materials, (3) Reduction of material usage, (4) Optimization of production techniques, (5) Optimization of distribution system, (6) Reduction of impact during use, (7) Optimization of initial lifetime and (8) optimization of end-of-life system [42]. The circular medical product design strategy recommends recycling as the most viable material recovery option for low-value, low-criticality medical products [44]. The strategy highlights the need of incorporating prompts within the product design, which guide users to correctly dispose the products. Furthermore, the design guidelines on optimal hospital plastics recycling were used during the concept development [45].

In order to evaluate the final concepts, the carbon footprint was estimated by making alterations to the input of the LCA model. The environmental impact of the final concepts was compared to their disposable and reusable counterparts that were investigated in the LCA study.

4 Results

4.1 Life Cycle Assessment results

In this section the results of the LCA inventory analysis, impact assessment, and interpretation are described. For the inventory analysis the material composition and the energy and material flows for the processes manufacturing, packaging, and use are presented. The impact assessment stage compares the relative characterised impact results of each absorbent mat. In the interpretation stage the contribution, sensitivity and scenario analysis are presented.

4.1.1 Inventory analysis LCA results

In this section the main results of the data collection are presented. The results of the inventory analysis are the inputs and outputs of every unit process for all studied absorbent mats which are called inventory tables, for detailed data see Appendix A. In this section the material composition, transport data and the energy and material flows for the unit processes manufacturing, packaging, and use are presented.

Material composition of the absorbent mats

In Table 4.1 the material composition and transport data for 1000 absorbent mat uses are presented. The transport data is included in the upstream processes, which means that, for example, the transport of the semi-finished product to the manufacturer is included in the process of the semi-finished product production. The table presents the data that are used in this LCA and in some cases, these materials do not exactly represent the materials that are used in the absorbent mats, as assumptions were made.

Table 4.1: Material and transport collection table of the absorbent mats for 1000 absorbent mat uses.

Absorbent mat	Total mass of one absorbent mat	Semi-finished product		Material	Amount in kg	Production process	Transport type and distance
Disposable A and B	Disposable A: 40 grams	Top sheet		Polypropylene (PP), granulate	3.31	Non-woven	0km[1]
		Soaker	Disp. A	Softwood pulp	31.54	Sulphate process	

	Disposable B: 28 grams	Disp. B	Softwood pulp	19.78	with bleaching	See details in Appendix A
		Bottom sheet	LLDPE, granulate	5.24	Film extrusion	0km
		Adhesive	Polyurethane adhesive	0.1	/ [2]	/
Disposable C	16 grams	Soaker	Viscose fibre	11.68	Non-woven	Lorry, 1800km
		Fluid barrier	Beeswax	0.16	/	Lorry, 1700km
		Bottom sheet	Poly lactide, granulate	3.04	Film extrusion	Train, 2700km
		Adhesive	Polyurethane adhesive	1.12	/	/
Reusable A	186 grams	Top sheet	Polyester fibre	0.36	Weaving	Lorry, 80km
		Soaker	80% polyester fibre, 20% viscose fibre	0.83	Non-woven	Lorry, 190km
		Bottom sheet	Polyester, granulate	0.31	Weaving	Lorry, 80km
		Plastic film bottom sheet	TDI based polyurethane (PU), foam	0.25	Film extrusion	Lorry, 350km
		Stitch	Polyester fibre	0.57	/	Lorry, 100km
		Label	Polyester fibre	0.5	Weaving	Lorry, 80km
		Adhesive	Polyurethane adhesive	0.01	/	/

[1] A zero indicates that the data is deliberately set to zero as no data was available.
[2] A backslash indicates that the production process or transport is incorporated in the process of the material.

For Disposable A and B, the material composition and transport data only differ in the amount of soaker that is used in each mat. For all other data they have the same material and transport flows. The transport data of the soaker material is translated from another process of which the transport is measured in 'tonnes*km' and therefore the data is not included in Table 4.1. For the adhesive of all absorbent mats, a transferring activity from the Ecoinvent database is used, which includes the transport to the customer. For this LCA model, the mass of the materials is summed up so that it matches the functional unit of 1000 absorbent mat uses. For disposable absorbent mats, the materials are summed up to 1000 mats, and for Reusable A the mass is summed up to ten mats, as each mat is used 100 times to represent 1000 absorbent mat uses.

Material and energy flows: manufacturing, use and packaging

In this section, the material and energy flows are presented for the unit processes manufacturing, packaging, and use, see Tables 4.2 and 4.3. The data of the end-of-life process and all other inventory tables are delineated in Appendix A.

Table 4.2: Energy and material flows for the unit processes manufacturing and packaging of 1000 absorbent mat uses.

Process	Energy/ material flows	Disposable A and B	Disposable C	Reusable A
Manufacturing	Electricity	38.28kWh	50kWh	2.9kWh
	Gas	$3.76m^3$	/ [1]	/
	Water/wastewater	8.98l / 8.98l	/	/

	Waste	4.25% of total material input		4.25% of total material input	7% of total material input
	Transport to customer	Lorry, 1150km		Lorry, 1500km	Container ship, 20000km and lorry, 210km
Packaging	Plastic packaging (HDPE)	1.12kg Disp. A	0.53kg Disp. B	0.185kg	/
	Board box	5.5kg Disp. A	3.5kg Disp. B	1.5kg	0.5kg

[1] A backslash indicates that the process manufacturing or packaging has no quantitative input for the energy or material flow.

Table 4.3: Energy and material flows for the use stage of Reusable A for 1000 absorbent mat uses.

Process		Energy/ material flows	Amount
Use	Transport (hospital to laundry)	Type and one way distance	Lorry, 120km
		Value	44.57 metric ton*km
	Washing	Surfactant	1.7kg
		Electricity	27.65kWh
		Gas	20.96m^3
		Water / wastewater	0.81m^3 / 0.81m^3

The outcome of the inventory results, encompassing all economic flows and environmental flows related to the each of the studied absorbent mats, serve as the inputs in the subsequent LCIA. In the LCIA the environmental flows are translated to a set of quantified impact categories.

4.1.2 Impact assessment LCA results

This section presents the results obtained from the LCIA of the four absorbent mats. The LCIA results refer to the functional unit of 1000 absorbent mat uses. The characterised results of each impact category serve as the main outcome measure and are also utilised in the interpretation stage. The absolute characterised and normalised results are presented in Appendices C1 and C2, respectively. In Table 4.4 the impact categories are listed together with their acronym that is used in the figures.

Table 4.4: ReCiPe impact categories and its acronym that are used in the figures.

Impact category	Acronym
Acidification: terrestrial	TAP
Climate change	GWP
Ecotoxicity: freshwater	FETP
Ecotoxicity: marine	METP
Ecotoxicity: terrestrial	TETP
Energy resources: non-renewable, fossil	FFP
Eutrophication: freshwater	FEP
Eutrophication: marine	MEP
Human toxicity: carcinogenic	HTPc
Human toxicity: non- carcinogenic	HTPnc
Ionising radiation	IRP
Land use	LOP
Material resources: metals/minerals	SOP
Ozone depletion	ODP
Particular matter formation	PMFP
Photochemical oxidant formation: human health	HOFP
Photochemical oxidant formation: terrestrial ecosystems	EOFP
Water use	WCP

Characterised impact

Figure 4.1 shows the relative impact of the characterised midpoint categories to the reference mat Disposable A, considering the cradle to grave life cycle of the products. Additionally, the absolute impact score of the reference absorbent mat, Disposable A, is presented on the right. The absolute impact scores for the characterised results for each of the absorbent mats are presented in Appendix C1. It is important to note that the distinct score of one impact category must never be compared with the distinct score of another impact category. It should not be concluded that, for example, an impact score of 270 kg CO_2-Eq for the carbon footprint is more severe than an impact score of 0.39 kg SO2-Eq for terrestrial acidification. The impact scores should only be compared within the same impact category.

The results show that the lowest scores in all impact categories, except fossil resources, marine eutrophication, and ozone depletion, have been obtained for Reusable A. The largest scores are obtained by Disposable A for eleven of the impact categories and for the remaining seven categories Disposable C has the largest scores, whereby the largest score for marine eutrophication is equal for Disposable C and Reusable A. The middle scores (second and third largest) for half of the impact categories are shared equally among Disposable B and C. It is noteworthy to mention that the mass of Disposable C is half that of Disposable B. A detailed analysis of the LCIA model revealed that the large impacts of Disposable C relative to its mass is, among other factors, due to the soaker material viscose. Viscose is produced from softwood pulp which is processed to viscose under a variety of chemical and mechanical processes [46]. Softwood pulp is the soaker material of Disposable A and B. For Disposable B, the impact categories scores are 5% to 37% lower than the scores for Disposable A. This is due to the reduction of soaker quantity and packaging material by approximately 30% and 53%, respectively.

The high impacts of Disposable C for ionising radiation, ozone depletion, and water use are striking. The ionising radiation score is more than four times higher than that of Disposable A, mainly because 39% of the electricity used in manufacturing comes from nuclear power plants. The high ozone depletion score is, among other factors, caused by the material production of the bottom sheet and the adhesive. Specifically, the production of maize grain for the bottom sheet and aniline for the polyurethane adhesive contributes 29% and 15%, respectively, to the overall ozone depletion impact score. It's important to note that the amount of adhesive used for Disposable C is eleven times more than that used for the other absorbent mats. The ozone depletion impact of Reusable A is notably high, particularly when considering that only 10 mats are produced for 1000 uses. A significant portion of its ozone depletion impact is attributed to the production of terephthalic acid for polyester, which accounts for 36% of the total ozone depletion impact score. The impact of water use is lowest for Reusable A despite the water use during washing. The water usage to produce materials for disposable absorbent mats outweighs that of washing Reusable A absorbent mats. The notably large water impact for Disposable C is primarily due to the cultivation of maize grain for the bottom sheet.

Other notable observations are the low impact score of Reusable A for land use and material resources. The low land use score mainly stems from the mat's predominant utilization of synthetic materials. Approximately 56% of the land use score is associated with the production of soybean and coconut oil, which is used in the surfactant for the washing process. The relatively low impact for material resources is due to the fact that for the disposable absorbent mats, magnesium is used during the production of softwood and viscose, and for Reusable A, it is mainly due to the allocated steel production for the lorry that is used for distribution between laundry and hospital.

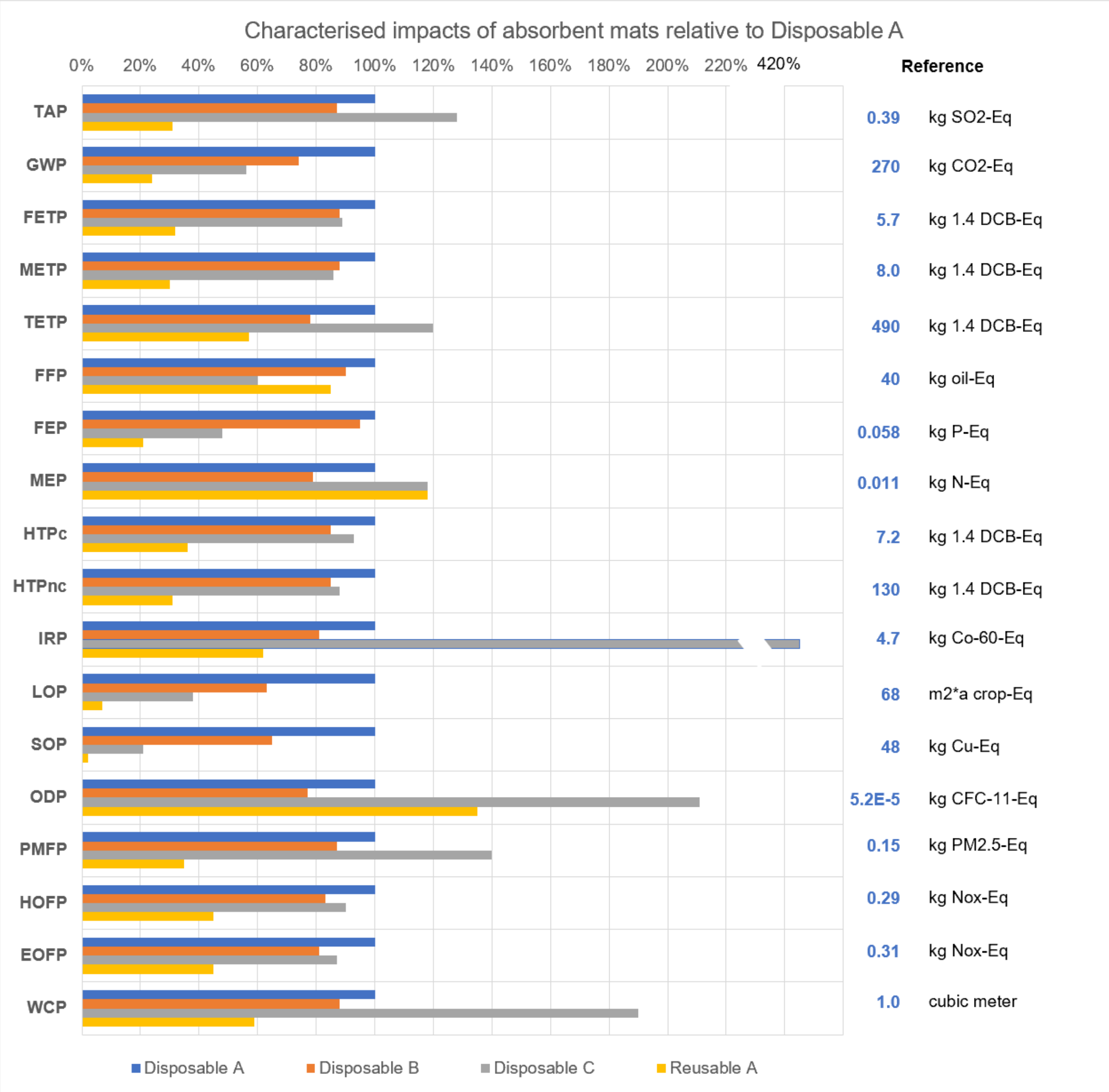

Figure 4.1: Characterisation results for each impact category of the studied absorbent mats for 1000 uses relative to Disposable A, and the absolute characterised impact scores for Disposable A. The absolute characterised impact scores for Disposable A, B, and C, and Reusable A are presented in Appendix C1.

4.1.3 Interpretation LCA results

In the interpretation stage the robustness and soundness of the results are analysed. Interpretation is done by performing a contribution analysis at three levels, a sensitivity analysis, and a scenario analysis.

Contribution analysis

Three levels are used to analyse the characterised results of the LCIA. The first level analyses the contributions of each life cycle stage, the second level analyses the contributions to the life cycle stage with the largest overall impact, and the third level analyses the impacts associated with the materials that are used in each of the absorbent mats.

Level 1: Life cycle contributions

The contribution of each life cycle stage for the absorbent mats is displayed in Figure 4.2. For the disposable absorbent mats, the use stage has zero contribution, which is due to the assumption that they have a negligible impact during the use stage. For the disposable absorbent mats, both the manufacturing stage and the material production stage make up more than 80% of the total impacts. For Reusable A, the use stage has the largest contribution to the overall environmental impact for most of the impact categories.

The life cycle stage contributions of Disposable A and B are approximately equal. Both these mats are produced by the same manufacturer and use the same materials and process steps. The only difference is that the quantity of soaker material is lower for Disposable B compared to Disposable A. This results in a slightly lower contribution of the material production stage for Disposable B compared to Disposable A. The manufacturing stage of Disposable A and B have the largest contribution for all impact categories, except for ionising radiation, land use and material resources. The land and material resource occupation are inherently largest for the production of raw materials. For Disposable C, the material production stage has the largest contribution for all impact categories, except for ionising radiation, which is due to the electricity demand during manufacturing that is produced by nuclear power plants. The relative high contribution of the material production stage for Disposable C is due to the use of viscose instead of softwood pulp for the soaker. The absolute impacts of Disposable C's viscose soaker are 200% to 600% larger than the Disposable A's softwood pulp soaker, despite the three times larger quantity of the soaker material of Disposable A. For the disposable absorbent mats, the disposal stage has the lowest overall contributions. For Disposable A and B, the treatment of waste softwood pulp has the largest contributions to the disposal stage followed by polyethylene and polypropylene. For Disposable C, the treatment of viscose waste has the largest contributions followed by polyurethane adhesive.

The largest life cycle stage contribution of Reusable A is the use stage, which contributes between 50% and 85% to the total impacts. This is because a total of 1000 mats are laundered, but only ten mats are manufactured to accumulate to a total of 1000 uses. For ozone depletion, the material production stage has a slightly higher contribution than the use stage. Overall, the material production stage has the second largest contribution followed by manufacturing or disposal, depending on the impact category. For the production stage, the soaker has the largest contributions followed by the bottom sheet with its polyurethane lamination. The largest contributions for the manufacturing and disposal stage are due to the electricity production and treatment of waste polyethylene, respectively.

Figure 4.2: Life cycle stage contributions for 1000 absorbent mat use. Top left: Disposable A, top right: Disposable B, bottom left: Disposable C, and bottom right: Reusable A.

The life cycle stage with the largest contribution for Disposable A and B is the manufacturing stage, for Disposable C it is the material production stage, and for Reusable A it is the use stage. When examining the absolute impact scores for each of these stages of the absorbent mats, it becomes evident that the use stage of Reusable A exhibits the lowest impact score in twelve out of eighteen impact categories. The use stage has the largest score in two impact categories, namely fossil energy resources and marine eutrophication, which are 45% and 10% larger than the manufacturing stage of Disposable A and B, and material production stage of Disposable C, respectively.

At the second contribution level, the manufacturing stage of Disposable A, B and C are analysed, even though Disposable C has the largest contributions in the material production stage. This choice is made as the material production stage is already analysed at the third level.

Level 2: Disposable manufacturing and reusable use contributions

The contributions of the manufacturing stage for Disposable A, B and C, and for the use stage of Reusable A are displayed in Figure 4.3. The manufacturing stage includes the packaging and the transport to the hospital. Disposable A and B have the same manufacturing process but different packaging quantity. Disposable B uses 53% less packaging material compared to Disposable A, which results in a decrease of the contribution by 4% to 11% depending on the impact category. For Disposable A and B, the electricity usage has the largest contribution to the manufacturing stage for most of the impact categories. Packaging or transport have the second largest contributions for Disposable A and B. For Disposable C, the inputs to the manufacturing stage are distributed more evenly among the impact categories. For all but one impact category, transport or electricity have the largest contributions. Disposable A and B use 25% less electricity than Disposable C, but still the contribution of electricity is larger. This is because they get their electricity from different sources. Based on the assumption of employing the electricity mix of the mat's manufacturing country, Disposable A and B predominantly rely on coal for electricity, whereas Disposable C relies on hydropower and nuclear power, which generally exhibit lower environmental impact scores across various impact categories. Nuclear power generation is also responsible for the high ionising radiation impact for Disposable C. For Disposable A and B gas usage and generated waste during manufacturing together have a contribution smaller than 20% and for most of the impact categories, it is smaller than 10%. The contribution of fresh water is between 0% and 3%. For the manufacturing of Disposable C, no gas and water are used and therefore their contribution is 0%.

The use stage of Reusable A consists of the washing and the distribution of the mats between hospital and laundry. Generally, the contribution of the distribution is lower than the washing process, except for terrestrial ecotoxicity due to brake wear emissions. For the washing process, the largest scores for the impact categories are due to the surfactant or electricity. The impact on land use and water use are particularly dominated by the contribution of surfactant. The high contributions for land use and water use are both due to the cultivation of soy and coconut to produce oils for the surfactant. The contribution of fresh water during washing is lower than 1% for all impact categories, even for water use. For sixteen out of eighteen impact categories, the contribution of gas used in the washing process is lower than 20%.

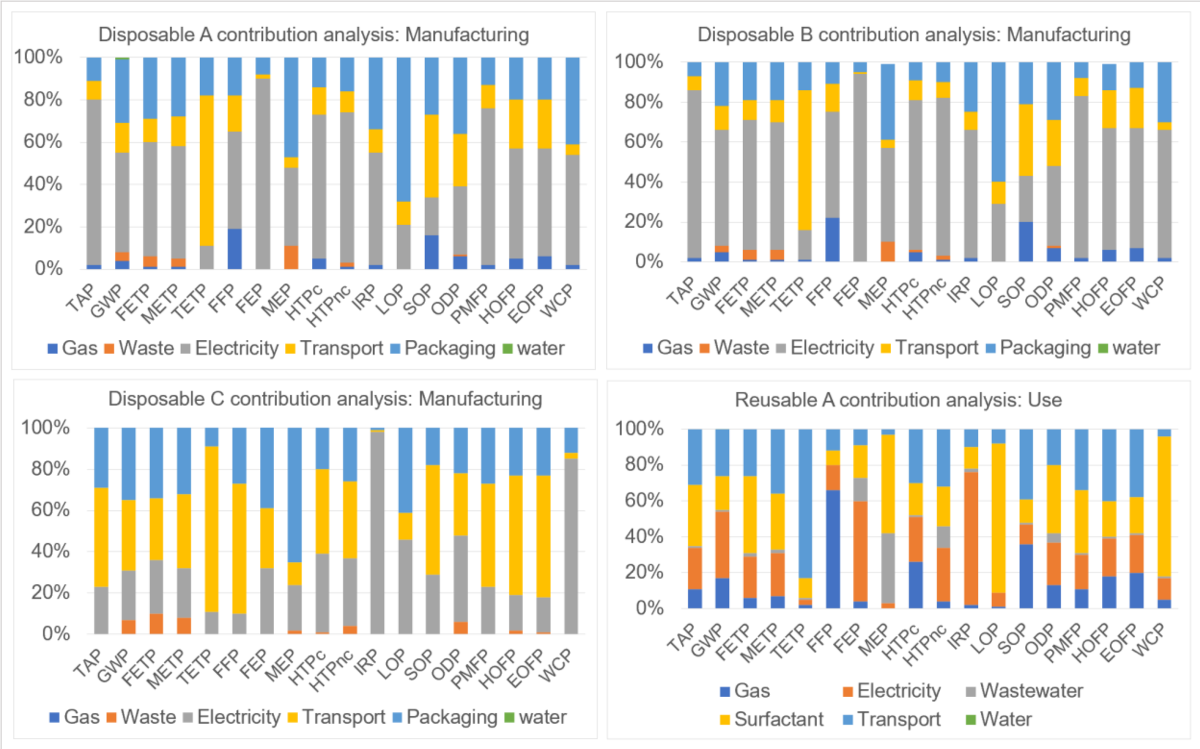

Figure 4.3: Manufacturing contributions for disposable absorbent mats and use contributions for the reusable absorbent mat. Top left: Disposable A and B, top right: Disposable C, and bottom: Reusable A.

Level 3: Material production contributions

The contribution of the production of the materials for all absorbent mats is displayed in Figure 4.4. Disposable A and B have approximately equal contributions for their materials, as they use the same materials and quantity, except for the amount of soaker material. The soaker quantity of Disposable B is 37% lower compared to Disposable A, which leads to a decrease of the soaker's contribution by 0% to 12% depending on the impact category. For Disposable A and C, and Reusable A, the largest contribution is due to the soaker material which is also largest in quantity. For Disposable B the contributions are evenly distributed among the material layers, and it depends on the impact category which material layer has the largest contribution. The large land use and material resources impacts of the disposable mats' soakers and the Disposable C's bottom sheet are due to the bio-based materials. The soakers originate from softwood and the bottom sheet of Disposable C is made from polylactic acid, which is a biobased plastic produced from maize grain. For the disposable absorbent mats, the lowest contribution is due to the adhesive. However, for Disposable C, the contribution is higher compared to Disposable A and B, because a relatively larger quantity is used.

Examining the relative carbon footprint impact of the materials, shows that the adhesive has a large contribution compared to its relatively quantity that is used in disposable A, B, and C. For Disposable A and B, the relative impact of the adhesive is largest compared to the other the materials. For disposable C the viscose soaker has the largest relative impact, followed by the adhesive. The relative contributions of the materials of Reusable A are uniformly distributed. For details on the relative carbon footprint of the materials, refer to Appendix D1.

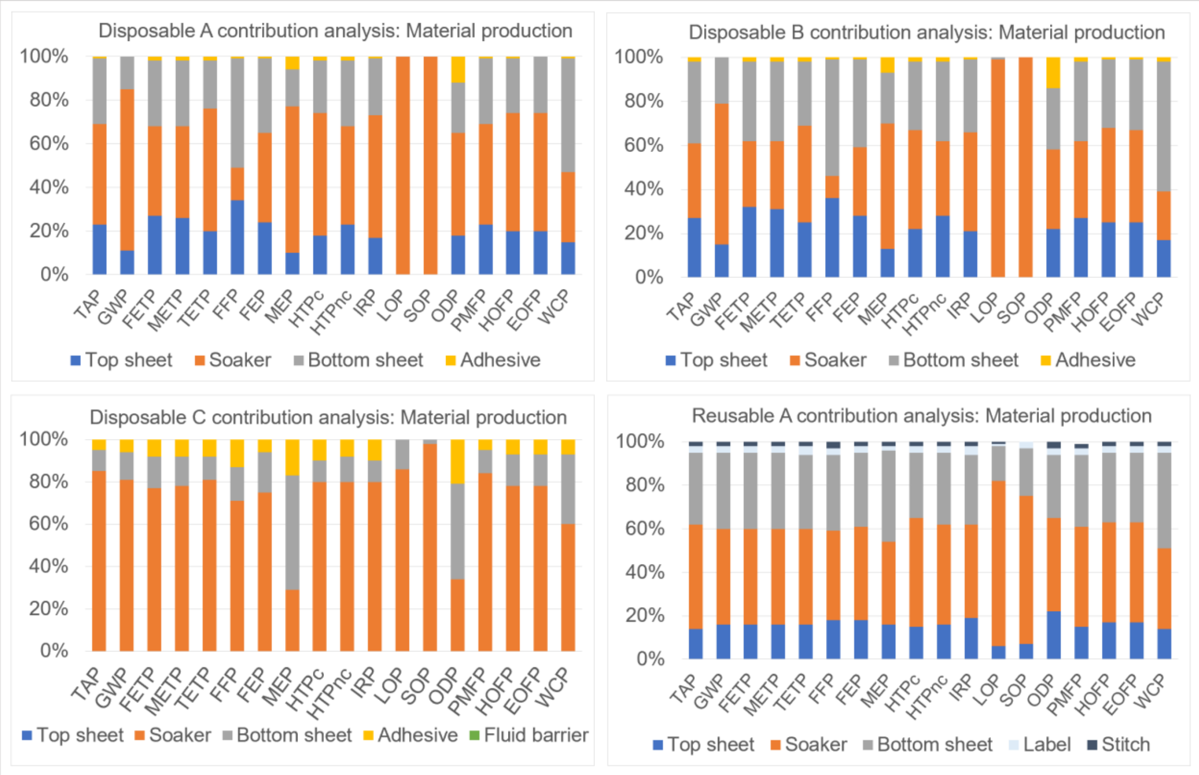

Figure 4.4: Material production contributions. Top left: Disposable A, top right: Disposable B, Bottom left: Disposable C, and bottom right reusable A.

Sensitivity analysis

Figures 4.5 to 4.7 show the sensitivity outcomes for carbon footprint, including the baseline results, for different sensitivity parameters, that were chosen based on the main assumptions for each of the absorbent mats. Additionally, sensitivity parameters were chosen based on the outcomes of the contribution analysis for the respective mats, focusing on economic flows or materials with high contributions.

Figure 4.5 shows the sensitivity analysis outcomes of Disposable A and B. The sensitivity to different parameters is similar for both absorbent mats and, thus, only Disposable A's sensitivity is investigated in detail. In the case of Disposable A, when the manufacturing flows are altered from the initially assumed flows used in disposable diaper manufacturing to those of Disposable C, the carbon footprint increases by 3%. When the electricity input doubles or is fully based on coal power, the carbon footprint increases by 15% and 3%, respectively. If the materials are increased by 5%, the carbon footprint increases by 5%. When electricity is changed fully into wind power, the carbon footprint decreases by 14%. The largest increase in carbon footprint of 59% occurs when switching the soaker material to viscose while keeping the quantity equal. For all sensitivity parameters, Disposable A continues to have the largest carbon footprint impact compared to all other absorbent mats. The outcomes of the sensitivity analysis conducted on both Disposable A and B reveal that, despite considerable variations in sensitivity parameters, the carbon footprint changes by a maximum of 15%, except when changing the soaker material to viscose.

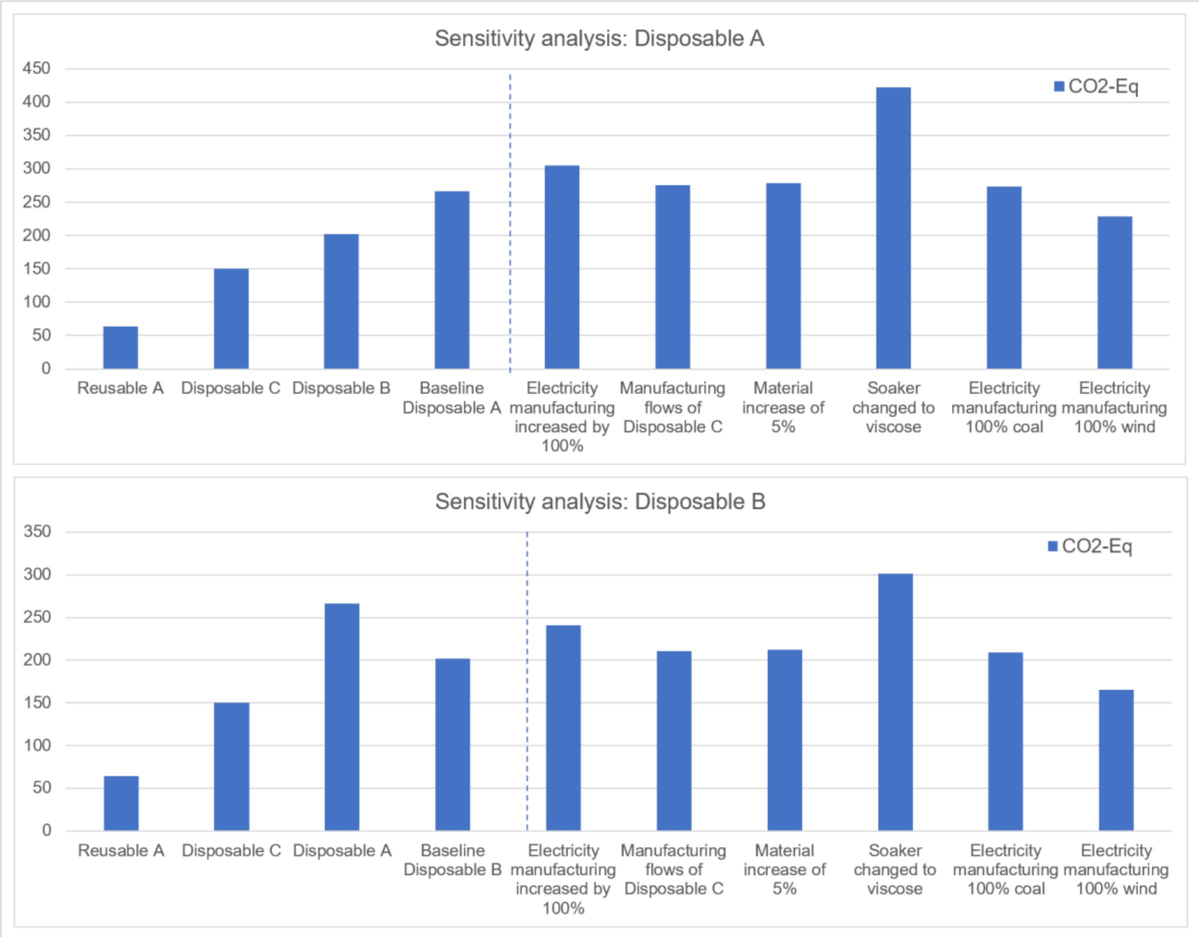

Figure 4.5: Sensitivity analysis of Disposable A (top) and Disposable B (bottom) for carbon footprint. Left of dotted line, baseline of the absorbent mats. Right of dotted line, effect on carbon footprint of different manufacturing inputs, different electricity inputs for manufacturing in both quantity and quality, and different soaker material.

Figure 4.6 shows the sensitivity outcomes of Disposable C. When decreasing the soaker quantity by two thirds to represent Lenzing viscose, or changing the soaker material to softwood pulp, the carbon footprint decreases by 39% and 38%, respectively. When the electricity input for manufacturing is increased by 100% or is fully based on coal power, the carbon footprint increases by 3% and 40%, respectively. A change to fully wind power generated electricity decreases the overall carbon footprint impact by 2%. These results show that with changes of sensitivity parameters, Disposable C continues to have the third largest carbon footprint impact compared to the baseline of the other mats.

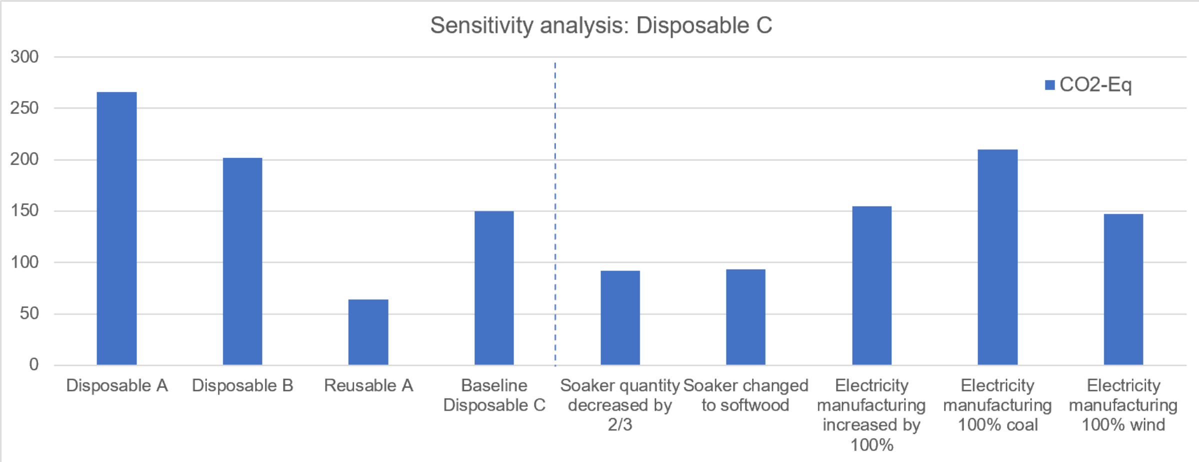

Figure 4.6: Sensitivity analysis of Disposable C for carbon footprint. Left of dotted line, baseline of the absorbent mats. Right of dotted line, effect on carbon footprint of different soaker quantity (amount of material) and quality (type of material), and different electricity inputs for manufacturing in both quantity and quality.

Figure 4.7 shows the sensitivity outcomes of Reusable A. The sensitivity of the main assumptions is analysed by decreasing the use cycles of Reusable A from 100 to 50 or the loading capacity for washing by 50%, or by incorporating the rolling container mass into the transport between laundry and hospital. For each of the sensitivity parameters, the carbon footprint increases by 34%, 48% and 6%, respectively. If the surfactant quantity doubles, the carbon footprint increases by 13%. If the electricity for washing increases by 100% or is changed to fully coal based or fully wind based, the carbon footprint increases by 25% and 19% for the former two and decreased by 22% for the latter. If the travel distance changes to 240km, the carbon footprint increases by 17%. Reducing the distance to 0km when the washing is inside the hospital decreases the carbon footprint by 16%. The results of the sensitivity analysis of Reusable A show that even with relatively large variations in changing parameters, the carbon footprint of Reusable A continues to have the lowest impact.

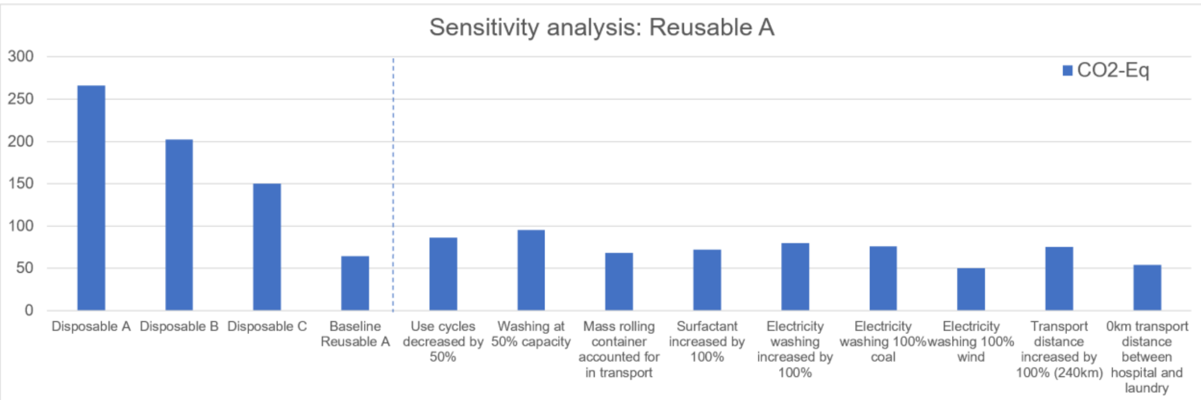

Figure 4.7 Sensitivity analysis of Reusable A for carbon footprint. Left of dotted line, baseline of the absorbent mats. Right of dotted line, effect on carbon footprint of different use cycles, different washing machine capacity, and different transport and washing inputs.

Scenario analysis: worst- and best-case and impact assessment method

The first scenario analysis compares the carbon footprint of the baseline scenario with a worst- and best-case scenario. The subsequent scenario analysis investigates the choice of impact assessment method and its influence on the relative environmental impact of the absorbent mats in relation to Disposable A mats.

Figure 4.8 shows the outcomes of the baseline, worst- and best-case scenario's carbon footprint impact for the absorbent mats. For the best-case scenario, the impact decreases by 18% for Disposable A, 22% for Disposable B, 2% for the Disposable C, and 39% for the Reusable A. The increase between the baseline and the worst-case scenario is 5% for Disposable A, 8% for Disposable B, 40% for Disposable C, and 140% for Reusable A. The results of this scenario analysis show that even under a worst- and a best-case scenario, Disposable A continues to have the largest carbon footprint impact followed by Disposable B or C, and Reusable A. Under a worst-case scenario of Reusable A, the carbon footprint increases by 140%, which surpasses Disposable C's baseline and is approximately equal to the best-case scenario of Disposable B. The largest relative increases for the worst-case scenario are due to decreasing the use cycles and the loading capacity for washing by 50% each. Furthermore, for impact categories other than carbon footprint, the hierarchy between mats also changed when comparing the worst-case scenario of Reusable A with the baseline scenario of the other mats. Reusable A has the lowest score for eight out of eighteen impact categories, while formerly having the lowest score for fifteen impact categories. Also, Reusable A now has the largest score for five impact categories while formerly having the largest score for one impact category. The largest impact difference, among the largest impact scores of Reusable A, compared to Disposable A occur for the impact category fossil resources (85%) and marine eutrophication (107%). Appendix C3 presents a detailed overview of all impact category scores for this scenario analysis.

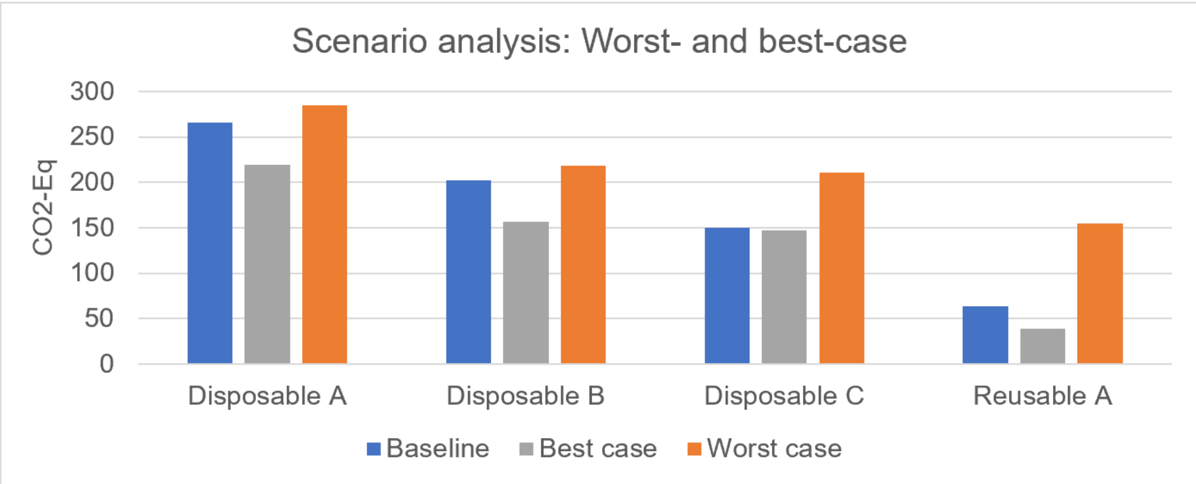

Figure 4.8: Comparison of the baseline carbon footprint impact to a worst- and best-scenario.

In Figure 4.9 results of the LCIA results are compared across impact methods with matching impact categories. In total, eleven ReCiPe impact categories scores for each mat are compared to the impact scores for CML and EFv3.1. For this analysis the impacts of Disposable B, C and Reusable A relative to Disposable A are compared. By looking at the relative impacts it can be determined whether the ranking of the mats in relation to each other changes depending on the impact category. For the impact categories of acidification, climate change, freshwater ecotoxicity, marine ecotoxicity, freshwater eutrophication, and water use, the impacts of the mats relative to Disposable A are consistent across all impact methods. This means that in each category, the ranking of the mats in relation to each other is consistent across impact methods.

For the impact categories terrestrial ecotoxicity, and human toxicity, and marine eutrophication the ranking changes substantially. For the first two mentioned categories Reusable A changes rank from lowest to largest impact when using CML or EF v3.1 instead of ReCiPe. And for marine eutrophication Reusable A changes rank from largest to lowest impact. Also, for ozone depletion Reusable A's impact is approximately six times larger when the impact methods CML or EF v3.1 are used instead of ReCiPe. These disparities among impact methods are due to an interplay between the difference in impact assessment indicators for certain environmental flows. Impact assessment indicators are multiplication factors for environmental flows so that their impact can be attributed to an impact category. Certain environmental flows have a high indicator in the CML method, while concurrently, in the ReCiPe method, the indicator is low, and vice versa. This is because there is not always a consensus or best practice for determining the impact assessment indicator of certain environmental flows [47]. For instance, in the CML method, the indicator factor of the environmental flow 'cypermethrin', an insecticide employed in coconut cultivation (for surfactant production), is more than a hundred times higher than in the ReCiPe method.

Scenario analysis: Impact assessment method

Absorbent mat	Impact method	Impact or impact difference	Impact categories										
			Acidification	Climate change	Freshwater ecotoxicity	Marine ecotoxicity	Terrestrial ecotoxicity	Freshwater eutrophication	Marine eutrophication	Human toxicity, carcinogenic	Human toxicity, non-carcinogenic	Ozone depletion	Water use
Disposable B / Disposable A (DB/DA)	ReCipe	DB/DA	0.89	0.76	0.88	0.88	0.78	0.94	0.76	0.85	0.88	0.77	0.85
	CML	DB/DA	0.89	0.88	0.89	0.85	0.84	/	/	0.84		0.81	/
		Difference	0%	16%	2%	-3%	7%	/	/	-1%	-4%	6%	/
	EF v3.1	DB/DA	0.88	0.88	/	/	/	0.94	0.81	/	/	0.82	0.85
		Difference	-1%	16%	/	/	/	0%	6%	/	/	7%	0%
Disposable C / Disposable A (DC/DA)	ReCipe	DC/DA	1.30	0.56	0.90	0.86	1.20	0.49	1.17	0.93	0.86	2.04	1.82
	CML	DC/DA	1.27	0.86	0.45	0.54	1.46	/	/	0.94		3.33	/
		Difference	-3%	52%	-50%	-37%	21%	/	/	1%	9%	63%	/
	EF v3.1	DC/DA	1.27	0.86	/	/	/	0.49	0.99	/	/	3.04	1.82
		Difference	-3%	52%	/	/	/	1%	-16%	/	/	49%	0%
Reusable A / Disposable A (R/DA)	ReCipe	R/DA	0.32	0.24	0.32	0.30	0.56	0.21	1.13	0.36	0.30	1.36	0.57
	CML	R/DA	0.32	0.44	0.38	0.17	13.61	/	/	1.04		8.08	/
		Difference	0%	82%	20%	-43%	2317%	/	/	185%	242%	493%	/
	EF v3.1	R/DA	0.39	0.45	/	/	/	0.21	0.60	/	/	10.70	0.57
		Difference	22%	86%	/	/	/	0%	-47%	/	/	493%	0%

Figure 4.9: Impact of the absorbent mats relative to Disposable A for the impact assessment methods ReCiPe, CML, and EFv3.1. The three main rows represent the absorbent mats, and each main row is split up into three sub rows representing the impact method. For each impact method the relative impact is denoted together with the percentual difference between the CML or EFv3.1 method and the ReCiPe method.

4.2 Sustainable redesign results

In this section the results of the sustainable design of absorbent mats are presented. The section is split up in three parts: (1) Problem analysis, (2) Concept generation and selection, and (3) Concept development and evaluation.

4.2.1 Problem analysis sustainable redesign results

The problem analysis investigates the design implications of the LCA study, the challenges inherent to the implementation of reusable absorbent mats, the handling of absorbent mats in hospitals, and builds up to a list of requirements and wishes for the sustainable absorbent mat redesign.

Environmental criticalities of the absorbent mats examined in the LCA study

In this section, the absorbent mats' main environmental criticalities that were identified in the LCA study are presented, see Table 4.5. Additionally, supplementary environmental criticalities are identified to ensure completeness.

Table 4.5: Environmental criticalities identified in the absorbent mat LCA study.

Life cycle stage	Environmental criticalities
Material production	• Abundant use of soaker material (DA, RA) • Use of virgin materials (DA, DB, DC, RA) • High impact of viscose soaker (DC) • Abundant use of adhesive (DC)
Manufacturing	• Electricity generated from coal sources (DA, DB) • Electricity generated from nuclear power sources (DC) • Cutting waste (RA)
Use	• Disposable products (DA, DB, DC) • Washing with standard surfactant (RA) • Electricity generated from coal sources for the washing process (R)
Disposal	• Multi-material use (DA, DB, DC, RA) • Difficulties in separating distinct material layers (DH, DL, DB, R)

	• Open loop end of life (DA, DB, DC, RA)

[1]DA= Disposable A, DB= Disposable B, DC= Disposable C, RA= Reusable A.

Challenges in the implementation of reusable absorbent mats in hospitals

The outcomes of the LCA study indicate that reusable absorbent mats exhibit a substantially lower environmental impact when compared to their disposable counterparts. Despite this clear environmental advantage, up until now, the situation in hospitals persists, where disposable absorbent mats remain the favoured choice over their reusable counterparts. One notable obstacle hindering the adoption of reusable mats is the budget constraints faced by healthcare institutions. Reusable mats, despite their environmental merits, often involve higher initial procurement costs when contrasted with disposable options. However, it is worth noting that the utilization of disposable absorbent mats results in a substantial volume of waste, which subsequently leads to increased costs due to the cost of waste disposal. However, these disposal costs are drawn from a budget separate to the one designated for absorbent mat procurement. This budgeting approach further complicates and hinders the transition to environmentally superior reusable absorbent mats. Additionally, this situation is complicated by the worsening financial landscape within the Dutch healthcare sector, with over 80% of hospitals reporting deficits in 2023 [48]. Moreover, the implementation of reusable absorbent mats poses logistical challenges for the operations at the LUMC. It is anticipated that, if introduced, these reusable mats can be managed within the existing logistics system used for hospital linen. However, approximately 239,000 disposable absorbent mats are used annually. Substituting all of these with reusable absorbent mats may present significant challenges to the logistics at LUMC and the laundry service provider. Based on these findings, it is expected that hospitals will continue to utilize disposable absorbent mats, while potentially incorporating the use of reusable absorbent mats alongside them. Therefore, in this design study, the primary emphasis is placed on the design of both reusable and disposable absorbent mats, rather than choosing to design only the environmentally superior reusable absorbent mats.

Handling of absorbent mats by healthcare staff in hospitals

To gain insights into the handling of absorbent mats within hospital settings, Alam's study on the use of absorbent mats in the obstetrics department of LUMC was utilized [14]. Throughout the LUMC, Disposable A is used alongside Disposable B. Disposable B was introduced after the study of Alam was conducted. However, handling of the mats is expected to be consistent among the two mats. Among all departments of the LUMC, the obstetrics department is the largest consumer of absorbent mats. Additionally, during the procedures performed at the obstetrics department, the largest quantity of fluid needs to be collected and retained. Therefore, the collected amount of fluid during procedures performed at the obstetrics department serves as a benchmark for the upper limit of absorption capacity. For other procedures throughout the LUMC, the amount of fluid that needs to be collected by absorbent mats is expected to be considerably lower.

The study conducted in the LUMC, quantified the number of mats used, amount of collected fluid per absorbent mat, and total collected fluid during one vaginal delivery or breaking of the membrane. These data are used to determine the upper limit of the absorption capacity for the redesign of absorbent mats. The distribution of collected fluid per mat and the total amount of collected fluid during one procedure is illustrated in Figure 4.10. The diagram on the left shows that in most of the cases an absorption capacity of 390 grams is sufficient, and that an absorption capacity of 164 grams is sufficient for more than half of the cases. The diagram on the right shows that for most procedures between 395 grams and 1835 grams of fluid is collected. Moreover, on average eight absorbent mats are used during one procedure. These results indicate that absorbent mats are underutilized, as only a fraction of the available absorption capacity (570 grams) is used in practice.

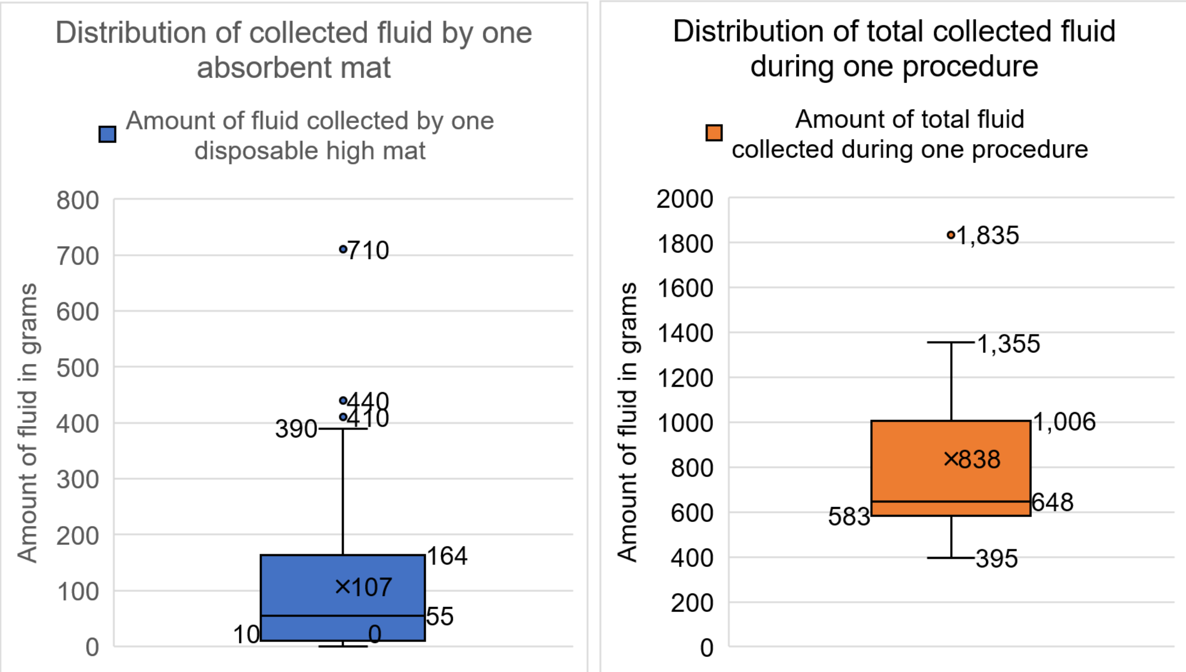

Figure 4.10: Distribution of collected fluid by one Disposable A mat and distribution of total collected fluid during one vaginal delivery or breaking of the membrane. The data is adapted from [14].

Furthermore, the study conducted observations on the handling of absorbent mats in the obstetrics ward. These findings are used to identify functions of the absorbent mat redesign. The absorbent mats are mainly used for collecting amniotic fluid, stool, urine, or blood. Besides their main function, absorbent mats are used to determine blood loss of the patient by weighing soaked absorbent mats on a scale, and to identify the colour and consistency of fluid. Besides their intended use, the mats are commonly misused for other applications such as packaging of medical instruments to prevent clinking, providing cushioning for patients, and cleaning the operating room floor in cases of spilled blood. Alternative products might be better suited for addressing this misuse, and therefore, this is not included in the redesign process.

Moreover, the study conducted interviews with users about their satisfactory with the current Disposable A absorbent mat, and on possible requirements for an alternative to Disposable A. These findings are used to set up a list of requirements and wishes for the sustainable redesign. Regarding the satisfaction of users, Alam concluded that "[users] agreed that they were very satisfied with the current cellulose absorbent mat" (cellulose absorbent mat refers to Disposable A). The reasons for this are the ease of use, the non-stickiness of the surface to other surfaces like bed linen and gloves, the enhanced patient comfort, and the enhanced hygiene standards. Also, users expressed their satisfaction about the absorbent mats as they reduce the necessity for extensive cleaning. Regarding the requirements users had for an alternative absorbent mat, users stated that the alternative must have sufficient absorption capacity, have equal quality and size, be comfortable for patients, and be made from a strong material with high tear resistance. Also, users mentioned that they would like an alternative absorbent mat that is biodegradable, takes allergies into account, and has a pleasant fragrance. Additionally, some users expressed that the alternative absorbent mat should have another colour than bright white to hide small blemishes while still having the needed visibility of fluid.

Based on the above finding the redesigned absorbent mat must have a minimum absorption capacity of 400 grams. Another feasible option is to utilize two absorbent mats with different absorption capacities, namely one with 175 grams and the other with 400 grams. Other functions and wishes that originate from the above findings are listed in Table 4.6 and 4.7.

List of requirements and wishes for the sustainable absorbent mat design

The list of requirements is based on the findings from the absorbent mat handling within the LUMC, and on the specifications of the investigated absorbent mats. The list of requirements is split up into three parts: the first part lists general requirements for both disposable and reusable absorbent mats, the second part lists requirements specific to disposable absorbent mats, and the third part lists requirements specific to reusable absorbent mats. Additionally, a list of wishes is presented.

Table 4.6: List of requirements for the redesign of absorbent mats.

General requirements	
Functional requirements	The absorbent mat must be able to collect up to 400 grams of fluid
	The absorbent mat must maintain dryness on the underlying surface
	The absorbent mat must allow for rapid fluid uptake so that no fluid is spilled
User requirements	The top sheet of the absorbent mat must allow for identification of the colour and consistency of collected fluid
	The absorbent mat must allow for a reduction of its dimensions so that it can be placed on the scale to determine its mass
	The absorbent mat must have sufficient tensile strength so that it does not tear apart under the mass of the collected fluid when being handled by healthcare staff
	The absorbent mat should not stick to the hands of healthcare workers (with and without gloves)
	The top sheet must give the sensation of dryness to the patient
	The top sheet must be comfortable (soft sensation to the skin to prevent irritation)
Specifications	The absorbent mat must have dimensions of 60x60 cm
	The maximum mass of the absorbent mat must be 300 grams
	The particle release of absorbent mats must be in the range of that for products used in the operating room
Disposable specific requirements	
	The absorbent mat must allow for identification that it is a disposable product
	The maximum price of one absorbent mat must be 50 cents
Reusable specific requirements	
	The absorbent mat must allow for identification that it is a reusable product
	The absorbent mat must maintain its performance after undergoing 50 cycles of washing
	The absorbent mat must allow that distinct uses are counted
	The maximum cumulative price of one absorbent mat use must be 50 cents

Table 4.7: List of wishes for the redesign of absorbent mats.

Wishes
The absorbent mat should be made from a mono-material
The absorbent mat components should be easily separable
The absorbent mat should be biodegradable
The reusable product life cycle should be extended as much as possible (>100 use cycles)
The absorbent mat should have a high-quality appearance and haptic feedback
The absorbent mat’s materials should take allergies into account
The absorbent mat should have a pleasant fragrance

4.2.2 Concept generation sustainable redesign results

In this section, the results of the function analysis, the morphological chart, and possible concepts for a sustainable redesign of absorbent mats are presented. Also, one sustainable disposable and one reusable absorbent mat are selected to be worked out in detail.

The function analysis was performed to identify additional functions to the ones identified in the problem analysis, and to give an overview of all the functions. The function analysis identified three main-, and subfunctions, and six user tasks, see Figure 4.11. The user tasks are translated to eight additional supporting functions of the absorbent mat. The identified main-, sub-, and supporting functions are used in the morphological chart. The supporting functions ‘Adapt to surface shape’ and ‘Allow handling without sticking to surface and gloves’ were omitted from the morphological chart as it they both are determined through the selection of materials.

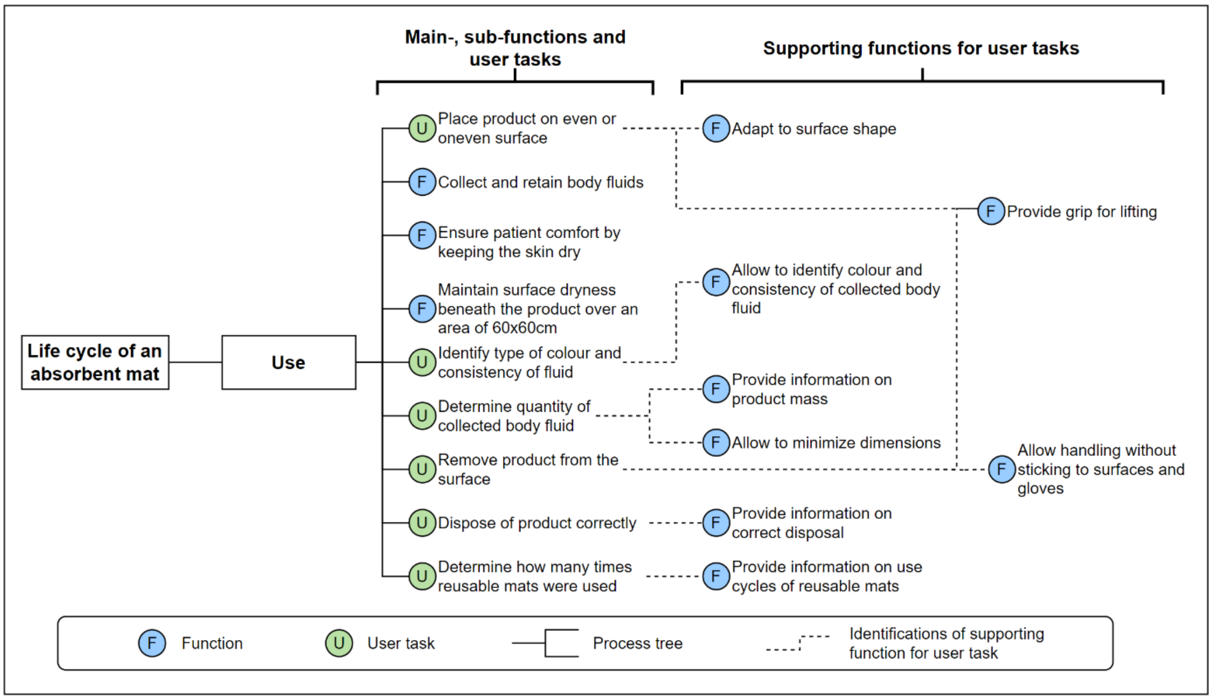

Figure 4.11: Function analysis including main-, sub-functions, and supporting functions for user tasks.

Figure 4.12 presents the morphological chart for the redesign of absorbent mats. The basic functional layers, namely top sheet, soaker, and bottom sheet, were not changed as a redesign was sought and not a new product design to collect fluid. For the remaining functions, solutions are provided individually for each specific function. Some of these solutions can be applied to both reusable and disposable absorbent mats, while others are applicable exclusively to one type. The last function listed in the morphological chart is unique to reusable absorbent mats. One solution for each of the functions are combined to generate two disposable and two reusable absorbent mat concepts.

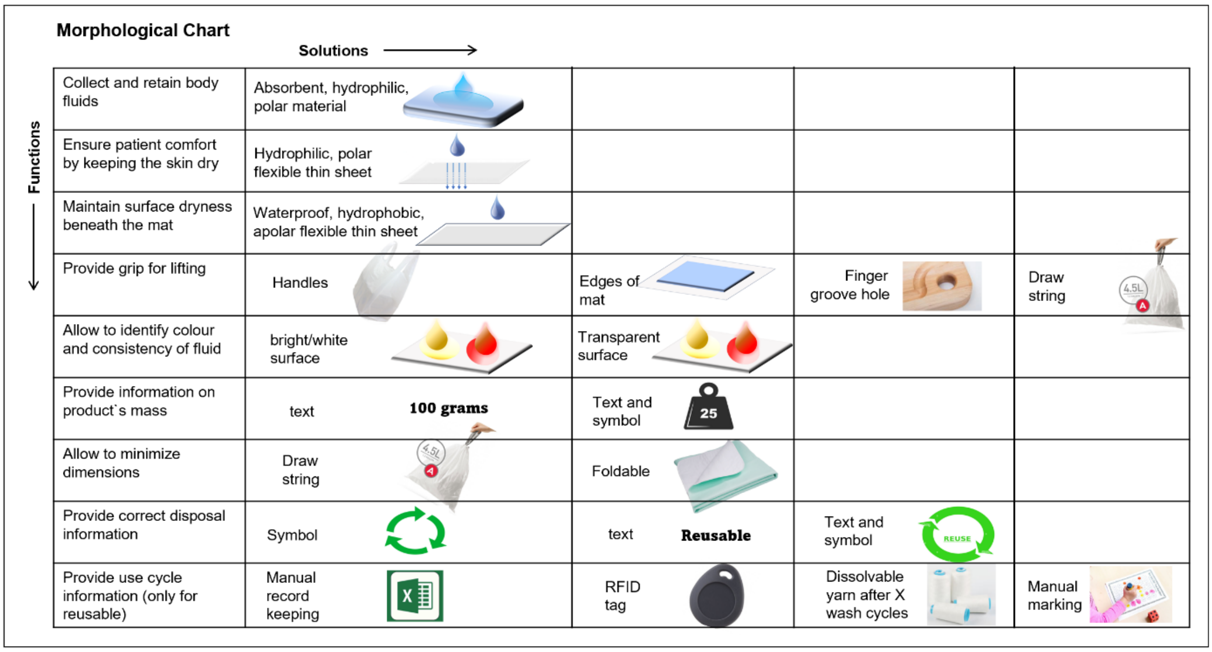

Figure 4.12: Morphological chart. For the first three functions the solutions to the studied LCA mats are used for the redesign as stated on the methods section.

Disposable absorbent mat concepts

Two concepts are generated for the redesign of a disposable absorbent mat. Both concepts consist of the three basic layers, namely top sheet, soaker, and bottom sheet, and additional components for the remaining functions, see Figure 4.13. Both concepts have a white surface so that the colour and consistency of fluid can easily be identified. Concept 1 has a draw string, similar to those used for garbage bags, which is used to lift the absorbent mat and to minimize its dimensions in order to be put on the scale. Information on the absorbent mat weight and correct disposal are printed on the top sheet, which allow for easy visibility. Concept 2 has handles that improve the lifting of the absorbent mat. Details regarding the absorbent mat's mass and proper disposal instructions are displayed on the underside of the absorbent mat, ensuring uniformity in colour across the top sheet. This concept is foldable to allow to minimize the dimensions in order to be able to put it onto the scale.

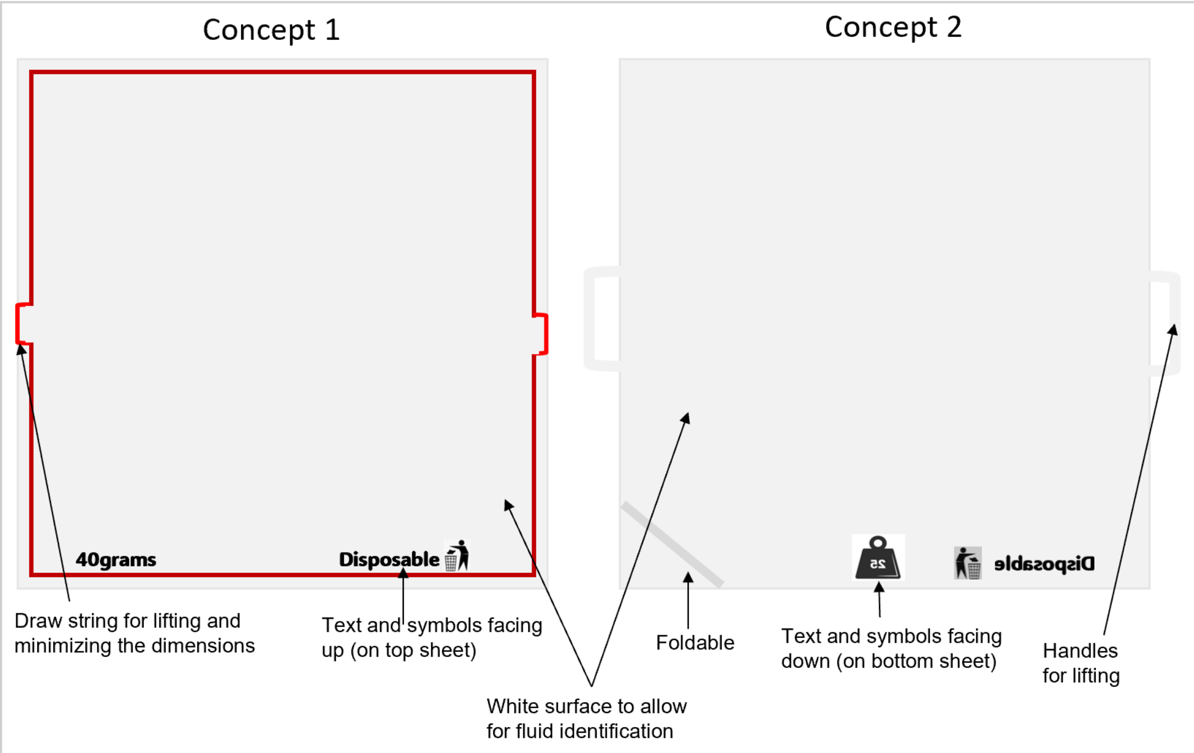

Figure 4.13: Concept 1 and 2: Top view of the disposable absorbent mat concepts. For concept 2, the text and symbols are not visible through the top sheet, the mirror writing indicates that they are on the bottom sheet.

Reusable absorbent mat concepts

Concepts 3 and 4 are made of a consistent white top sheet to allow for the identification of the collected fluid by its colour and consistency, see Figures 4.14. Details regarding the absorbent mat's mass and proper disposal instructions are displayed on the bottom of the absorbent mat, ensuring uniformity in colour across the top sheet. Both reusable concepts are foldable to minimize the dimensions which enable them to be put onto the scale. Concept 3 has finger grooves in each corner of the absorbent mat, in order to enhance the handling of the mats. To identify the number of use cycles of distinct mats, a RFID tag is sewed into the edge of the reusable concept. Every time the absorbent mat is washed, the RFID tag is scanned, and the information is stored. Concept 4 has two handles opposite to each other, which improve the lifting of the absorbent mat. To track the use cycles of concept 4, every time the absorbent mat was used or washed, a box is filled out by a permanent marker, or stamped to indicate the number of use cycles.

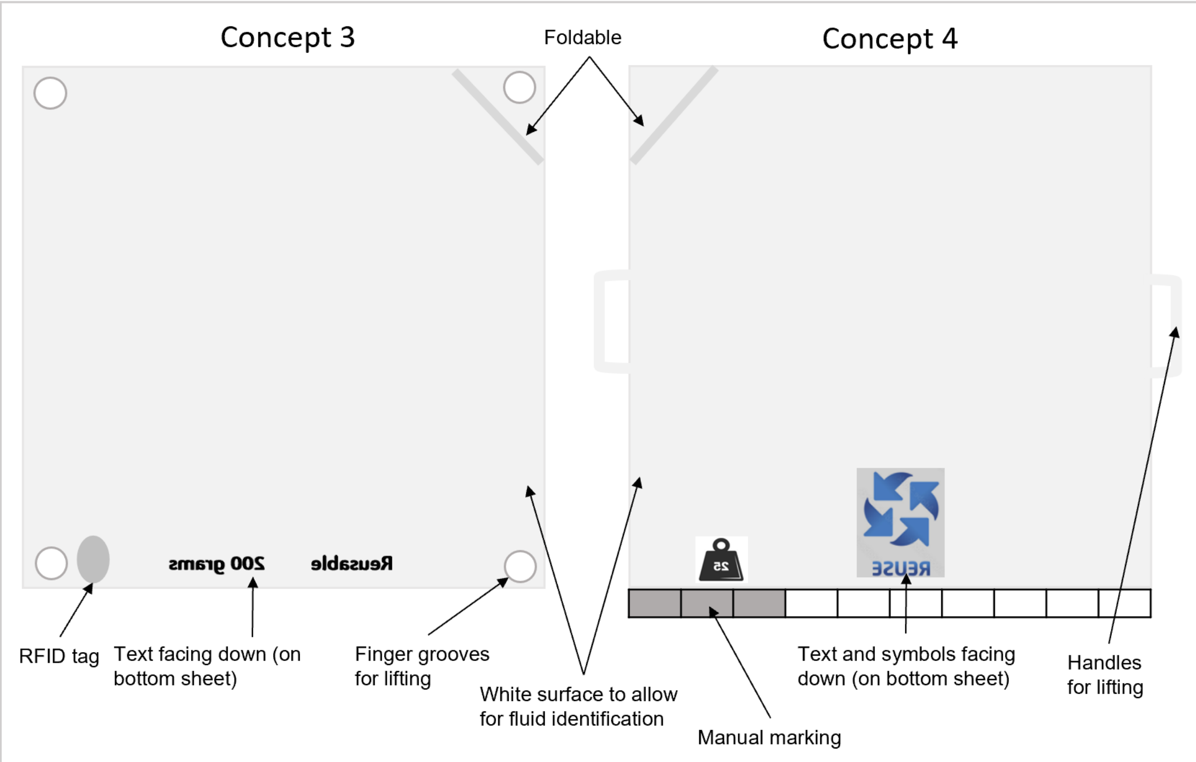

Figure 4.14: Concept 3 and 4: Top view of the reusable absorbent mat concept. The text and symbols are not visible through the top sheet, the mirror writing indicates that they are on the bottom sheet.

Concept selection

The Harris Profile, depicted in Table 4.8, shows that for the disposable concepts, in general, concept 2 has higher scores than concept 1. For the reusable concepts, the overall scores are approximately equally distributed. However, when considering that sustainability criteria rank higher, concept 3 is preferred over concept 4. Therefore, concept 2 and concept 3 form the basis for further development of the final disposable and reusable concepts. The chosen concepts will be elaborated upon in the following section, focusing on the implementation of sustainable design strategies.

Table 4.8: Harris Profile of the four concepts.

	Disposable concepts								Reusable concepts							
	Concept 1				Concept 2				Concept 3				Concept 4			
	-2	-1	+1	+2	-2	-1	+1	+2	-1	-2	+1	+2	-2	-1	+1	+2
Reusability	■	■			■	■					■	■			■	■
Quantity of material(s)		■					■				■	■			■	
Recyclability	■	■				■					■				■	
Separability of components	■	■				■				■				■		
Ease to identify disposal			■	■			■				■				■	■
Complexity design	■	■					■				■				■	
Complexity manufacturing		■					■		■	■			■	■		
Costs per use cycle			■				■	■		■				■		
Comfort for the patient		■					■				■	■			■	
Efforts for the staff			■				■				■			■		
Ease to lift the absorbent mat			■				■	■			■				■	■
Ease to identify fluid type			■				■	■			■	■			■	■
Ease to identify mass of mat			■				■	■			■				■	■

Sustainability criteria General criteria Usability criteria

4.2.3 Detailed concept development and evaluation sustainable redesign results

In this section, the two selected concepts, namely concept 2 and concept 3, are further developed. To do so, first, materials for the basic layers of absorbent mats are identified and after that the EcoDesign Wheel and Circular Medical Product design strategies are applied to the two selected concepts. The utilization of eco-design strategies is denoted using 'EcoDesign [number]' or 'Circular Design' in brackets where applicable. The identified materials for the basic functional layers of absorbent mats are listed in Table 4.9. To assist the selection of low-impact materials the carbon footprint for the production of the materials was determined by performing additional LCA steps, see Appendix D.

In the preceding design step several eco-design strategies were already unintentionally applied by the designer. By developing new concepts and adding and optimizing functions to support user tasks EcoDesign strategy 1 and 7 were applied. The inclusion of user supporting functions aimed at enhancing user tasks and potentially lowering the frequency at which absorbent mats are replaced (EcoDesign 6, 7).

Table 4.9: Identified disposable and reusable materials for the top sheet, soaker, and bottom sheet.

Absorbent mat layer	Disposable materials	Carbon footprint/kg	Reusable materials	Carbon footprint
Top sheet	Non-woven polypropylene	3.2 CO2-Eq	Woven polyester	5.3 CO2-Eq
	Specialised paper (similar to wet toilet paper or tissue paper)	3.5 CO2-Eq	Woven cotton	12 CO2-Eq
			Woven linen	/
			Merino wool	53 CO2-Eq
Soaker	Softwood pulp	2.3 CO2-Eq	Non-woven polyester-viscose mix	6.3 CO2-Eq
	Superabsorbent polymer	5.3 CO2-Eq	Non-woven polyester	5.8 CO2-Eq
	Non-woven viscose	6.7 CO2-Eq	Non-woven viscose	6.7 CO2-Eq
	Pearl millet, banana stem, hibiscus bast, sugarcane, eucalyptus, sunflower stem, jute, flax, esparto grass, bamboo, corn husk, and aloe vera derived pulp	Approximately equal to softwood pulp	Cotton-terry (towel)	Approximately equal to woven cotton
	Cotton	4.8 CO2-Eq	Chicken feather-cotton cloth mixture	Approximately equal to woven cotton
			Woven linen	/
			Woven hemp	/
			Non-woven bamboo wadding	/
Bottom sheet	Polyethylene film	3 CO2-Eq	PU coated woven polyester	5.1 CO2-Eq
	Polylactic acid film (PLA)	4.2 CO2-Eq	PVC coated woven polyester	17 CO2-Eq
	Polyhydroxyalkanoate film	Approximately equal to PLA	PET coated woven polyester	2.9 CO2-Eq
	Polyethyleenfuranoate film	Approximately equal to PLA	Ripstop nylon fabric	/
	Wax coated kraft paper (same as paper bag paper)	3.1 CO2-Eq	Gore-Tex	/

Final disposable and reusable absorbent mat concepts

Both final concepts have an absorption capacity of 400 grams and are 60x60 cm in dimensions. The final absorbent mat concepts consist of the three distinct layers, namely top sheet, soaker, and bottom sheet. Information facilitating the determination of proper disposal and the mass of the mat is presented in a dual format, including both symbolic representation and textual description (Circular Design). The information is displayed on each corner on the underside of the absorbent mats to not interfere with the ability to identify the fluid colour and consistency. The solution to allow lifting of the absorbent mats, namely finger grooves and handles, are discarded in the final concepts. The introduction of these solutions leads to additional manufacturing steps, possibly increasing the absorbent mat's environmental impact. Additionally, user expressed their satisfaction with the current Disposable A absorbent mat which has no handles or finger grooves.

To select the materials for the basic layers of the final disposable concept, the impact (carbon footprint) and mass of the materials are considered (EcoDesign 2,3). The top sheet materials non-woven polypropylene and specialised paper have approximately equal carbon footprints. However, the mass of paper is substantially larger than PP. which leads to an overall larger carbon footprint when utilizing paper for the top sheet. The same applies to the two lowest impact bottom sheet materials polyethylene and wax coated kraft paper. Kraft paper has high elasticity and high tear resistance and is designed for packaging products with high demands for strength and durability [49]. For the soaker of the final disposable design softwood pulp is used. Among the disposable absorbent materials, softwood pulp has the lowest impact per kg of absorbed fluid, see Appendix D2 for details on the carbon footprint relative to the ability to absorb fluids. The utilization of PP, softwood pulp, and PE would lead to the lowest carbon footprint for the redesign. These materials are utilized for Disposable A and B, which means that the design remains the same. However, the designer decided to utilize paper for both the top- and bottom sheet, and softwood pulp for the soaker of the final disposable concept. These design choices lead to a mono-material product, that makes recycling a feasible option for the end of life. This redesign aims to enhance the understanding of the influence of recycling on the environmental impact by incorporating this into the LCA evaluation of the final concepts. The mono-material design of the absorbent mat is intended to facilitate a closed-loop end-of-life scenario where the entire absorbent mat can be recycled without the necessity to separate its layers (EcoDesign 8, Circular design). Therefore, the packaging is also made from paper and 50 mats are packed into one packaging, as opposed to 30 pieces for Disposable A (EcoDesign 5).

For the final reusable absorbent mat, the choice was made to employ polyester as the primary material. This decision was prompted by a scarcity of information regarding the performance of the reusable materials outlined in Table 4.10. Crucial details concerning the potential number of wash cycles a material could endure and its impact on characteristics such as absorption capacity, dimensions, durability, and more were lacking. Also, for the reusable absorbent mat, the aim was to design a mono-material product (Circular Design). To do so, compared to Reusable A, the material viscose is not used in the soaker of the final reusable concept. It is expected that the influence on the washing process and other properties are negligible. Additionally, for the bottom sheet the polyurethane sheet laminated to the woven polyester is replaced with a mylar sheet. Mylar is a heat and shrink resistant plastic film made from the same raw material as polyester, namely polyethylene terephthalate [50]. Thus, it is expected that the performance will remain the same compared to the initial design. Also, for the final reusable concept the mono-material design facilitates recycling of the absorbent mat without the necessity to separate its layers (EcoDesign 8, Circular design).

Furthermore, for the redesign of both disposable and reusable absorbent mats preferably recycled materials are utilized (EcoDesign 2). Also, exclusively electricity generated from renewable energy sources for the manufacturing of the final disposable concept and for the use stage of the final reusable concept is employed (EcoDesign 4). The quantity of materials for the basic layers of the final disposable and reusable absorbent mat concept are listed in Table 4.10.

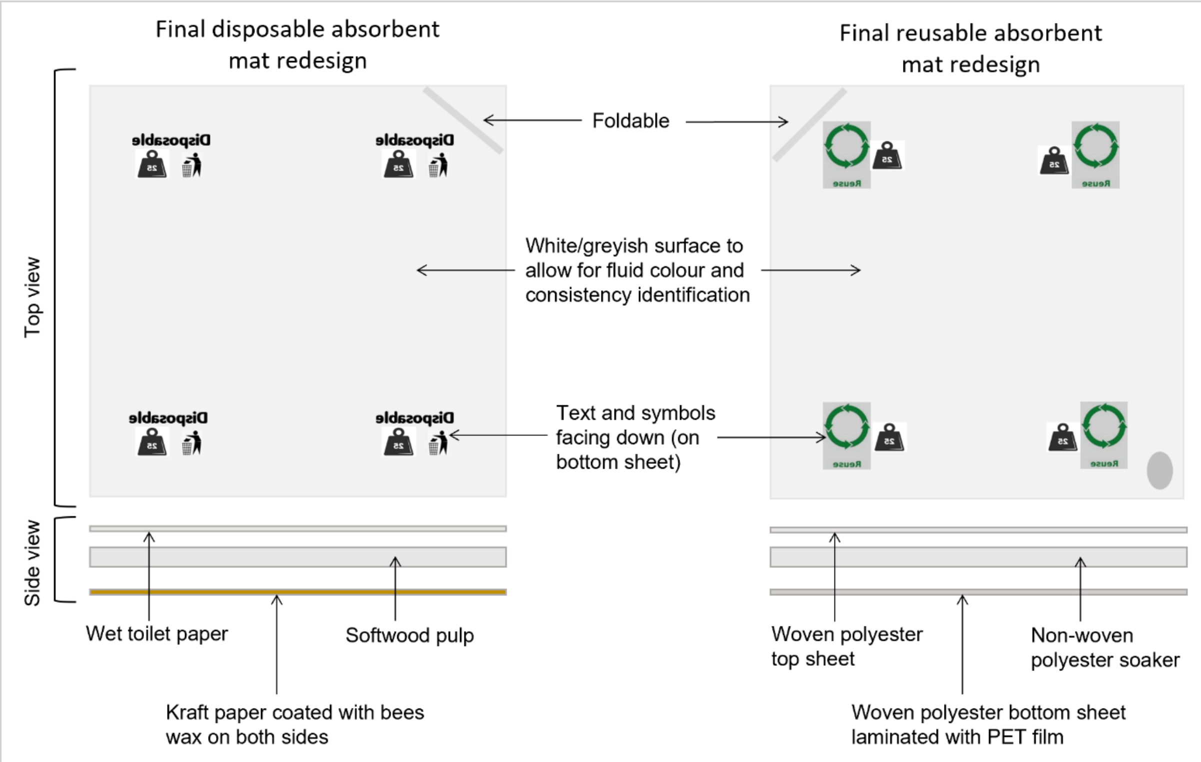

Figure chapter 4 15: Final absorbent mat concept. Left: Final disposable absorbent mat concept, right: Final reusable absorbent mat concept. The text and symbols are not visible through the top sheet, the mirror writing indicates that they are on the bottom sheet.

Table 4.10: Material composition of the final disposable absorbent mat concept.

Absorbent mat	Absorbent mat layer	Material	Amount
Disposable	Top sheet	Specialised paper (similar to wet toilet paper)	13g (based on 35gsm[2])
	Soaker	Softwood pulp	27g
	Bottom sheet	Kraft paper	16g (based on 45gsm)
		Bees wax	5g
Reusable[1]	Top sheet	Recycled woven polyester	36g
	Soaker	Non-woven polyester	48g
	Bottom sheet	Recycled woven polyester	31g
		Mylar film	25g

[1]The quantity of the reusable materials is based on the quantities of Reusable A.
[2]gram per square metre (gsm) gives an indication of the strength of kraft paper. 40gsm is typically used for tissue paper and 45gsm is typically used for paper bags [51], [52].

Concept evaluation

The redesign of disposable and reusable absorbent mats aimed at reducing their carbon footprint while maintaining user handling satisfaction. Both final design concepts satisfy most of the requirements, as far as conclusions can be drawn from the concepts worked out on paper. Additionally, the wish of employing mono-materials is satisfied.

To assess their environmental impact, the carbon footprint of the final disposable and reusable concepts were compared to Disposable B and Reusable A, respectively, see Appendix D3 for details. These mats were chosen as their properties, such as absorption capacity, are closest to that of the final concepts. For comparison of the final concepts, it is assumed that recycling of Disposable B and Reusable A is not feasible, as the absorbent mats are made from multiple, inseparable distinct materials. Both final disposable and reusable concepts have a lower carbon footprint compared to their pre-design counterparts, namely 60% lower for the final disposable concept and 39% lower for the final reusable concept, see Table 4.11. It is striking that the carbon footprint associated with the material production stage of the final disposable concept is approximately two times higher than that of Disposable B. This is mainly due to the increase in weight. Moreover, switching to electricity generated from renewable sources leads to a substantial reduction in carbon footprint in the manufacturing stage for both the final concepts, as well as in the use stage for the final reusable concept. For both final concepts, the end-of-life stage makes a negative contribution to the total carbon footprint impact (the contribution of the final reusable concept is so small that it is rounded to zero). The redesign of disposable and reusable absorbent mats effectively decreased their carbon footprint. Also, when examining the final disposable concept's scores of other impact categories, it becomes apparent that the redesign resulted in a decrease in environmental impact for most other categories, see Appendix . The final disposable concept has a lower score in thirteen out of eighteen impact categories compared to Disposable B. In the case of the final reusable concept, all impact category scores are lower compared to the standard reusable mat. The evaluation of the final disposable and reusable concepts, reveals that the environmental impact can effectively be reduced by implementing eco-design strategies in the design process, while still maintaining the necessary user handling requirements.

For the determination of the environmental impact of the final concepts it was assumed that recycling was feasible due to the utilization of mono-materials. However, in practice all waste is incinerated in the LUMC. As long as all waste is incinerated at the LUMC, Disposable B continues to maintain the lowest environmental impact among the disposable absorbent mats Disposable A, as well as the final disposable concept. A feasible option to reduce the environmental impact of disposable absorbent mats used in the LUMC is to use two different absorbent mats, namely one with an absorption capacity of 400 grams and the second with 175 grams. For half of the absorbent mat uses an absorption capacity of 175 grams is sufficient on for nearly all other uses 400 grams is sufficient. When both absorbent mats are correctly used the carbon footprint is reduced to 160 kg CO_2-Eq. Compared to only utilizing Disposable B, the two absorbent mat option leads to a reduction by 4% to 79% depending on the impact category.

Table 4.11: Carbon footprint scores of the final concepts compared to their initial design.

Life cycle stage	Global Warming Potential in kg CO_2-Eq			
	Disposable B	Final disposable concept	Reusable A	Final reusable concept
Material production	78	169	13	9
Manufacturing	67	15	5	3
Use	/[1]	/	41	27
End of life	57	-103[2]	5	0[2]
Total carbon footprint	202	81	64	39

[1]For the use stage of disposable absorbent mats the environmental impact is assumed to be negligible.
[2]The impact of recycling was approximated by assuming that 80% of the products materials, avoided the production of virgin materials. The assumption is based on the study of the European union that performed an LCA on the recycling of textiles [53]

5 Discussion

The primary objective of this research was to evaluate the environmental impact of reusable and disposable absorbent mats, with the additional aim of contributing to sustainable product development within this domain. To assess the achieved objective, an elaborate discussion on both the LCA study and the sustainable design are conducted separately. Additionally, the LCA and the design study's limitations are presented and recommendations for future research are highlighted. Finally, a separate section is devoted to the implications for practice and policy. This section delves into the recommendation on which absorbent mat to use in hospitals and suggests potential modifications manufacturers and other industry partners can make to reduce the environmental footprint of their absorbent mat products.

5.1 Life Cycle Assessment discussion, limitations, and recommendation

5.1.1 LCA discussion

The goal of this LCA study was to determine the cradle-to-grave environmental impact of disposable and reusable absorbent mats, and to identify hotspots that had a substantial environmental impact, in both material usage and process stages. The main findings of this study demonstrated that the Reusable A had a considerable environmental benefit as opposed to Disposable A, B, and C. For most of the impact categories, the score of Reusable A was between 33% and 64% lower, when compared to the lowest scoring disposable absorbent mat. The second lowest score was shared equally between Disposable B and C, and the largest score was obtained by Disposable A for most of the impact categories.

There are only two comparable studies available on the life cycle environmental impact of reusable and disposable absorbent mats. Overcash et al. [15] conducted an LCA of disposable and reusable absorbent mats. The absorbent mats are smaller in size but have similar material compositions compared to Reusable A and Disposable A and B, except for the addition of superabsorbent polymer in the disposable absorbent mat's soaker. The relative low impact of reusable mats compared to disposable absorbent mats is in line with Overcash et al. [15] that show that the environmental impact of reusable mats is 52% to 97% lower as compared to disposable absorbent mats. Furthermore, Geene [16] conducted an LCA of similar reusable and disposable absorbent mats. She concludes that the impact of reusable absorbent mats is lower compared to disposable absorbent mats, which is in line with the findings of this study. Additionally, the findings of this study for the carbon footprint, determined through the impact assessment method EF v3., of reusable mats is 55% lower as compared to Disposable A. This finding is in line with Geene [16], who suggested that the carbon footprint, determined through the same impact assessment method, of reusable absorbent mats, is 58% lower as compared to disposable absorbent mats.

The contribution analysis showed that Disposable A and B have their largest impacts during the manufacturing and material production stage. The relative high impacts of these two life cycle stages are in line with other studies that showed that the production of materials and the manufacturing of the finished product is a critical stage for the environmental footprint of disposable absorbent mats [15], [16]. A hotspot with substantial environmental impact in material usage is the bleached fluff pulp soaker, which is in line with the study of Geene [16] and several other studies on disposable diapers with similar material compositions [26], [27]. For Disposable C, the production stage has the largest environmental impact. This is in line with the study conducted by Mirabella that showed that the production of biodegradable materials for diapers has the largest contribution to the environmental impact [54]. The study even suggests that the energy consumption of the diaper's manufacturing stage is negligible. This suggestion aligns partly with the findings of this study, which indicate that the manufacturing stage contributes about 10% to the overall impact for most of the impact categories. The findings for Reusable A showed that the use stage has the largest share of the environmental impact compared to the other life cycle stages. These findings are in line with other studies on reusable absorbent mats and reusable diapers [15], [16], [26]. The studies showed that the washing and transport during the use stage have the largest contributions to the overall life cycle impact.

The sensitivity analysis for the disposable absorbent mats showed that high changes in quantity and quality of energy inputs to the manufacturing stage had a small effect on the overall carbon footprint. One study investigated the sensitivity of switching to a renewable electricity mix for the manufacturing of disposable diapers [55]. The study showed that the overall carbon footprint did decrease by approximately 15% which is also the case for this study [55]. Furthermore, for disposable absorbent mats, the findings of the sensitivity analysis showed that the switching of the soaker material from softwood pulp to viscose and vice versa had the largest impact on the overall carbon footprint. For Disposable C, the assumption was made to use standard viscose from Ecoinvent, whereas the supplier stated that Lenzing viscose was used [56]. This assumption could potentially have a large effect on the overall results of Disposable C. According to Lenzing, the carbon footprint impact of their viscose is 3.2 kg CO_2-Eq whereas in this study, the standard viscose has a carbon footprint impact of 5.2 kg CO_2-Eq [56]. Additionally, according to literature, the overall impact of Lenzing viscose is approximately 2.5 times lower compared to standard viscose [57], [58]. Due to the large contribution of the soaker material of disposable absorbent mats to their overall environmental impact, the results of Disposable C should be interpreted with care. Therefore, the impact of Disposable C might potentially be substantially lower when compared to Disposable A and B. The sensitivity analysis for Reusable A indicates that both loading fewer absorbent mats into the washing cycle and decreasing the use cycles have a considerable impact on the overall carbon footprint. The relative high impact of the washing cycle is in line with the studies of Overcash et al. [15] and Geene [16] that assumed 46 and 100 use cycles for one reusable mat, respectively.

The scenario analysis demonstrated that, even in the worst-case scenario for Reusable A, its carbon footprint remains lower than that of Disposable A in its best-case scenario. The carbon footprint impact of the best-case scenario of Disposable B and C is approximately equal to that of Reusable A's worst-case scenario. This shows that an accumulation of unfavourable process changes during the use stage can to a great extent influence the overall environmental impact of reusable mats. Hence, it is recommended to be cautious when extrapolating the outcomes obtained for Reusable A when varying washing processes are used. Furthermore, the results of the impact assessment method scenario analysis, indicate that the overall impact of Reusable A is slightly larger than presumed through ReCiPe. Reusable A now has the lowest impact score for thirteen (formerly fifteen) impact categories and the largest impact score for three (formerly one) impact category. Nonetheless, for all impact assessment methods, the overall impact of the reusable mat remains to be the lowest for most of the impact categories. This finding is further supported when considering the outcomes of Overcash et al. [15], which show that utilizing reusable absorbent mats results in a decrease in the overall usage of absorbent mats when compared to disposable ones.

Returning to the first research question, 'What is the environmental impact of reusable absorbent mats compared to disposable absorbent mats?' the conclusion can be drawn that the environmental impact of reusable absorbent mats is considerably lower than those of disposable absorbent mats. For most of the eighteen ReCiPe impact categories, except of fossil resources, marine eutrophication and ozone depletion, the impact score of reusable absorbent mats is considerably lower than that of disposable absorbent mats. Regarding the second research question, 'What are the environmental impact associated with each of the life cycle stages of reusable and disposable absorbent mats?' the findings suggest that the use stage of reusable absorbent mats and the stages encompassing material production and manufacturing of disposable absorbent mats make the most substantial contributions to their environmental impact.

Facing climate change challenges and following the Green Deal Sustainable Healthcare of the Netherlands, it seems evident that the environmental impact needs to be reduced [5]. The findings of this study offer the potential to contribute to the objectives of the Green Deal to reduce the carbon footprint and waste of the healthcare sector. By fully switching to reusable absorbent mats in the Netherlands, a reduction in emissions totalling 4.5 million kg CO_2-Eq would be achieved. This reduction is approximately equivalent to the cumulative environmental impact over the entire lifecycle of 180 passenger cars [11], [59].

5.1.2 LCA limitations and recommendations

The findings in this study are subject to several limitations. The major limitation of this study is the assumption that the clinical performance is equal among all mats. However, the mats vary in performance regarding their ability to collect and absorb fluids. The total amount of fluid that can be collected by Disposable A and Reusable A is substantially larger than that of Disposable B and C. This difference may potentially impact the number of absorbent mats required to collect a specific amount of bodily fluids, consequently affecting the environmental impact. Additional research should be done to determine the influence of mat choice, especially between reusable and disposable alternatives, on the frequency of changing the patient's absorbent mat.

An issue that was not addressed in this study was the distinction between clean and dirty absorbent mats. Dirty mats become saturated with bodily fluids, leading to a substantial increase in their mass, possibly exceeding several times their original mass. This could have adverse effects on the transportation, incineration and washing of absorbent mats with respect to their environmental impact. A further LCA study on absorbent mats could incorporate an assessment of the collected fluid’s impact.

Furthermore, several limitations regarding the assumptions for the inventory analysis need to be acknowledged. For the use stage of Reusable A specific data, derived from one laundry and hospital are used. It would be interesting to know the impact on the LCA study if different washing processes and distances between the hospital and laundry are used. In order to better relate the model and study results to different washing processes (e.g., in house hospital laundry and varying washing processes) a study expansion is needed that includes different washing processes. Additionally, it was assumed that the absorbent mats could be effectively cleaned using standard hospital linen washing settings. Given that absorbent mats tend to accumulate considerable soil, it is advisable to conduct a pilot study to assess whether reusable mats can be adequately cleaned or if additional washing procedures are necessary.

Another arguable weakness of the inventory analysis is the use of standard viscose instead of Lenzing viscose for Disposable C. Detailed inventory data are not available about Lenzing viscose. Also, no inventory data are available for the manufacturing process of disposable absorbent mats. To address this, a study utilizing openly accessible inventory data of the Lenzing viscose production process, and the manufacturing process of disposable absorbent mats would be required. Regarding the impact assessment method, it is important to note that the impact categories are not complete. For instance, they do not encompass the release of microplastics that occur during the washing of the polyester reusable mats. Lastly, it is worth noting that the implications of these findings may not extend to the usage of absorbent mats in hospitals within developing countries, primarily due to the reliance on inventory choices predominantly based on European standards.

5.2 Sustainable redesign discussion, limitations, and recommendations

5.2.1 Sustainable redesign discussion

The objective of the design process was to enhance the design of both disposable and reusable absorbent mats, with a focus on reducing their environmental impact while maintaining handling satisfaction among users. Through the redesign of both disposable and reusable absorbent mats, the total carbon footprint was effectively reduced for both final absorbent mat concepts. For the final disposable concept this only holds true under the assumption that the absorbent mat is recycled; otherwise, the initial disposable absorbent mat should be employed, which in that case has a lower environmental impact. The reusable absorbent mat, regardless of whether it underwent redesign or not, remains to be the absorbent mat with the lowest overall environmental impact, also when compared to the redesigned final disposable concepts and the solution to employ to different disposable absorbent mats.

In calculating the environmental impact of the final concepts, it was assumed that absorbent mats would be properly disposed of in order to be recycled. However, waste management in Dutch hospitals hinders this ideal scenario, as waste separation at hospital level is absent, leading typically to the incineration of all hospital waste. Therefore, if the final disposable concept is implemented in Dutch hospitals, its environmental footprint would be notably higher than that of the currently employed Disposable A mat. Furthermore, there was an unexpected increase of environmental impact for the material production stage of the final disposable concept. This outcome is primarily attributed to the larger mass of the final disposable concept compared to Disposable A, which is mainly due to the use of paper for both the top and bottom sheets.

The results of the LCA study informed the redesign of the absorbent mats by the identification of both material and process hotspots of the reusable and disposable absorbent mats. Especially strategy 2 ‘Selection of low-impact materials’ was greatly facilitated by the results of the LCA study and its supplementary results. Additionally, the LCA was successfully employed to evaluate the environmental impact of the final reusable and disposable concept. This integration of LCA findings into the redesign process and the subsequent evaluation of the final concepts demonstrated the significant value of this approach in making informed, environmentally friendly design choices.

Regarding the third research question ‘How can the design of reusable and disposable absorbent mats be improved to reduce their environmental impact?’ the findings suggest that the reduction of materials, utilizing a mono-material approach, and employing renewable energy sources for both the manufacturing and use stage, reduce the environmental impact of absorbent mats. Additionally, the final design concepts demonstrate that an environmentally enhanced design does not necessarily impede user satisfaction with the product. Furthermore, the LCA evaluation of the final disposable concept showed that substantial environmental improvements are achievable when disposable products are fully recycled.

5.2.2 Sustainable redesign limitations and recommendations

In this design study, several important limitations along with recommendations for future research are considered. The main limitation of this study revolves around the study's focus on environmental optimization, to the exclusion of other critical factors like safety, user comfort, manufacturability, and cost-effectiveness. Therefore, the incorporation of considerations related to the above-mentioned critical factors, specifically that of safety due to the hospital setting, into the design process is paramount for the development of a well-rounded absorbent mat design. Furthermore, a life cycle cost analysis should be performed to evaluate the financial viability of the developed concepts.

Another constraint is linked to the fact that the design remains in the conceptual phase, untested. To overcome this limitation, it is advisable to conduct a usability or pilot study on prototypes of the absorbent mat. This study should evaluate whether the design concepts and materials meet the established requirements. Another constraint is the narrow focus on a single user group, primarily the healthcare staff of the obstetrics department, despite the absorbent mat's use throughout the entire LUMC. It is recommended to involve multiple user groups from the LUMC to identify additional functions and requirements.

Lastly, the design study was limited by the single-designer approach, where one designer oversaw the entire design process. To foster a more diverse range of ideas, it is advised that future design efforts are performed within group settings. Group settings in general act as a catalyst for creativity, resulting in more effective and multifaceted design solutions.

5.3 Hospital and industry implications

For hospitals, industry, and policymakers it is important to realize that the reduction of the environmental impact of medical devices, such as absorbent mats, potentially have a positive effect on climate change. Making the transition from disposable to reusable medical products can be a valuable step in this direction. In this study, an LCA was conducted for both disposable and reusable absorbent mats, and subsequently these absorbent mats were redesigned. The intended application of the LCA study was to guide decision making within Dutch hospitals by identifying the environmental impact associated with the use of disposable and reusable absorbent mats.

Overall, reusable absorbent mats are environmentally superior compared to their disposable counterparts. Therefore, Dutch hospitals need to fully switch to reusable absorbent mats. If transitioning to a reusable absorbent mat is not a feasible, it is advised to opt for the use of two disposable absorbent mats: one with an absorption capacity of 400 grams and the other with 175 grams. Furthermore, the LUMC must abandon the use of Disposable A and fully switch to Disposable B, as the latter is sufficient for 90% of absorbent mat uses. Furthermore, it is imperative for hospitals to provide education and training to users regarding the appropriate utilization of absorbent mats. Particular attention should be given to visualize the absorbent capacity of these mats to the users.

Moreover, manufacturers and laundry service providers must fully switch to renewable energy sources to effectively reduce the environmental impact of their products. The recycling of medical products, particularly when facilitated using mono-materials, has the potential to reduce the environmental impact of products by 60% and minimize waste generation. Nevertheless, the achievement of circularity and waste reduction in healthcare settings is impeded as separation of waste and other sustainable waste practices are not embraced by the stakeholders across the product life cycle. Therefore, policymakers must encourage collaboration among life cycle partners and allocate financial support to endorse sustainable waste management principles within the healthcare sector.

Finally, to gain deeper insights into the environmental impact of the healthcare sector, more comprehensive and accurate data is essential. This data needs to be provided by manufacturers of medical products. Manufacturers must improve transparency regarding the materials and manufacturing processes they employ for their medical products. Additionally, policymakers must consider implementing regulations that compel manufacturers to adhere to these transparency standards.

6 Conclusion

This present study was designed to determine the environmental impact of disposable and reusable absorbent mats and to improve their environmental impact by a sustainable redesign. One of the major findings to emerge from this study is that reusable absorbent mats are environmentally superior compared to their disposable counterparts, even if the impact of disposable absorbent mats is mitigated by product redesign.

The LCA study has shown that the environmental impact score of the reusable absorbent mat is lower in fifteen out of eighteen impact categories compared to disposable absorbent mats. The environmental impact of absorbent mats is largest in the use stage for reusable absorbent mats, and in the material production and manufacturing stage for disposable absorbent mats. These findings emphasize the significance of targeting these life cycle hotspots to reduce the environmental footprint of absorbent mats. The LCA study's strength lies in its comprehensive examination of multiple mats, encompassing four distinct variants, and the assessment of the environmental impact across eighteen different impact categories. Furthermore, for at least one disposable absorbent mat and for the reusable absorbent mat, industry data was employed. The use of primary data and the extensive scope enhances the reliability and comprehensiveness of the findings, contributing to their robustness. The major limitation of the LCA study lies in the utilization of data from a single laundry service provider and the assumption that the cleaning processes used for hospital bed linen are sufficient for effectively cleaning reusable absorbent mats.

The utilization of eco-design strategies for the redesign of absorbent mats has identified various design interventions to mitigate the hotspots identified in the LCA study. These strategies include material reduction, mono-material approaches to facilitate recycling, and the use of renewable energy sources in both manufacturing and us stages. Recycling of the disposable absorbent mats can substantially improve the total environmental impact. The design process showcases its strengths in the utilization of a multifaceted design process incorporating eco-design strategies as well as human-centred design principles to improve product usability and sustainability. Major limitations of the redesign study are that only handling data from users of the obstetrics department is incorporated into the design process, and that no prototype is developed. The results of the LCA study have noticeably influenced the redesign of absorbent mats by identifying material and process hotspots. This integrated study approach underscores the practical application and benefits of LCA in aiding sustainable product development and fostering environmentally conscious design choices.

The major recommendation that comes forth from this study is to fully switch to reusable absorbent mats. In cases where the implementation of reusable absorbent mats is not feasible, hospitals this is not feasible, hospitals may consider employing a dual-system approach using two disposable absorbent mats. These absorbent mats should possess different absorption capacities to effectively manage varying fluid collection requirements. Moreover, all life cycle partners should encourage a circular economy in which absorbent mats are fully recycled.

This study has showcased the multifaceted utility of LCA in supporting sustainable hospital decision-making and offering valuable insights for sustainable product design. Looking to the future, the findings presented here pave the way for reevaluating the choices in healthcare settings between the use of disposable and reusable medical products and promoting environmentally friendly design strategies for these products. Reassessing these decisions has the potential to substantially decrease the environmental impact of the Dutch healthcare sector. Through the dual lenses of LCA and sustainable design, this study emphasizes the potential to simultaneously reduce environmental impact and improve user experiences, underlining the essence of sustainable design.

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