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A Comparative Life Cycle Assessment (LCA) of Nonwoven Products

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ABSTRACT

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The necessity to transform the existing economic approach, impacting the environment, became clear even for sceptics. As most technologies and productions remain linear with the take-make-waste model, the economic actors seek to adopt new circular practices incorporating nature into the equation. To address the gap in understanding the real burden that daily consumption patterns bring to the ecosystems, and provide decision-makers with the essential guidelines for improvement in products and services, the Life Cycle Assessment (LCA) method is likely the most valuable scientific-based tool available.

The objective of the study was to assess the environmental impacts of nonwoven textile materials used to produce single-use consumer wipes manufactured with two distinct raw materials and methods – polypropylene granulate with spunbound technology based upon the plastic extrusion process (system A) and cellulosic wood fibers using the wetlaying technology resembling papermaking process (system B). The study was conducted in SimaPro LCA software using a methodology compliant with ISO 14040/44 Standards. The subsequent comparison of these product systems was performed to uncover the most affected impact categories and reveal environmental hotspots and areas for improvement.

The LCA results show that the most affected environmental impact categories for both product systems in descending order were Human carcinogenic toxicity, Freshwater ecotoxicity, Marine ecotoxicity, Freshwater eutrophication, Fossil resource scarcity and Ionizing radiation, with a cumulative contribution of over 90 per cent of the total impacts. The environmental hotspots refer to different life cycle phases: the main contributors to the impacts in system A are the raw material production and conversion stages, whereas the main contributor in system B is the core nonwoven manufacturing stage. For both product systems, at least half of the total impact was attributed to the human carcinogenic toxicity category and directly linked to energy production. The improvement in this area of the supply chain of both systems would significantly enhance the overall sustainability of the products. It was concluded that further expansion of the scope of the study to include omitted stages of the life cycle would add to the holistic comprehension of the environmental impact of nonwovens. The study also revealed for the broader implementation of the LCA method, the most significant limitation was data availability issues.

Keywords: lca, circular economy, nonwoven, sustainability

CONTENTS

ABBREVIATIONS AND TERMS

EDANA	European Disposables and Nonwovens Association
INDA	Association of the Nonwoven Fabrics Industry
CSRD	Corporate sustainability reporting
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
ISO	International Organization for Standardization
PET	Polyethylene terephthalate
PP	Polypropylene
UNECE	United Nations Economic Commission for Europe
SUP	Single Used Plastics Directive
SETAC	Society of Environmental Toxicology and Chemistry
UNEP	United Nations Environment Program
CF	Carbon Footprint
EPD	Environmental Product Declaration
PCR	Product Category Rule
NIST	National Institute of Standards and Technology
TRACI	Tool for the Reduction and Assessment of Chemical and other environmental Impacts
ETH	Swiss Federal Institute of Technology
WRI	World Resources Institute
WBCSD	World Business Council for Sustainable Development
WDI	Water Depletion Index
CFm	Characterization Factor

1 INTRODUCTION

The imbalanced natural processes cause climate cataclysms. With the unprecedented temperature anomalies of the current year, we are on track to witness the warmest year on record. The existing technologies and economic practices are under constant building pressure due to growing fears of inevitable catastrophic consequences for the planet if we fail to decouple economic growth from the rate of fossil and mineral materials extraction. The need for a deeper understanding of the effects that bring our consumption patterns and products is of high importance. In addressing the assessment of the environmental impact of products, the method gaining increasing popularity is Life Cycle Assessment (LCA). Utilization of the LCA technique in different decision-making processes, such as R&D, strategic planning, and marketing, gives companies a powerful tool to rump up the sustainability of the business and facilitate a necessary circular transition.

1.1 Goals and Objectives

The goal of this thesis is to produce and report information regarding the environmental impact of two different nonwoven processes and raw materials, fossils-derived polypropylene (PP) and renewable cellulosic pulp, using the Life Cycle Assessment (LCA) tool and reveal which of the production methods and raw material is more sustainable. The study consists of two parts modelling separate production processes and subsequent comparison of their environmental burden. For this study the SimaPro 9.3 Classroom Edition software is used along with the industrial Ecoinvent database. Another objective of this thesis is to spotlight the LCA as an essential instrument with multiple applications from product innovation and compliance with regulation to a mean of comparing the environmental performance of different products with the same function and an enabler for consumers and investors to make more informed decisions promoting sustainability and circularity. Providing this research is an independent study, the main source of information used for modelling was open sources such as articles, books, corporate websites, life cycle inventory databases, thesis works, etc.

1.2 Thesis Structure

The thesis consists of four parts. The introduction part sets the goals and objectives of the study. The second part is a theoretical background, which gives an overview of nonwoven products and the present state of the industry as well as touches on a circular economy transition and emphasises the importance of materials and process innovation in the nonwoven industry, taking into account the significance of the nonwovens for the economy and its complex interconnections. Introduces an LCA method in detail, describing the history of the development of the method and mandatory stages of the process according to the ISO standards. The chapter is based on a literature review and other publicly available materials. In the third part of the study, the Life Cycle Assessment of a spunbound nonwoven produced from polypropylene and the Life Cycle Assessment of a nonwoven produced from cellulosic wood pulp with wetlaid technology is conducted. Detailed descriptions of the modelled processes, data collection and assumptions are made. Results and discussions are presented in the fourth part, and final conclusions on the comparative Life Cycle Assessment are made.

2 THEORETICAL BACKGROUND

2.1 Overview of Nonwoven Industry and Products

Textile fabrics can be produced using three distinct methods: weaving, knitting, and nonwoven. Among these techniques, the nonwoven process stands out as a more recent approach to fabric production. Nonwoven fabrics are a category of textile materials representing manufactured sheets comprised of a layer of fibers. This layer can take the form of a carded web, a fiber web, or a composition of randomly oriented or arranged fibers or threads. These fibers may also be combined with other materials of diverse origins, including traditional woven fabrics, plastic films, foam layers, metal foils, and other components. The assembly of these materials results in the formation of a textile product, stabilised together by means of mechanical binding, thermal or chemical bonding processes. (Elise 2020, 2; Textileblog 2020)

Nonwoven fabrics can be classified based on the manufacturing method and bonding type. There are three main categories of web formation techniques. **Dry-laid** nonwovens have their origins in textile technology, where the yarn-spinning stage is omitted. It is the staple fiber-based sheet laying process including three major steps. The fiber preparation stage usually involves opening and mixing processes, web formation by air-lay (randomly laid web) or carding (parallel laid, cross laid) processes and finally web bonding process which can be either one or a combination of mechanical bonding, thermal bonding, or chemical bonding. Typically, the size of used raw material fibers varies between 12 to 100 mm in length. (Russell & Smith 2015, 169–172; Textileblog 2020)
Wet-laid web manufacturing is rooted in the papermaking process. This technology is suitable for shorter fibers less than 10 mm in length. The wet-laid nonwoven technique offers several advantages, such as high productivity, consistent quality with lower material weight, and the better possibility to control fiber direction, in contrast to the dry-laid method. The fiber preparation stage consists of dispersing fibers in fluid (water with added chemicals) and manufacturing fiber-water suspension. In the web-forming step, the suspension is spread onto a perforated lattice belt, followed by the dehydration and finally bonding stage. (Russell & Smith 2015, 169–172; Textileblog 2020)

Spunmelt term refers to nonwoven products created with either spunbound or meltblown production technique based upon the extrusion of continuous filaments from polymer raw material. The main difference between the two is that the melt blowing produces very fine fibres compared to spunbound. These web formation methods apply to synthetic polymers. They are relatively simple processes in comparison with wet-laid and dry-laid methods. Web formation and bonding are seamlessly interconnected, resulting in the direct path from polymer chip to final fabric within a unified and integrated process. (Russell & Smith 2015, 169–172; Textileblog 2020)

Depending on bonding type, nonwovens can be divided into mechanically bonded (needle punch, hydroentanglement, stitch bonding), thermal bonded (calendaring, through air bonding, ultrasonic) and chemically bonded (impregnating, spraying, foam coating, print bonding). (Muralidhar n.d.)

Nonwovens are defined by ISO standard 9092. These standards are regularly reviewed and updated by industry experts in order to better reflect the current comprehension of nonwovens. The present definition of a nonwoven adopted by leading industry associations: “An engineered fibrous assembly, primarily planar, which has been given a designed level of structural integrity by physical and/or chemical means, excluding weaving, knitting or paper making” (EDANA n.d.). To distinguish wet-laid nonwovens from papers, the European Disposables and Nonwovens Association (EDANA) recognises a material as a nonwoven if more than 50% by mass of its fibrous content is made up of fibres with a length-to-diameter ratio greater than 300 (Russell 2022, 5). The physical properties of nonwoven products are greatly varied. Therefore, they are widely used in numerous other industries, see TABLE 1.

TABLE 1. Nonwoven products application

Industry	Products
Apparel	Clothes, Footwear
Agriculture	Covers for crops, Weed control fabrics
Automotive / Transportation	Boat furnishings, Acoustic insulation
Consumer Products	Interior design, Carpet
Electronics	Battery separators, Cable wrap
Filtration	Filtration membranes
Furnishings / Bedding	Ceilings, Coverings
Geotextiles / Construction	Hydro membrane, Insulation, Drainage
Hygiene	Diapers, Feminine hygiene, Single-use
Medical / Healthcare	Surgical drapes, Dressings, Bandages
Packaging	Tea bags, Food pads, Canisters
Wipes	Mops, Cleaning wipes

Nonwoven products have various applications that can be categorized based on their duration of use. The approximate service life of different nonwoven products on a temporal scale is shown in FIGURE 1.

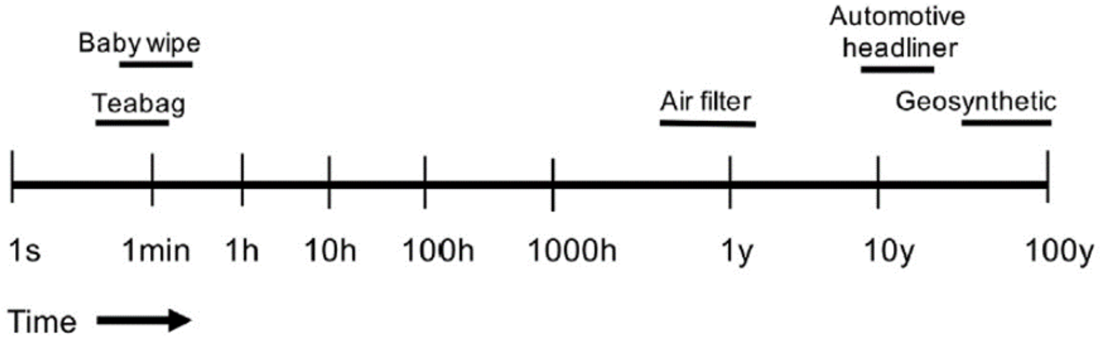


FIGURE 1. Service life of nonwoven products (Russell 2022)

Single-use nonwoven products typically have a relatively short service life, ranging from a few seconds to a few hours before being disposed of. The proportion of nonwovens falling into the single-use category varies across Europe, the United States, and Asia but generally constitutes a significant share. Single-use nonwovens are dominant in the hygiene and wipes applications, including products such as diapers, feminine care items, and baby wipes, as well as packaging food items like teabags, coffee filters, and personal protective equipment. In contrast, multiple-use nonwoven products typically have a longer service life, spanning weeks to months. These products are used intermittently before being discarded and thus remain in service for a more extended period than their single-use counterparts. Multiple-use nonwoven products are created to be washed, laundered or otherwise cleaned to restore functionality. For instance, heavy-duty industrial wipes and mops for surface and floor cleaning, protection covers for bedding and filters for vacuum cleaners. Long-life nonwovens, on the other hand, have service lives measured in years, extending to several decades in some cases. Products within this category include clothing interlinings, artificial leather, carpet underlay and floor coverings, thermal insulation materials, roofing membranes, geosynthetics, and automotive interior parts. Long-life products are usually heavier than those intended for single-use or multiple-use, which translates to higher manufacturing costs. (Russell 2022, 15)

According to several analyses, including those from Association of the Nonwoven Fabrics Industry (INDA), EDANA and Smithers, around 13.4 million tons of nonwovens are now produced annually, with roughly half being dry-laid or wet-laid and the other half made by spunbound and meltblown technologies (Russell 2022, 11; INDA, n.d.). Smithers reported the expected average annual global nonwoven market growth rate for 2022–27 at a level of 6.8% (Mango, 2021). The nonwoven industry today is a healthy multibillion-dollar profitable, and very sophisticated business area with a high degree of process automation and, therefore, highly capital-intensive at the same time. As a result, 90% of the total global sales are attributed to only around 40 companies. World-leading nonwoven manufacturers, grouped by production technique presented in TABLE 2. Historically, much of the nonwoven industry was based in North America, Europe, and Japan, where most manufacturing technologies were invented and developed. While the Western market become extensively saturated and competitive, certain segments of the nonwoven industry in other parts of the world experiencing double-digit annual growth. (Russell 2022, 10)

TABLE 2. The 20 leading nonwoven manufacturers in 2020 by overall turnover (Handbook of Nonwovens modified)

Drylaid and wetlaid nonwovens		Spunmelt nonwovens	
Company	Headquartered	Company	Headquartered
Berry Global	United States	Berry Global	United States
Freudenberg	Germany	Freudenberg	Germany
Ahlstrom	Finland	Ahlstrom	Finland
DuPont	United States	Kimberly-Clark	United States
Kimberly-Clark	United States	DuPont	United States
Fitesa	Brazil	Fitesa	Brazil
Glatfelter	United States	PFNonwovens	Czech Republic
Lydall	United States	Zhejiang Kingsafe	China
Suominen	Finland	Avgol	Israel
TWE Group	Germany	Toray Advanced Materials	S.Korea/Japan
Hollingsworth & Vose	United States	Fibertex Personal Care	Denmark
Zhejiang Kingsafe	China	Asahi Kasei	Japan
Sandler	Germany	Mitsui Chemicals	Japan
Toray Adv Materials	S.Korea/Japan	Gulsan	Turkey
Jacob Holm	Switzerland	Union Industries	Italy
Georgia-Pacific	United States	Hassan Group	Turkey
Nan Liu	Taiwan	Xingtai Nonwovens	China
Fibertex Nonwovens	Denmark	Dalian Ruiguang	China
Union Industries	Italy	Toyobo	Japan
Hassan Group	Turkey	Halyard Health	United States

Currently, artificial materials are dominant over the production of nonwovens, accounting for up to 99% of the total output. Man-made fibres are split into three categories – made from natural polymers, made from synthetic polymers, and made from inorganic materials. Polypropylene (PP) is the primary polymer used for creating nonwovens, with polyester, regenerated cellulosic, acrylic, polyamide, cotton, and other specialized fibers following suit. Utilizing PP fibers as the foundation of nonwovens presents several advantages, including lightweight, softness and comfort, melting processability, enhanced bulk and coverage. This unique amalgamation of qualities grants nonwoven manufacturers access to a valuable, high-performance polymer or fiber at a remarkably competitive cost. (Russell 2022, 9)

Nevertheless, as the pressure on oil-based synthetic materials intensifies, there is an increasing demand for cellulosic materials, with a focus on regenerated cellulose fibres such as lyocell derived from wood pulp, along with various other natural fibres. These natural polymer materials are not suited for melt processing. As a result, the prevailing production trend shifts towards dry laid web production, in contrast to the spunlaid thermoplastic methods. In response to the growing demand for eco-friendly nonwoven products, there is also a significant rise in the utilization of recycled synthetic polymers, notably polyester (PET). A growing number of PET nonwovens coming into the market today are made from recycled plastic bottle waste. (Russell 2022, 10) These practices are a specific source of growing concern of the European Commission, reflected in the EU Strategy for Sustainable and Circular Textiles. Especially the accuracy of green claims made by producers on using recycled plastic polymers in textiles where these polymers do not come from fibre-to-fibre recycling but from sorted PET bottles. Such sustainable claims often risk misleading consumers, and the practice is actually not in line with the EU circular model for PET bottles. The food-grade materials are supposed to be kept in a closed-loop recycling system and are subject to extended producer responsibility obligations, including fees. These green claims face further challenges, given the role of synthetic fibres in microplastic pollution. (EC 2022, 6)

This thesis aims to look closer specifically at two raw materials for nonwovens: polypropylene and cellulose. A broader outlook on these materials will be given later during an LCI analysis of the product systems. The comparative LCA objective is to study and reveal the environmental impact of these materials together with different production techniques by spunbound and wetlaid methods.

2.2 Imperative of Circular Transition

Global extraction of natural resources has more than doubled since 1990 and has the potential to repeat this doubling by 2060 if corrective measures are not implemented. The UN International Resources Panel reports that 90% of worldwide biodiversity loss and water contamination, along with half of total greenhouse gas (GHG) emissions (not including climate impacts related to land use), are attributed to resource extraction and processing (IRP, 2019). The United Nations Economic Commission for Europe (UNECE) region, including more than 50 countries from North America through Europe to Central Asia, holds significant responsibility as major consumers and producers of natural resources. While resource efficiency within this region is improving, the overall material footprint, inclusive of raw materials in imports, increased between 2000 and 2017 by over 17%. The prevailing take-make-waste model, which has been dominant for the past 70 years, is no longer fit for purpose. (Algayerova, 2021)

The global economy, particularly the nonwoven industry, can be described as "linear", primarily based on extraction, manufacturing, use, and disposal. This linear economic approach results in the exhaustion of resources, biodiversity losses, waste generation and pollution, causing substantial damage to the Earth's ability to sustain the requirements of future generations. Furthermore, numerous planetary boundaries have already been met or surpassed, see FIGURE 2. (ISO, 2023). It means we consume more than our planet is capable of regenerating.

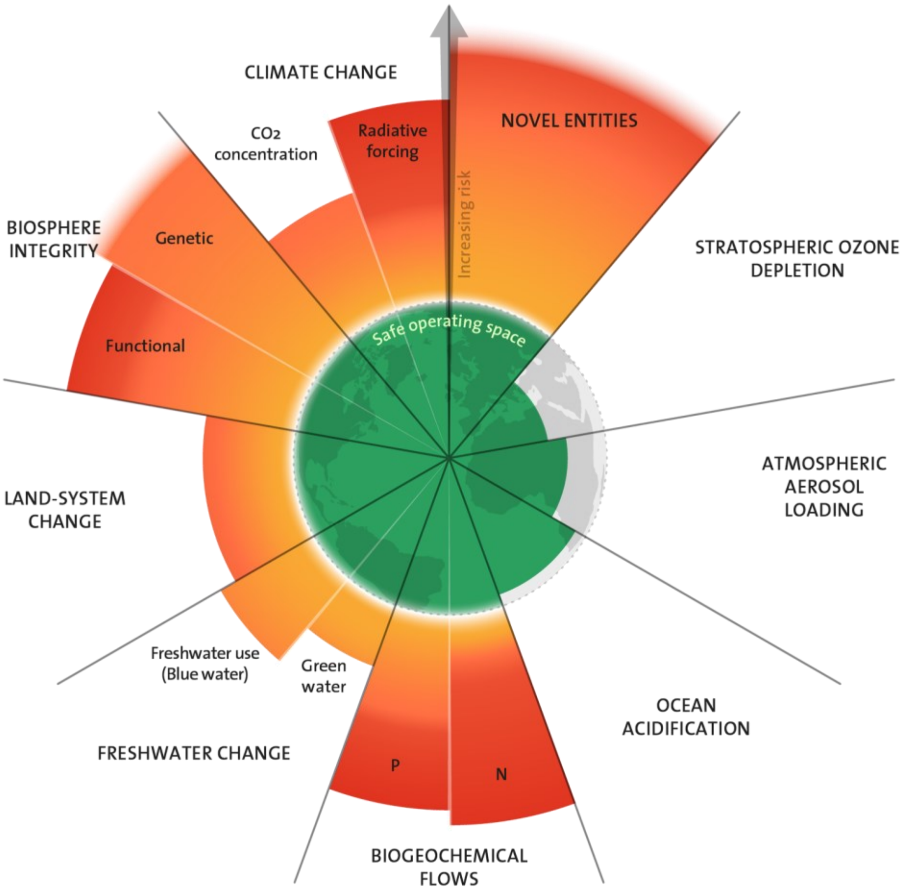


FIGURE 2. Planetary boundaries (Stockholm Resilience Centre 2023)

The planetary boundaries framework defines a global safe operating space for humanity's pressure on nine biophysical systems and processes that regulate the state and resilience of the Earth system. The relatively stable interglacial Holocene (~11,700 years ago) is used as the baseline. According to Wang-Erlandsson's et al. (2022) latest assessment the planetary boundary for freshwater indicates that it has now been transgressed. (Wang-Erlandsson et al. 2022, 380)

To address our present and future human requirements (housing, food, healthcare, transportation, etc.), there is a growing recognition that shifting to an economy based on a circular flow of resources can bring more value to society and stakeholders. This approach handles and regenerates natural resources sustainably, strengthening the quality and resilience of ecosystems. Companies recognize multiple incentives to be involved in a circular economy, for instance, offering competitive and more sustainable products, maintaining better relationships with stakeholders, meeting commitments or regulatory requirements, taking part in climate action, addressing the risks of resource scarcity, boosting overall resilience in environmental, social, and economic aspects, all while fulfilling human needs. In order to harmonize the understanding and support the implementation and measurement of the circular economy the ISO 59000 series of documents was developed. The series also contributing to the achievement of the UN Agenda 2030 for Sustainable Development. (ISO, 2023)

The Ellen MacArthur Foundation (n.d.) defines the circular economy as a system where materials never become waste and nature is regenerated. In a circular economy, the main focus is maintaining products and materials within a closed loop, achieved through various processes such as repair, reuse, refurbishment, remanufacturing, recycling, and composting. This approach to the economy addresses critical global issues like climate change, biodiversity loss, waste management, and pollution by decoupling economic activity from the extraction of finite resources. (The Ellen MacArthur Foundation n.d.) The circular economy operates on three guiding principles, based on design: eliminate waste and pollution, circulate products and materials as long as possible at their highest value and regenerate nature.

In our current economy, we take materials from the Earth, make products from them, use and finally throw them away as waste – the process is linear. In a circular economy, by contrast, waste is stopped from being produced in the first place. The circular economy system diagram, FIGURE 3, known as the butterfly diagram, illustrates the continuous flow of materials in a circular economy. There are two main cycles – the technological cycle and the biological cycle. In the technological cycle, products and materials are held in circulation through processes such as reuse, repair, remanufacture and recycling. In the biological cycle, the nutrients from biodegradable materials are returned to the Earth to regenerate nature. (Ellen MacArthur Foundation, 2019)

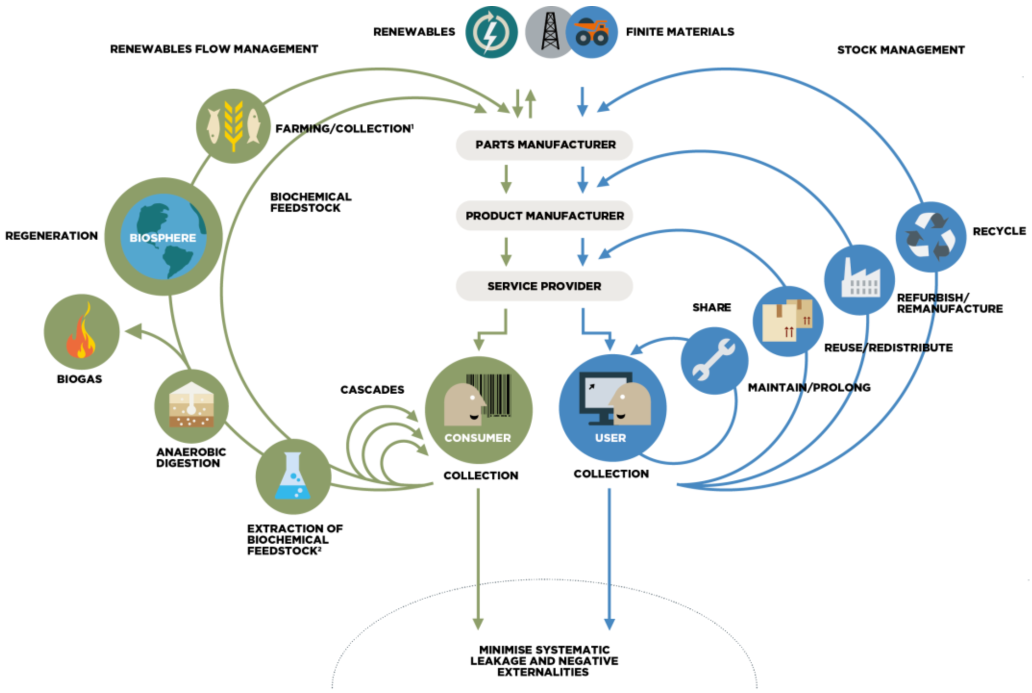


FIGURE 3. The butterfly diagram of Circular Economy (Ellen MacArthur Foundation, 2019)

One of the evolving megatrends identified recently by Sitra, called "Cracks are showing in the foundation of the economy". Described by increasing inequality and the ecological crisis mainly result from the weaknesses of the current linear system. The transformation of work by digitalisation penetrates every aspect of life, also trembling the foundations of the economy, which is under increasing pressure to change. The circular economy provides the tools to tackle climate change and biodiversity loss while addressing essential social needs. It has the power to preserve economic prosperity while preventing irreversible climate change, waste pollution and extinction. (Sitra, 2023)

A white paper published by the Ellen MacArthur Foundation in collaboration with Bocconi University and Intesa Sanpaolo provide evidence on how circular economy strategies can reduce investment risk by decoupling economic growth from resource consumption, diversifying business models, and allowing businesses to better forecast stricter regulation and shifting customer preferences. The authors analysis of over 200 European companies across 14 industries revealed that the more circular a company is, the lower its risk of default on debt over a five-year time horizon, and the higher the risk-weighted returns on its stock. The research also demonstrated that applying circular economy principles reduces business exposure to supply chain disruptions and resource price volatility. (Bocconi University, Ellen MacArthur Foundation, Intesa Sanpaolo, 2021)

Notably, new rules on corporate sustainability reporting (CSRD) entered into force in the beginning of 2023. The EU latest directive aims to update and enhance regulations related to the disclosure of social and environmental data. These revised guidelines are designed to guarantee that various interested parties have adequate access to the necessary information for evaluating the impact of business activity on society and the environment. These regulations will facilitate investors in estimating financial risks and opportunities associated with climate change and other sustainability matters. (EC, 2023) CSRD, along with the EU Single Used Plastics Directive 2019/904 (SUP) aimed to reduce plastic pollution and marine litter through increasing public awareness, reducing consumption, labelling and design requirements, and steadily growing consumer demand for products compliant with the ISO 17088 Organic recycling (Industrial composability) standard will be shaping the environment in which the nonwoven industry operating.

An increasingly challenging regulatory landscape, particularly related to environmental sustainability, together with stricter product performance requirements, means the improvements in design, materials, and technological processes of nonwoven products are no longer a voluntary choice but an urgent necessity. For many companies across the nonwoven industry, this induced a search for alternative, bio-based polymers or a focus on increasing the use of recycled materials along with a desire to comprehend the existing environmental footprint of their products (McIntyre, 2022).

Nonwoven waste streams are especially problematic due to their complex structure, represented by a combination of several materials of different origins and bonding chemical agents, which sometimes make it almost impossible to recycle. With most of the end-of-life nonwovens being either incinerated or landfilled, the nonwoven industry is actively seeking ways to make production patterns more sustainable and pay more attention to the entire life cycle of items, a significant portion of which have an ultra-short use phase as minor as a few seconds.

Peña et al. and the Life Cycle Initiative promote the use of LCA as a methodology to build more consistent and robust circular strategies that consider upstream and downstream flows and address crucial resources and impacts, leading to better business decisions for sustainability. According to Peña et al., the application of LCA in assessing and planning new projects, designing products, monitoring and evaluation, as well as in data collection and assessment, would lead to the creation of a better circular economy system. (Peña et al. 2021, 218)
The LCA technique serves as a powerful instrument capable of bringing a more in-depth understanding of the complex nonwoven product's environmental performance, revealing the weak and opportunity points of the entire supply chain, and helping companies address them directly and precisely.

2.3 Life Cycle Assessment

The International Standard ISO 14040 serves as a framework for practitioners and details the requirements for conducting an LCA, defining LCA as follows:

> “LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave). (ISO 14044, 2006, V)”

A similar definition of LCA was accepted in the “Code of Practice” by the Society of Environmental Toxicology and Chemistry (SETAC) as early as 1993. Back then, it had no regulatory powers, nor the authority of a standards organization. Life Cycle Assessment is a complex approach that quantifies the ecological, natural resources and human health impacts of a product or service (also called product system) over its entire life cycle. (Consoli et al. 1993, ii; Klöpffer & Grahl 2014, 1)
The inception of LCA dates back to the early 1970s, a period during which the first LCA studies were carried out across several nations spanning Europe, Japan, and North America. Rooted in energy and waste management, the

approach primarily centred on the examination of items such as beverage containers and diapers during its initial phase. Throughout the 1970s and 1980s, multiple studies on life cycles were conducted, utilizing diverse methodologies, and lacking a cohesive theoretical framework. Initial attempts to unify methodologies were undertaken by previously mentioned the Society of Environmental Toxicology and Chemistry (SETAC). The SETAC guidelines for Life Cycle Assessment: A "Code of Practice", published in 1993, introduced LCA standards. Subsequently, beginning in 1994, the International Organization for Standardization (ISO) played a major role in formally establishing methodology standards, which is now reflected in the ISO 14040 series of standards. Since 2000, the United Nations Environment Program (UNEP) has actively contributed to promoting the practical application of life cycle approaches. As LCA methods gain wider adoption, dedicated software and databases continue to evolve. (Heijungs & Udo de Haes 2008, 138)

According to the ISO 14040 Standard, LCA studies comprise four mandatory phases. The sequence and relationship of the phases is illustrated in FIGURE 4. (ISO, 2006, V)

These phases are:

– the goal and scope definition,
– inventory analysis,
– impact assessment, and
– interpretation.

LCA results might serve as valuable inputs to a variety of decision-making processes. Direct applications of the results of an LCA study are established in the goal and scope definition stage of the research, for example, product development and improvement, strategic planning, policymaking, marketing, etc. An iterative approach is used in the process of LCA study. (Klöpffer & Grahl 2014, 27).

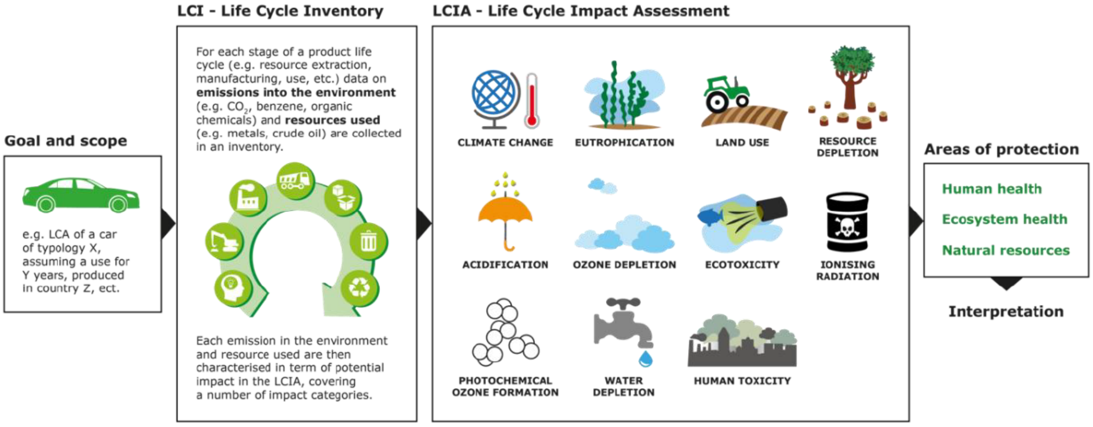


FIGURE 4. Stages of LCA (Sala S. et al. 2016)

2.3.1 Goal and Scope Definition

During the goal and scope stage, a study defines its objectives, including the intended use, the reasons behind conducting the research, and the target audience. Key methodological decisions are formulated at this step. These include the exact definition of the functional unit, outlining the system boundaries, specifying allocation methods, selecting relevant impact categories for assessment, determining the models for Life Cycle Impact Assessment (LCIA), and outlining criteria for data quality, also all assumptions made are identified and justified at this stage. (Sala S. et al. 2016, 6)

For every LCA conducted according to ISO 14040/44, to provide the required transparency of the work, the goal definition must explicitly state the following items:

- The purpose of the study and its intended application
- The intended target audience, to whom the results are to be communicated
- The reason for conducting a study and what decisions must support an LCA
- Whether the comparative assertions can be drawn from the results and be disclosed to the public. (ISO 2006, 7)

There has been a limited amount of comprehensive LCA studies on the different nonwoven textiles; therefore, for demonstrating purposes, this thesis uses a Life Cycle Assessment of various product systems. Castellani and Cardamone (2022), in their Comparative LCA on single-use and multiple-use tableware systems for takeaway services conducted for the European Paper Packaging Alliance, stated the goal of the study as the comparative evaluation of the environmental performances of two systems (single-use items, and multiple-use items) for takeaway services in quick service restaurant. The reasons behind the decision are quick service restaurants operate under a standardised system that is well-established, quantifiable, and robust data is available. Furthermore, takeaway services cover more than half of the total sales from quick service restaurants, and this figure has increased recently due to the pandemic and the spread of delivery services. Likewise, the widespread general opinion that reusable products and containers are innately more environmentally sustainable, yet there might be evidence that the actual environmental performance could be counterintuitive and very sensitive to the handling context. The intended audience of the study is primarily quick-service restaurant operators, companies producing single-use and multiple-use containers for restaurants, consumers, and policymakers. Regarding the probable use of results in comparative assertions, the authors suggest that the results from the study are not directly comparable with other sources and results. (Castellani & Cardamone 2022, 37)

In outlining the scope of an LCA, the following items shall be considered and clearly described, in line with the study goal: the functions of the system(s) to be studied, the functional unit, system boundaries e.g. the life cycle stages to be covered, allocation procedures, impact assessment methodology and interpretation approach to be used, the assumptions made about data and method issues, value choices, data quality and limitations. (Wolf et al. 2012, 18)

The function and functional unit are crucial point of scope definition. Given that any product system comprises interconnected processes linked by flows of intermediary products and materials, the system can be defined either by the function it provides or by the performance characteristics of a product. (Curran 2015, 42)

Most LCAs are performed to compare two or more systems. System comparisons rely on assessing identical functions measured using the same functional unit in the context of their reference flows. Determining this functional unit is decisive in establishing a basis for comparability across systems. This comparability becomes especially crucial when evaluating different systems to guarantee that assessments are conducted on a common basis. The functional unit serves as a means to express the functions delivered by the products, thus allowing for the equation of differences in performance. (Curran 2015, 42) A relevant example of an appropriate definition of a functional unit, enabling the correct comparison between two very different product systems, can be found in the LCA study for disposable and reusable nappies. The functional unit of the study is defined as “the use of nappies during the first two and a half years of a child’s life” (Aumônier, Collins & Garrett 2008, 2). Another example present itself in the LCA of North American aluminium cans prepared by Sphera, the functional unit of the study was defined as the volume of beverage contained by 1,000 aluminium beverage cans. With a weighted average can size of 402.2 ml per can, equalling 402.2 litres of beverage in total. Based on this functional unit, the reference flow was calculated as 13.46 kg of finished aluminium cans. (Toro & Rybl 2021, 19) The functional unit also can be defined as the amount of the end product leaving the product system, this was the case in the Comparative LCA of production processes of tissue paper. The authors set the functional unit as 1 ton of produced tissue paper (Masternak-Janus & Rybaczewska-Błazejowska 2015, 48).

The system boundary is a set of criteria that determines which unit processes (activities), inputs, outputs, and impacts are included in the studied system, and which are omitted. The possibility to exclude energy and material flows, unit processes, or whole life cycle stages is determined and justified during the scoping step. (Sala S. et al. 2016, 7) A unit process is a discrete step in the life cycle of a product, such as raw material extraction, intermediate materials manufacturing, product manufacturing, use, disposal, recycling, and transportation occurring between stages, as depicted in FIGURE 5. A system boundary defines the spatial, temporal, and functional aspects of LCA, as well as the level of detail and data quality required.

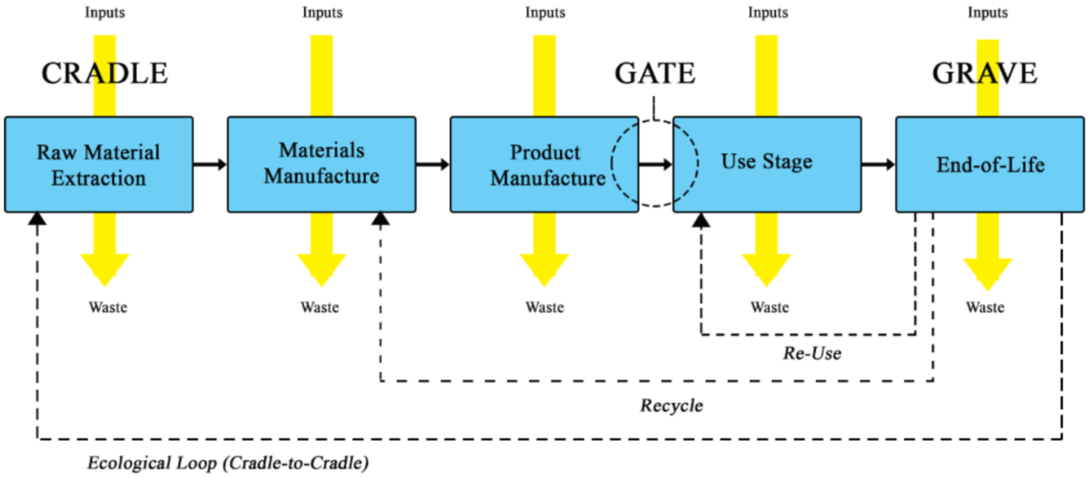


FIGURE 5. Lifecycle stages (wikimedia.org)

Comprehensive LCA studies are typically include all stages from the of raw material acquisition point to the products' end of life treatment - disposal and/or recycling. In this case the boundaries of the study determined as cradle-to-grave. A good example of the cradle to grave study is the Life cycle assessment of single-use surgical and embedded filtration layer (EFL) reusable face mask performed by Lee et al. The study considered the entire value chain from material acquisition to the end of life, see FIGURE 6 (Lee et al. 2021, 2).

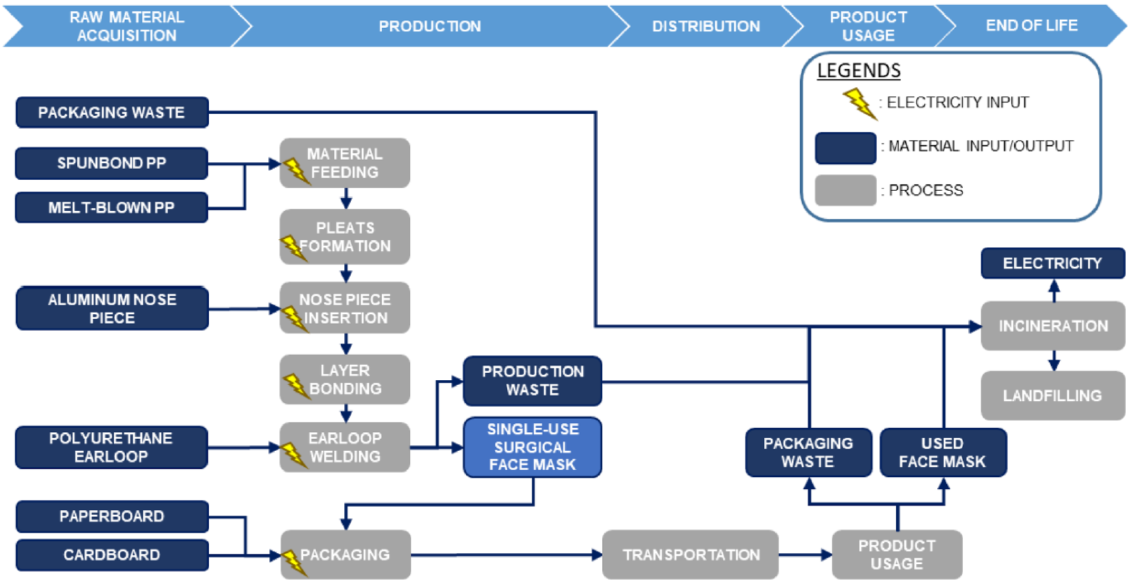


FIGURE 6. Process map of a Single-use surgical face mask (Lee et al. 2021, modified)

However, LCA can also be limited to include only certain selected stages of the products' life cycle. Subsequently, cut-off criteria applied to exclude any unit processes or flows that are insignificant or irrelevant to an LCA goal and scope. As a rule, a proportion of <1% (mass, energy, etc.) of the product system is chosen as the cut-off criterion. Generally, the most common scope of LCA performed by the companies for internal purposes includes stages from virgin raw materials acquisition point to the point where product or service is ready to be delivered or consumed. These studies called cradle-to-gate. The authors of the Life Cycle Assessment of wastewater treatment systems for small communities, for instance, comprised system boundaries to include input and output flows of material and energy resources for the construction and operation of these systems over a 20-year period. But the demolition and dismantling phases were not considered due to the marginal impact of these phases compared to the overall impact of the systems (Garfí, Flores & Ferrer 2017, 213).

In some cases, due to the specific aims of the study or other reasons known in advance such as insignificant overall impact of certain LCA stages or data scarcity, system boundaries may be reduced to the specific production processes. For example, in the Comparative LCA of production processes of tissue paper the system boundaries have been restricted from the point where the main raw material has been delivered to the mills manufacturing papers to the point where the final products are made. Justified by the main aim of this research being to determine the environmental impacts that arise from manufacturing of tissue paper using virgin pulp or wastepaper pulp (Masternak-Janus & Rybaczewska-Błazejowska 2015, 48). In this case, the boundaries of the study were strictly limited gate-to-gate.

Many processes produce more than one useful output, these processes are called multi-functional. This situation makes it necessary to use some method to divide or partition the process input and output flows among the useful outputs. The rules for dividing the input and output of the system between the main product and co-products are established at the allocation step and should be well documented and explained. (Curran 2015, 48)

According to ISO14044 standard, allocation should be avoided wherever possible in the first place by either dividing the unit process in question into two or more sub-processes or expanding the product system to include the additional functions related to the co-products. If allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them. When it is not possible to establish a purely physical connection to use as the basis for allocation, the input and output flows might be allocated between co-products based on the economic value of the products. (ISO 2006, 14) For example, in the Comparative LCA on packaging solutions for food to enable a comparison between the two systems single-use corrugated board boxes and multiple-use plastic crates, the avoided burdens approach was used for end-of-life allocations. The Circular Footprint Formula was applied for modelling. (Castellani, Aigner & Aagaard 2022, 60)

When outlining the scope of an LCA project, it is important to define the impact categories and the LCIA methodology that will form the final report. This decision significantly influences data procurement. For instance, a project defined as a life cycle carbon footprint analysis will require a significantly different set of data compared to one that comprises a complete range of life cycle impact indicators. The chosen impact assessment categories establish connections between potential consequences and their effects on the protected matters. Usually, the areas of protection covered by LCA are Natural Resources, Ecosystem Health, and Human Health. A certain number of studies are performed in a way that includes three out of four phases defined by the ISO 14040 standard: Goal and scope definition, Life cycle inventory (LCI) analysis and Interpretation. The Life cycle impact assessment (LCIA) phase is completely omitted, or only one impact category is used, such as in the earlier mentioned example of a climate change study quantified by the global warming potential (GWP). These studies have recently adopted the term Carbon footprint (CF) studies. According to the standard ISO 14040, these studies must not be referenced as LCA. An analysis shortened by the omission of the LCIA phase is then called an LCI study. (Klöpffer & Grahl 2014, 45; Curran 2015, 48) More in-depth examination of existing impact assessment categories and methods will be given later in the chapter dedicated to the third step of an LCA study.

Data quality and availability are fundamental issues for the LCA study. During the goal definition phase, it must be decided which data will presumably be available for the study. Also, it shall be specified whether it is possible to use already existing data and which data should be approximated by estimated values or calculated from other sources. (Klöpffer & Grahl 2014, 43) In practice, LCA data always include a mixture of measured, calculated, and estimated data. All limitations concerning the data quality, gaps and assumptions shall be transparently reflected in the scoping phase.

Due to the iterative nature of the LCA calculations, the goal and scope of the study may be adjusted on the grounds of unsuspected limitations, data gaps or as a result of additional information obtained during the later stages of the study. Such modifications, together with their justification, should be reflected accordingly. (ISO 2006, 7)

2.3.2 Life Cycle Inventory Analysis

The second phase of LCA - Life Cycle Inventory (LCI) analysis is a scientifically based material and energy analysis stage, including collecting all data related to environmental and technical amounts for all unit processes within study boundaries that compose the product system and quantification of inputs and outputs for a product system throughout its entire life cycle. LCI analysis involves data collection and modelling of the product system, as well as description and verification of data. Initially defined in a study's Goal and scope phase, a plan is further elaborated in the life cycle inventory step. The product tree roughly estimated during the scoping now should be refined—a graphic representation of a product system consisting of process units to be created. An example of the production processes tree, constructed in the Comparative LCA of single-use and multiple-use dishes options for in-store consumption in quick service restaurants in Europe, performed by Ramboll for the European Paper Packaging Alliance (EPPA), is presented in FIGURE 7.

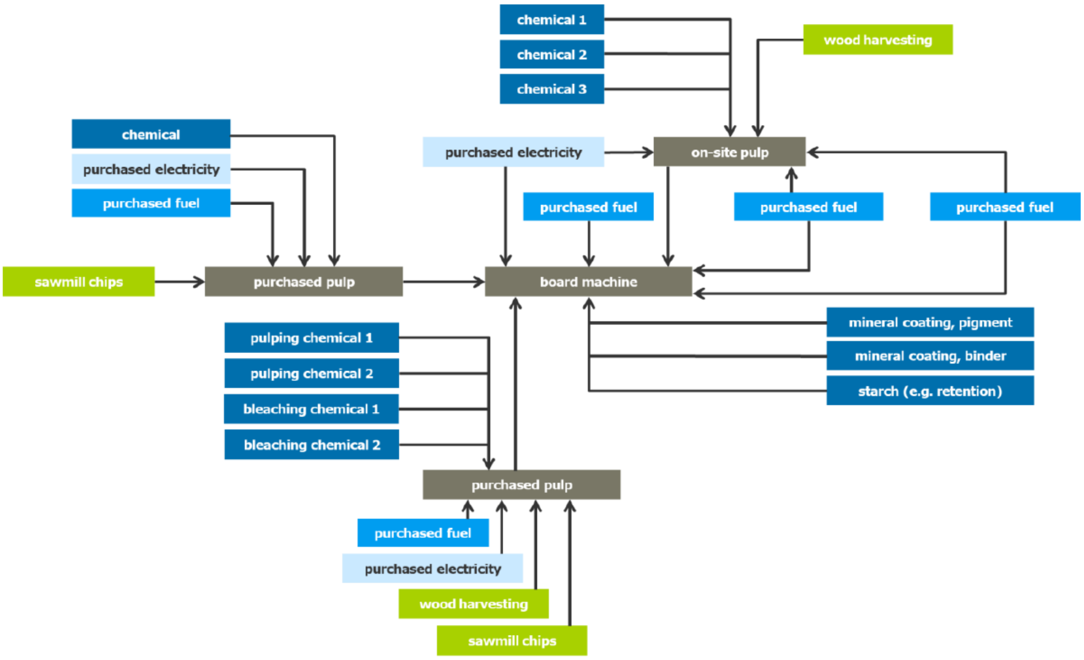


FIGURE 7. Single-use System Tree (Abraham, Aigner & Castellani 2020)

LCI is predominantly based on the following laws of nature: conservation of mass and conservation of energy - it applies to the conversion of thermal energy into other forms of energy (first principle of thermodynamics), the increase of entropy of a substance which is used for the thorough examination of a certain chemical reactions, for example, the determination of CO_2 emissions by incineration of solid fossil materials (second principle of thermodynamics), principles of stoichiometry is a basis for all chemical reactions analysis, where the total mass of the reactants equals the total mass of the products and Einstein's theory of special relativity – the equivalence of mass and energy $E = MC^2$. These principles provide a solid scientific framework for LCA analysis. (Heijungs & Udo de Haes 2008, 140; Klöpffer & Grahl 2014, 45) The operational steps of the life cycle inventory analysis according to ISO 14044 standards are presented in

FIGURE 8. When executing the LCI in practice, iterative steps are presumed, although not specified in the scheme. (ISO 2006)

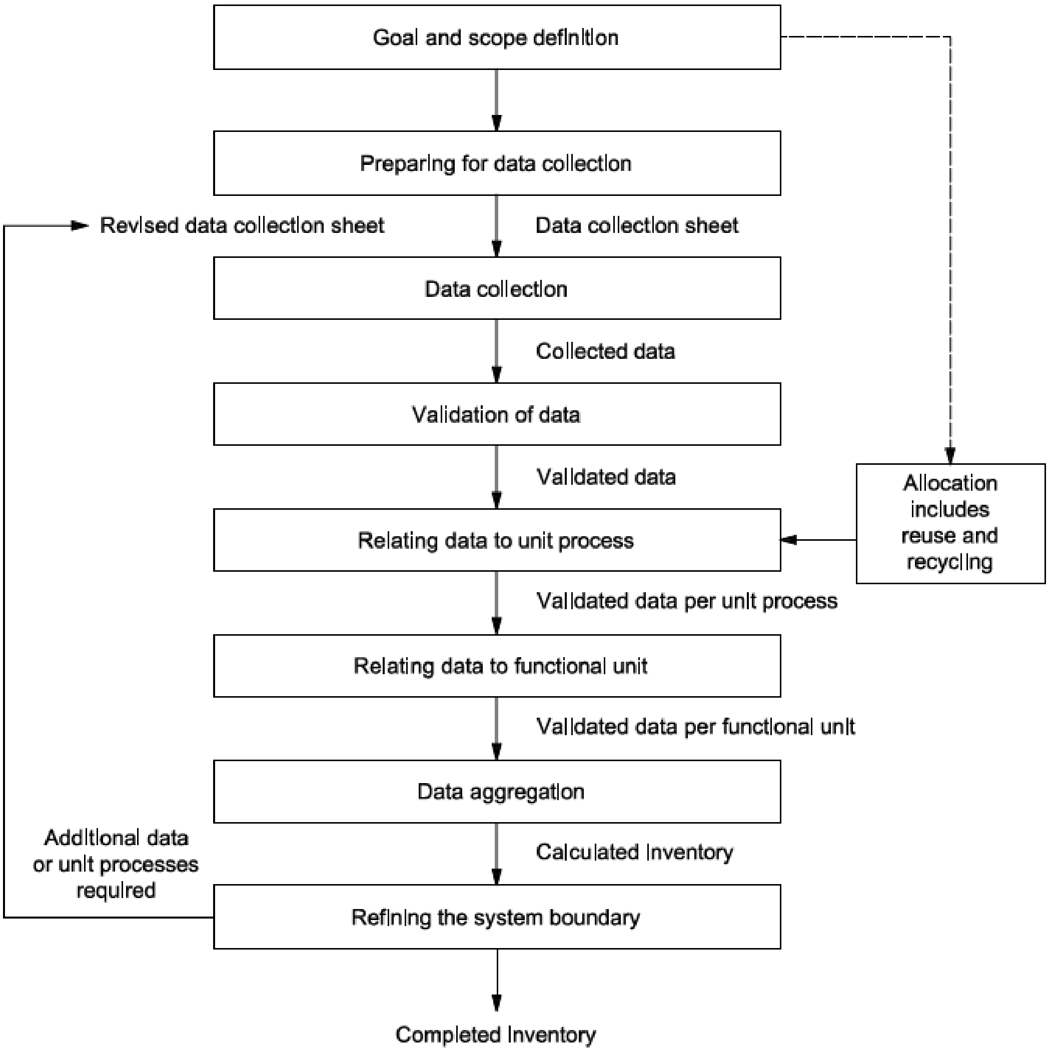
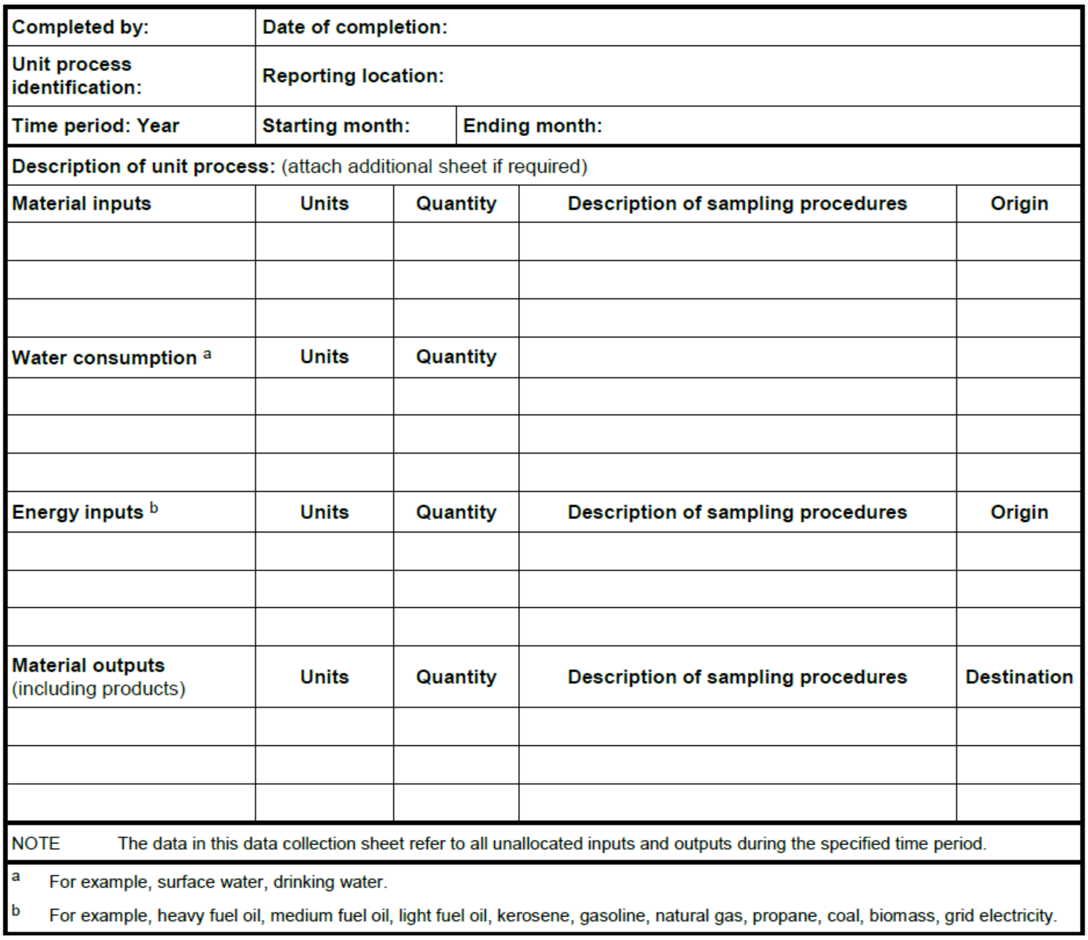


FIGURE 8. Procedures for inventory analysis (ISO 14044 2006)

The process begins with preparation for data collection. The drawing flow diagrams that outline all the unit processes intended for modelling according to system boundaries would provide assistance to systematise the task. Further, each unit process described in detail with respect to factors influencing inputs and outputs, listing flows and relevant data associated with each unit process (Guinée et al. 2002, 32). The major categories under which data may be gathered include energy inputs, raw material inputs, ancillary inputs, and other physical inputs; products, co-products, and waste outputs; and releases to air, water, and soil (ISO 2006, 11). The result of the step is acquiring an individual data sheet to be filled to meet the goal of the study, see FIGURE 9.



Completed by:	**Date of completion:**			
Unit process identification:	**Reporting location:**			
Time period: Year	**Starting month:**	**Ending month:**		
Description of unit process: (attach additional sheet if required)				
Material inputs	**Units**	**Quantity**	**Description of sampling procedures**	**Origin**
Water consumption [a]	**Units**	**Quantity**		
Energy inputs [b]	**Units**	**Quantity**	**Description of sampling procedures**	**Origin**
Material outputs (including products)	**Units**	**Quantity**	**Description of sampling procedures**	**Destination**

NOTE The data in this data collection sheet refer to all unallocated inputs and outputs during the specified time period.

[a] For example, surface water, drinking water.

[b] For example, heavy fuel oil, medium fuel oil, light fuel oil, kerosene, gasoline, natural gas, propane, coal, biomass, grid electricity.

FIGURE 9. Data sheet for unit process (ISO 14044 2006)

Next, the data for inclusion in the inventory is collected for each unit process within the system boundary. The collected data, irrespective of its nature: measured, calculated, or estimated, are used to quantify the inputs and outputs of a unit process. Data collected from public sources should be referenced. For data sensitive for the conclusions of the study, the information about data quality should state whether it meets quality requirements. Since there may be several different sources of data collection, it is essential to pay attention to the uniformity and consistency of data with modelled product systems. A description of each unit process may be recorded in order to avoid the risk of miscalculation, such as double counting. (ISO 2006, 11-12)

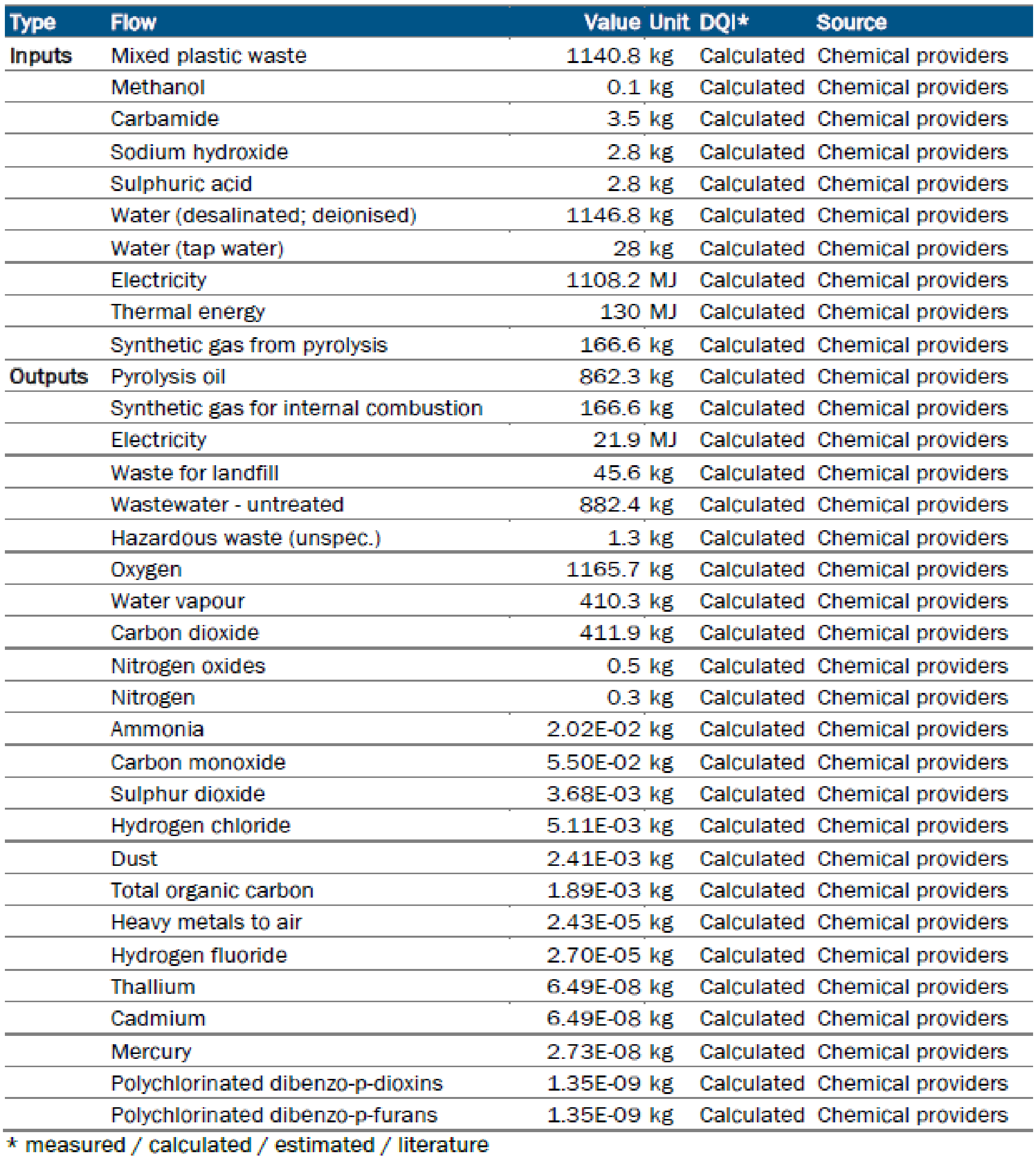
Every calculation performed must be properly described, and any underlying assumptions should be explicitly declared and justified. Consistency in the application of the calculation methods is essential across the entire study. To confirm the quality of data, validation should be conducted. For example, through mass and energy balances or comparative analyses of release factors. As was mentioned in the beginning of the chapter, all processes obey the laws of conservation of mass and energy. These balances provide useful checkpoints for the validity of gathered data. If anomalies are identified, alternative data is required to replace the corrupted. (Guinée et al. 2002, 35; ISO 2006, 13)

Relating data to unit process and functional unit is the step of inventory analysis where all collected data is connected to the unit processes. The stage leads to the alignment of all system inputs and outputs data with the functional unit. When aggregating the inputs and outputs within the product system, it is essential to pay attention to the level of consolidation; it should align with the goals of the study. Data aggregation is acceptable only when dealing with comparable substances and similar environmental effects. The inputs and outputs of the unit processes are allocated to the different products according to selected procedures. (Guinée et al. 2002, 36; ISO 2006, 13)

Finally, the necessary refinement of the system boundary is made at the conclusion of the LCI phase. At this point, reflecting the iterative nature of LCA, it should be decided whether to revise the initial system boundary defined in the goal and scope phase. For example, exclusions of specific inputs and outputs, unit processes, or entire life cycle stages should be considered when a lack of significance is discovered during the analysis. Conversely, the boundaries can be expanded to include relevant and significant flows initially excluded from the system. Decisions regarding the inclusion of data should be based on the LCI analysis. (ISO 2006, 14)

The result of the inventory analysis is an LCI table, which provides information about all inputs and outputs of the product system in the form of elementary flows to and from the environment generated by unit processes included in the study boundaries and serving as input data for the next phase - LCIA. (Heijungs & Udo de Haes 2008, 140) The example of the inventory table for the Py-CR recycling process from the LCA study on Chemical recycling for food-grade film, conducted by Sphera for The Consumer Goods Forum, is presented in TABLE 3.

TABLE 3. Inventory for the Py-CR process (Viveros, Imren & Loske 2022,36)



Type	Flow	Value	Unit	DQI*	Source
Inputs	Mixed plastic waste	1140.8	kg	Calculated	Chemical providers
	Methanol	0.1	kg	Calculated	Chemical providers
	Carbamide	3.5	kg	Calculated	Chemical providers
	Sodium hydroxide	2.8	kg	Calculated	Chemical providers
	Sulphuric acid	2.8	kg	Calculated	Chemical providers
	Water (desalinated; deionised)	1146.8	kg	Calculated	Chemical providers
	Water (tap water)	28	kg	Calculated	Chemical providers
	Electricity	1108.2	MJ	Calculated	Chemical providers
	Thermal energy	130	MJ	Calculated	Chemical providers
	Synthetic gas from pyrolysis	166.6	kg	Calculated	Chemical providers
Outputs	Pyrolysis oil	862.3	kg	Calculated	Chemical providers
	Synthetic gas for internal combustion	166.6	kg	Calculated	Chemical providers
	Electricity	21.9	MJ	Calculated	Chemical providers
	Waste for landfill	45.6	kg	Calculated	Chemical providers
	Wastewater - untreated	882.4	kg	Calculated	Chemical providers
	Hazardous waste (unspec.)	1.3	kg	Calculated	Chemical providers
	Oxygen	1165.7	kg	Calculated	Chemical providers
	Water vapour	410.3	kg	Calculated	Chemical providers
	Carbon dioxide	411.9	kg	Calculated	Chemical providers
	Nitrogen oxides	0.5	kg	Calculated	Chemical providers
	Nitrogen	0.3	kg	Calculated	Chemical providers
	Ammonia	2.02E-02	kg	Calculated	Chemical providers
	Carbon monoxide	5.50E-02	kg	Calculated	Chemical providers
	Sulphur dioxide	3.68E-03	kg	Calculated	Chemical providers
	Hydrogen chloride	5.11E-03	kg	Calculated	Chemical providers
	Dust	2.41E-03	kg	Calculated	Chemical providers
	Total organic carbon	1.89E-03	kg	Calculated	Chemical providers
	Heavy metals to air	2.43E-05	kg	Calculated	Chemical providers
	Hydrogen fluoride	2.70E-05	kg	Calculated	Chemical providers
	Thallium	6.49E-08	kg	Calculated	Chemical providers
	Cadmium	6.49E-08	kg	Calculated	Chemical providers
	Mercury	2.73E-08	kg	Calculated	Chemical providers
	Polychlorinated dibenzo-p-dioxins	1.35E-09	kg	Calculated	Chemical providers
	Polychlorinated dibenzo-p-furans	1.35E-09	kg	Calculated	Chemical providers

* measured / calculated / estimated / literature

2.3.3 Life Cycle Impact Assessment (LCIA)

The Life cycle impact assessment (LCIA) is the third phase of LCA and along with the Life cycle inventory analysis also scientifically based phase, together they are forming the scientific core of the tool. (Klöpffer & Grahl 2014, 181)

The purpose of the Life cycle impact assessment (LCIA) phase of an LCA is to convert the results of the Inventory analysis into contributions to selected impact categories, such as depletion of mineral resources, global warming, acidification, etc., with aims to facilitate the understanding and evaluation of the extent and

significance of potential environmental impacts for a studied product system throughout the life cycle of the product. (Hauschild & Huijbregts 2015)
According to the ISO 14044 standard, there are three mandatory elements for the LCIA phase, which shape the profile of the product system. These are the selection of impact categories and characterization model, classification - assignment of LCI results to the selected impact categories, and characterization step - calculation of category indicator results. (ISO 2006, 16) The main objective is to answer the questions formulated in the goal definition of the study. Contemporary LCA software automatically performs classification and characterization tasks following the selected LCIA model.

LCIA methods is a classification and characterization model for grouping impacts that processes have on various aspects of the environment, such as water use, climate change or ecotoxicity. Different emissions with similar environmental impacts are converted into the same units and aggregated into one impact category. For example, different GHGs like $\mathrm{CO_2}$ and $\mathrm{CH_4}$ can be assigned into an overall impact category indicator GWP100 by converting them into a common unit kg $\mathrm{CO_2}$-equivalents with multiplication on a specific characterization factor 1 for $\mathrm{CO_2}$ and 25 for $\mathrm{CH_4}$. The results of an LCA are presented in terms of different impact categories. Various methods were created to quantify different impact categories depending on the main focus of the study. The use of a specific LCIA method or restricting to certain impact categories is determined in the goal definition phase of the study. (Ecochain n.d.; Klöpffer & Grahl 2014, 192)
There are several internationally recognised LCIA methods developed by independent institutions for categorising impacts, which are widely used and represented in various LCA software solutions and databases. For the purpose of this thesis the LCIA methods implemented in SimaPro software will be used as an example. The methods outlook is not intended to be exhaustive but to give a general understanding of the existing approaches. Although there are other methods not represented in the SimaPro solution, it contains the majority of the most common methods, for example, European methods: **CML-IA** method was developed since 2001, when a group of scientists under the lead of CML (Center of Environmental Science of Leiden University) proposed a set of impact categories and characterization methods for the impact assessment step of LCA. **EDIP 2003** is a Danish LCA methodology that is an updated version of the initially

developed in 1997 methodology and represents 19 different impact categories. (PRé 2018, 8) **EPD (2013)** method is used for the creation of Environmental Product Declarations (EPDs) which provide transparent, verified, and comparable information about the environmental impact of products and services lifecycle. An EPD is a voluntary product certification that must be created according to a Product Category Rule (PCR). This method is essential for companies reporting under PCR set by The International EPD System. (EPD International n.d.). **ILCD 2011 Midpoint+** based on recommendations of The International Reference Life Cycle Data System (ILCD) for LCIA in the European context. The European Commission analysed several methodologies for LCIA and made steps towards their harmonization. (EC-JRC–IES, 2011)

The commonly used method for the LCIA created by the National Institute for Public Health and the Environment of The Netherlands in collaboration with Radboud University Nijmegen, Norwegian University of Science and Technology, and PRé Consultants is an updated and extended **ReCiPe 2016** method which is now can be used not only for the European scale but for the global scale too includes both midpoint (problem-oriented) and endpoint (damage oriented) impact categories with associated sets of characterization factors available for three different perspectives: Individualist (I) 20 year time horizon, Hierarchist (H) 100 years, and Egalitarian (E) 1000 years. The default setup of the method most often used in LCA studies is midpoint hierarchist. Total 18 impact categories at the midpoint level are then aggregated into three endpoint categories by multiplication on damage factors. The scheme of the impacts and the damage pathways is presented in FIGURE 10. (Huijbregts et al. 2017, 19)

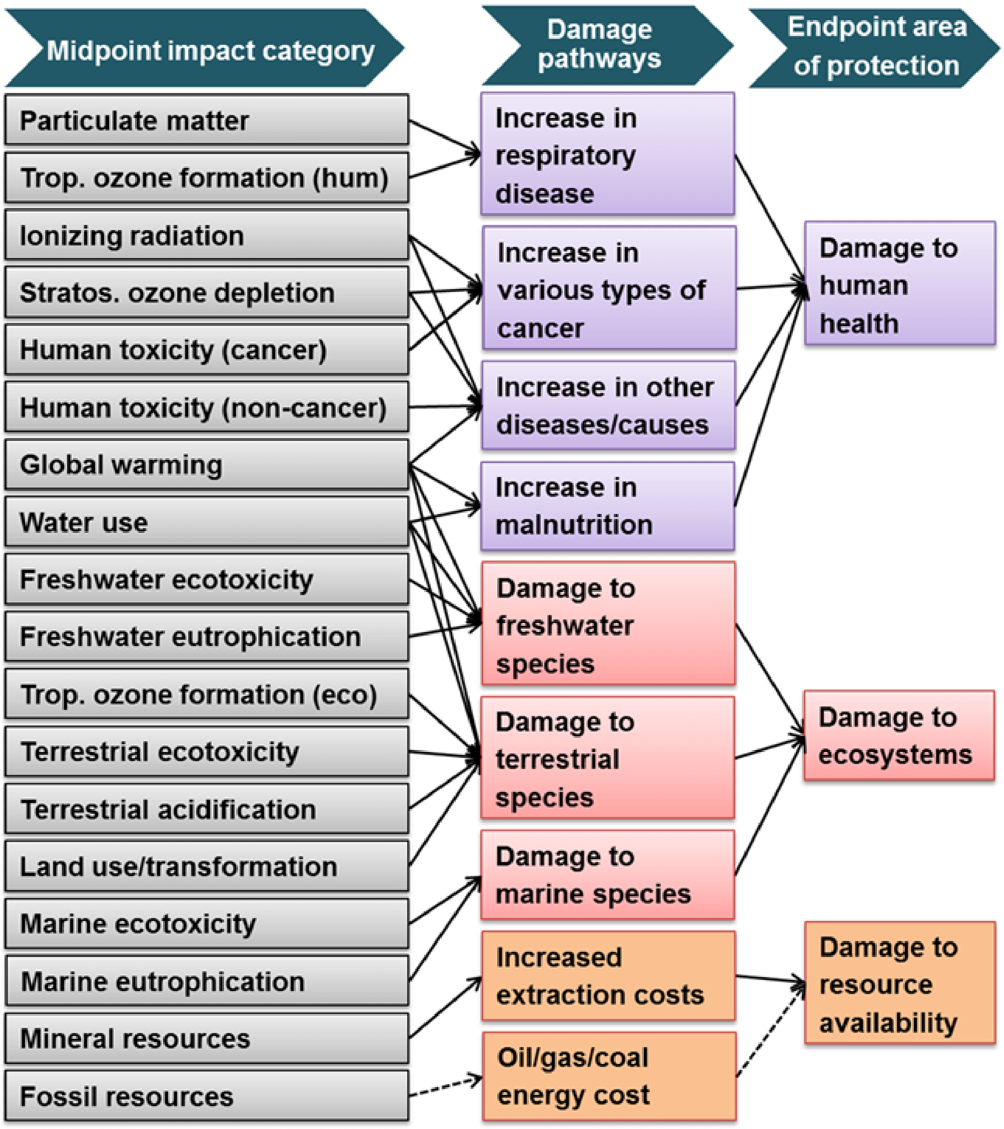


FIGURE 10. ReCiPe2016 Impact categories (Huijbregts et al. 2017)

Apart the European and Global methods, SimaPro offer also North America oriented methods, for example, **BEES** which is the acronym for Building for Environmental and Economic Sustainability, a software tool developed by the National Institute of Standards and Technology (NIST). BEES combines a partial life cycle assessment and life cycle cost for building and construction materials into one tool. BEES uses the SETAC method of classification and characterization. **TRACI 2.1** The Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI), also offered as a stand-alone computer program developed by the U.S. Environmental Protection Agency specifically for the US using input parameters consistent with US locations. Site specificity is available for many of the impact categories, but in all cases a US average value exists when the location is undetermined. (PRé 2018, 23)

For previously mentioned LCI studies where the life cycle impact assessment phase is reduced to include only one impact category, for example, Carbon footprint (CF) study, it is possible to use a single-issue methodology to quantify a specific impact category. The Ecosystem Damage Potential (**EDP**) is a life cycle impact assessment methodology for the characterization of land occupation and transformation developed by the Swiss Federal Institute of Technology (ETH), Zürich. It is based on impact assessment of land use on species diversity. Greenhouse Gas Protocol (**GHG Protocol**), developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), is an accounting standard of greenhouse gas emissions. **IPCC 2013** developed by the International Panel on Climate Change. This method lists the climate change factors for the direct global warming potential of air emissions with a timeframe of 20 and 100 years. Finally, there are several methods dedicated to quantifying impacts on water, such as **AWARE**. A regionalized, water use midpoint indicator representing the relative Available WAter REmaining per area in a watershed after the demand of humans and aquatic ecosystems has been met. AWARE is used to assess water consumption impact assessment in LCA. **WAVE** (Water Scarcity) This method is based on the publication Berger et al (2014). The method analyses the vulnerability of basins to freshwater depletion. Based on local blue water scarcity, the water depletion index (WDI) denotes the risk that water consumption can lead to the depletion of freshwater resources. (PRé 2018, 29, 33)

The selection of the LCIA methodology depends on the goals of the study and a decision is made during the goal and scope definition phase. For example, in the LCA study on Chemical recycling for food-grade film the methodological choice for Climate change (global warming potential) impact category was IPCC 2013 characterisation factors for a 100-year timeframe (GWP100) as the most commonly used metric. (Viveros, Imren & Loske 2022,30). Whereas, in the post-pandemic LCA study on non-medical masks: a Brazilian case, the authors chose the ReCiPe 2016 method and used the whole range of midpoint and endpoint indicators, because it provides global scale factors and allows a holistic assessment to evaluate products. (Maceno et al. 2022, 8066)

2.3.4 Life Cycle Interpretation

The fourth and final phase of an LCA is Interpretation. The objective of this stage is to structure the data gathered from the LCI or LCIA phases and determine if the question posed in the goal and scope definition could be answered. The ISO 14044 standard defines three main stages of the phase. The interpretation begins with the identification of significant issues. These could be, for example, significant contributions to LCI or LCIA results from certain life cycle stages or individual unit processes like transportation and heating, most affected impact categories, such as resource use or climate change and various inventory data, like energy, emissions, discharges, and waste. (Hauschild, Bonou & Olsen, 2018, 323) In the LCA of a Nordex wind farm with Delta4000 turbines conducted by Sphera for the Nordex Group, the identified dominant contribution stage of the life cycle of the wind farm for all impact categories was the production of the Delta4000 turbine. Moreover, despite the concrete foundation being the major portion of the turbine by mass - 73%, its impact potential across all categories was significantly lower than other components. The tower made of steel, which accounts for 13% of the mass of the turbine, has a much higher impact than the concrete foundation of the turbine. Notably, however, the blades only contribute 3% of the mass of the turbine; they bear significant values in several impact categories. Due to the polymer parts, resin glass fibres and electricity required to manufacture the blades, freshwater eutrophication potential for these parts was the highest. (Russ, Reid-McConnell & Shonfield 2020, 62)

After identifying the significant environmental issues, evaluation - the next step of the phase is starting. The results of the evaluation should be provided in a way that gives the intended audience of the study a clear and understandable view of the outcome of the LCA. Completeness, sensitivity, and consistency checks are the parts of the evaluation step conducted in order to enhance the confidence and reliability of the results. Sometimes, LCA research may generate unexpected outcomes contrary to the initial intuitive assumptions. On this occasion, the odd results provide an opportunity to reveal the true weakness of the product system and gain knowledge, and due to the iterative nature of the LCA, may lead to a reformulation of the goal and scope definition. (ISO 2006, 26)

A great example of the counterintuitive results of the LCA was brought by Castellani and Cardamone (2022) in their Comparative LCA on single-use and multiple-use tableware systems. The report reveals that reusable tableware generates 2.8 times more CO_2-equivalent emissions than the paper-based single-use system, consumes 3.4 times more freshwater, produces 2.2 times more fine particulate matter, increases fossil and metal resource depletion by 3.4 times, and increases terrestrial acidification by 1.7 times. (Castellani & Cardamone 2022)

In the final step of the interpretation phase of LCA, conclusions are drawn, any identified limitations are reported, and recommendations are made. If the goal of the study was to provide supportive information for specific purposes like decision-making or design improvement, recommendations must relate to the intended application.

3 MATERIALS AND METHODS

3.1 Comparative LCA on Spunbond and Wetlaid Nonwoven

In the following chapters a comparative LCA on two nonwoven product systems in accordance with the ISO 14040 standards is conducted.

3.1.1 Goal and Scope Definition

There are a few different ways and raw materials to produce nonwoven fabrics widely used for several applications, with single-use items being one of the major segments. A number of alternatives provide the same function for the end customer. The goal of the study is to perform a comparative Life Cycle Assessment in compliance with the ISO 14040 series of standards between the utilisation of polypropylene to produce spunbound nonwoven sheets and cellulosic pulp to produce wetlaid nonwoven sheets for the following reasons:

- Production of single-use items has increased in recent years due to the pandemic and continues to grow with a dominant synthetic base.
- Single-use waste presents an evolving pollution problem. With tightening regulations, the nonwoven industry actively looks for ways to make production more sustainable.
- There might be hidden hotspots in the materials supply chain and production processes which are not intuitively assumed and, therefore, not addressed.

The objective is to understand potential environmental consequences related to single-use consumer nonwoven items. Likewise, to evaluate environmental hotspots and reveal areas for improvement.

The intended audience is the public, the university community represented by a number of research projects, consumers, and all affected parties interested in the topic of this LCA, as well as in the tool are also considered potential target audiences. The results of this LCA can be used for general information purposes and as a starting point for broader research in the future, for example, expanding the scope of the study to include omitted stages of the life cycle. This LCA is not applicable for a public comparative assertion.

The study is conducted independently of any company, therefore only openly available sources of information are used.

The function of the systems under consideration is the rolled nonwoven fabric sheet produced either from polypropylene granules or cellulosic pulp with different techniques, which is then used for the production of consumer single-use wipes, assuming the same thickness and length of fabrics, capable of providing an equal amount of end product. The functional unit of the study is **1 ton** of produced rolled nonwoven textile web.

The system boundaries of the LCA for both systems are set to include the whole upstream supply chain of the materials and the production of nonwoven webs up to the gate of the facility. For the comparative assessment, two distinct systems were considered:

- Nonwoven web produced with spunbound technology based upon the extrusion from polypropylene granulate (system A) and
- Nonwoven web produced with wetlaying technology resembling the papermaking process from cellulosic pulp (system B)

The system boundaries of the studied product systems are represented in FIGURE 11.

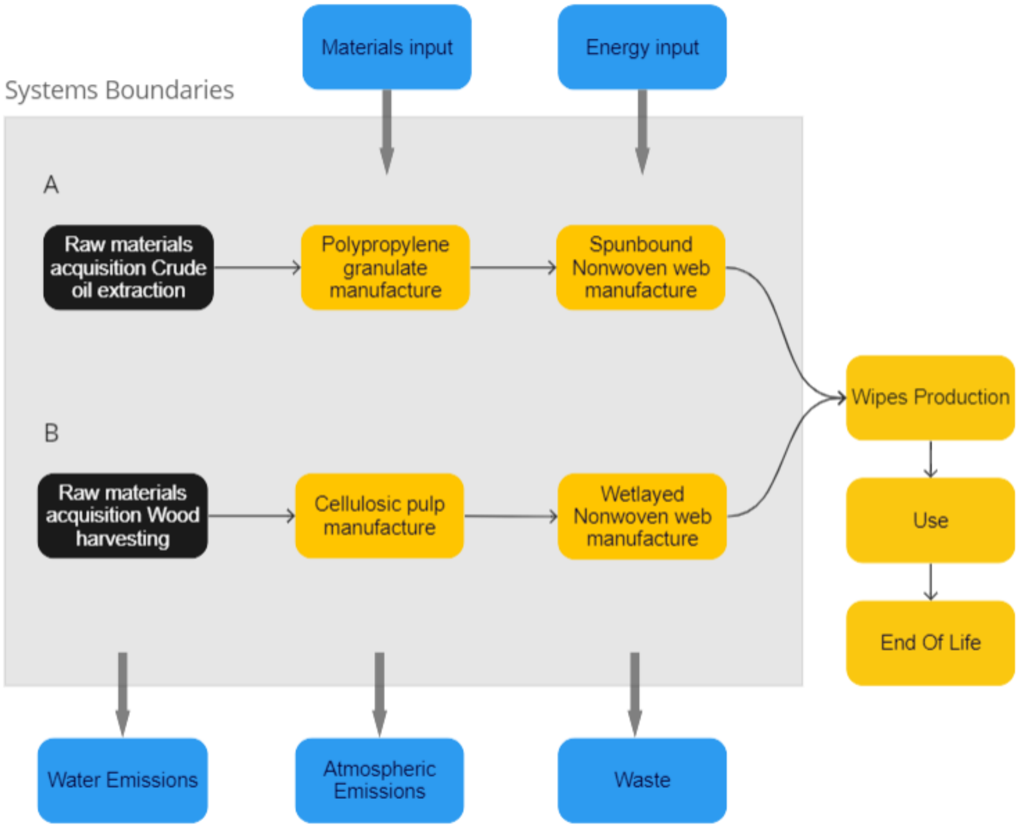


FIGURE 11. Systems boundaries

The production of wipes, usage and end-of-life treatment stages of the lifecycle were omitted due to the data availability issues. With the assistance of the university community, several attempts were made to acquire data on the production processes from the industry representatives and research projects or attract a commissioner to the study, but there was no success in getting relevant data to complete a more detailed LCA. Therefore, this research is a simplified LCA from cradle to gate in scope. The unit processes included in the study are raw materials extraction and harvesting, intermediate materials - polypropylene granulate and cellulosic pulp manufacturing, and production of nonwoven fabrics. The transportation of raw materials between the conversion or production sites and nonwoven facilities was not modelled separately but included in the scope of product systems through the usage of market activity inputs modelled in the Ecoinvent database instead.

The geographical scope of the study is regional, covering Europe. This geographical boundary is reflected in the assumptions around the systems and background datasets (e.g., electricity from the grid). Time boundaries of the data are the most recent available. The data used from the Ecoinvent database is dated 2021. The primary data used for modelling product system B is not explicitly dated but was published in 2022 and is considered actual and valid.

Both studied processes are mono-functional and produce only one valuable output; therefore, no allocations were made in the LCA.

The study uses the ReCiPe 2016 classification and characterization model, detailing the environmental impacts of the product systems in eighteen impact category indicators at a midpoint level from a hierarchical perspective (100-year time horizon). Addressed impact categories together with midpoint characterization factors (CFm) and a short description are presented in TABLE 4.

TABLE 4. ReCiPe 2016 model Midpoint impact categories (Huijbregts et al. 2017)

Midpoint impact category (CFm)	**Unit**	**Description**
Climate change (GWP)	kg CO_2-eq to air	Atmospheric concentration of GHG leading to an increase in the global mean temp. (°C). Based on the IPCC 2013 report
Ozone depletion (ODP)	kg CFC-11-eq to air	Destruction of the stratospheric ozone layer by anthropogenic emissions of ozone depleting substances (ODS)
Ionising radiation (IRP)	kBq Co-60-eq to air	Accounts for the level of exposure to radionuclide for the global population
Fine particulate matter formation (PMFP)	kg PM2.5-eq to air	Air pollution with primary and secondary aerosols in the atmosphere that have a substantial negative impact on human
Photochemical oxidant formation: terrestrial ecosystems (EOFP)	kg NO_x eq to air	Ozone formation due to reactions of NO_x and Non-Methane Volatile Organic Compounds (NMVOCs). Ecosystems consequences
Photochemical oxidant formation: human health (HOFP)	kg NO_x eq to air	Ozone formation due to reactions of NO_x and Non-Methane Volatile Organic Compounds (NMVOCs). Human health consequences
Terrestrial acidification (TAP)	kg SO_2-eq to air	Atmospheric deposition of inorganic substances, such as sulphates, nitrates and phosphates, that cause a change in acidity in the soil
Freshwater eutrophication (FEP)	kg P-eq to freshwater	Discharge of nutrients into soil or freshwater bodies and the subsequent rise in nutrient levels (i.e., P and N)
Marine eutrophication (MEP)	kg N-eq to marine water	Discharge of nutrients into riverine or marine systems and the subsequent rise in nutrient levels (i.e., P and N)

Human toxicity: cancer (HTPc)	kg 1,4-DCB*-eq to urban air	The characterization factors of human toxicity and ecotoxicity account for the environmental persistence, accumulation in the human food chain, and toxicity (effect) of a chemical
Human toxicity: non-cancer (HTPnc)		
Terrestrial ecotoxicity (TETP)	kg 1,4-DCB-eq to industrial soil	
Freshwater ecotoxicity (FETP)	kg 1,4-DCB-eq to freshwater	
Marine ecotoxicity (METP)	kg 1,4-DCB-eq to marine water	
Land use (LOP)	m^2 × yr annual cropland-eq	Accounts for the amount of land transformed or occupied for a certain time
Water use (WCP)	m^3 water-eq consumed	The amount of freshwater consumption in a way that the water is evaporated, incorporated into products, transferred to other watersheds or into the sea
Mineral resource scarcity (SOP)	kg Cu-eq	The primary extraction of a mineral resource that leads to an overall decrease in ore grade (OG), the concentration of that resource in ores worldwide
Fossil resource scarcity (FFP)	kg oil-eq	Accounts for fossil resource scarcity, based on the extraction rate of lowest cost fuels and the higher heating value

* dichlorobenzene equivalent

Due to the extensive number of categories covered by the method and for the sake of the readability of the thesis, for the detailed environmental performance comparison in this study, the following impact categories from the above list are selected:

- Global warming
- Fine particulate matter formation
- Human carcinogenic toxicity
- Land use
- Fossil resource scarcity
- Water consumption

Data required for completing the study are raw materials, water, and energy consumption. Since the production of 1 ton of nonwoven fabrics takes a significantly shorter period of time in comparison to the lifespan of machinery and facility infrastructure like roads, etc., these inputs were cut off the scope of the LCI due to insignificance. The production of nonwoven fabrics in the amount of the functional unit takes minutes to hours depending on technology while the depreciation period of the equipment takes dozens of years.

Data for modelling the production process of the nonwoven web with spunbound technology was obtained from the Ecoinvent LCI database. For the purpose of modelling the wetlaying web formation process, the data on the resource consumption of the CTMTC-HTHI Wet-Laid Spunlaced Nonwoven Line developed by CTMTC corporation was used as a proxy to complete the study. The quality of data provided in the Ecoinvent is deemed reliable as it is the most complete industrial LCI database available, and data published by CTMTC company is considered trustworthy given that the company was founded in 1984 by the government of China and has a four-decade-long history of development, claiming they delivered over three hundred nonwoven production lines worldwide.

3.1.2 Life Cycle Inventory Analysis (LCI)

In this section, the main assumptions and calculations referring to the life cycle of each of the modelled systems and unit processes are presented. Necessary data and related information used in this LCA are collected from different sources. No primary data was received for this thesis from any company, although the data used for system B modelling can be considered as a primary source. The secondary data was collected through publications, scientific literature, LCI databases, and corporate websites.

Inventory of the Spunbound Product System

Spunbound product system includes the following major lifecycle stages:

- Raw materials production and processing. Crude oil extraction (upstream)
- Intermediate materials conversion. Oil refining and polymerisation (upstream)
- Production of nonwoven fabrics by extrusion and spunbonding processes (core)

The flowchart of the Spunbound nonwoven product system is presented in FIGURE 12.

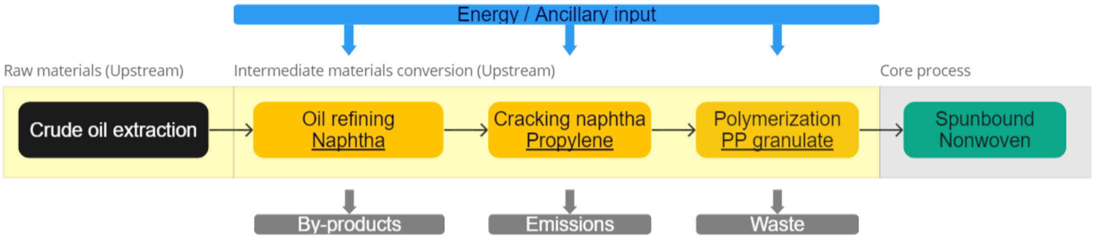


FIGURE 12. Spunbound nonwoven product system

The primary raw material for the spunbound nonwoven is polypropylene (PP). The acquisition of polypropylene granulate occurs in four main stages. First, crude oil is extracted and delivered to the refining facility. Depending on the possibilities of the refinery, the following processes might be performed inside one or different entities. The oil refining process produces light distillate - naphtha, which is a flammable liquid hydrocarbon mixture. By further cracking naphtha, propylene is obtained. Along with ethylene and higher alkenes, they are separated by low-temperature fractional distillation. The production of polypropylene (PP) takes place by slurry, solution, or gas phase process, in which the propylene monomer is subjected to heat and pressure in the presence of catalysts. Polymerisation is achieved at relatively low temperature and pressure, and the product yielded is translucent but readily coloured. Differences in catalyst and production conditions can be used to alter the properties of the plastic. (British Plastics Federation, n.d.)

The nonwoven spunbound production process is relatively simple and straightforward. All stages of the process are seamlessly integrated see FIGURE 13. Production begins when raw material – PP granules, is fed into the melting hopper. By spinning and stretching molten polymer resin filaments are then formed. Next, separated fibre bundles of many filaments lay down on a collector belt to form a web. In order to fix the structure of the sheet thermal bonding is performed with a heat roll. At last, the ready nonwoven sheet winds up.

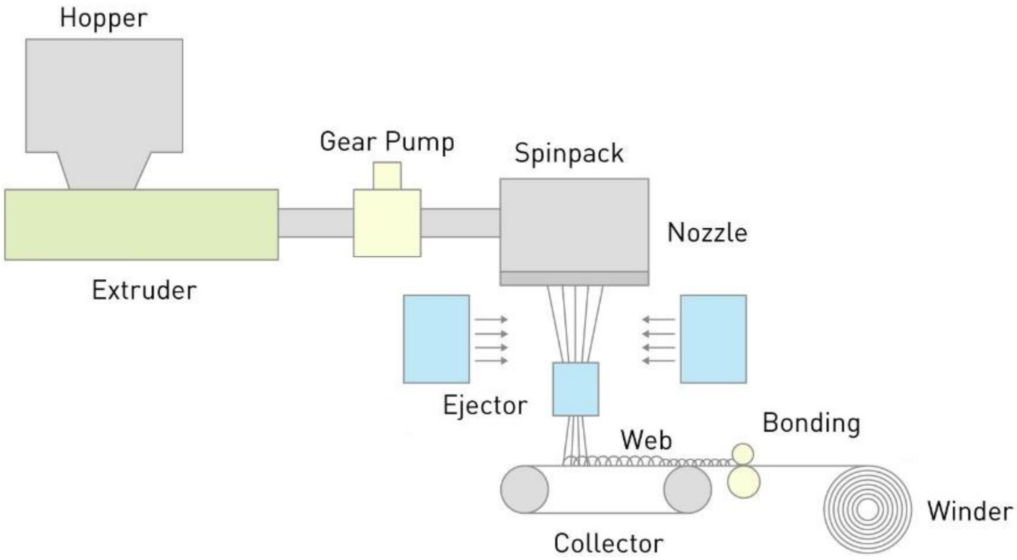


FIGURE 13. Spunbound web formation process (Kasen Nozzle Inc., n.d.)

For the purpose of modelling the spunbound web formation process, the existing Ecoinvent Indian dataset was used as a proxy. Local resource providers were substituted for the European sources (RER), and the amounts of consumed resources were transferred to the unit process without changes. Upstream unit process models for raw materials and intermediate materials conversion using unchanged data provided in the Ecoinvent LCI database. The market activity input from the technosphere, such as polypropylene granulate, represents the consumption mix of a product in a given geographical area. The market category also accounts for transport to the consumer and for the losses during that process according to the Ecoinvent model. Sima Pro inputs into the product system A presented in TABLE 5.

TABLE 5. Input and output values of the product system A

Input/Output Product System A			
Outputs to technosphere: Products and co-products	**Amount**	**Unit**	**Category**
Textile, nonwoven polypropylene {RER}| textile production, nonwoven polypropylene, spunbond | Cut-off, U	1	kg	Textiles/ Transformation
Inputs from technosphere: materials/fuels	**Amount**	**Unit**	**Comment**
Building, hall {GLO}| market for | Cut-off, U	3.70E-05	m^2	m^2 of building/ production per lifetime
Polypropylene, granulate {GLO}| market for | Cut-off, U	1	kg	Granules are recirculated
Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U	0.025	kg	Ancillary
Tap water {RER}| market group for | Cut-off, U	2.0867	kg	Humidification and cleaning granules
Inputs from technosphere: electricity/heat	**Amount**	**Unit**	**Comment**
Diesel, burned in diesel-electric generating set, 18.5kW {GLO}| market for | Cut-off, U	0.1593	MJ	Disel used for power backup
Electricity, low voltage {RER}| market group for | Cut-off, U	0.8065	MJ	Sum of electricity used
Emissions to air	**Amount**	**Unit**	**Comment**
Water/m3	0.000417	m^3	20%Evaporation
Outputs to technosphere: Waste treatment	**Amount**	**Unit**	**Comment**
Wastewater, average {Europe without Switzerland} | market for wastewater, average | Cut-off, U	0.001669	m^3	80% Wastewater generation

The complete inventory analysis table, calculated in the SimaPro software based on the provided input values contains information about all inputs and outputs of the Spunbound nonwoven product system in the form of elementary flows to and from the environment generated by unit processes included in the study boundaries and account for over 1800 elements. The example of the inventory table for the Mineral resource scarcity impact category with applied cut-off criteria 1.00E-12% is presented in APPENDIX 1.

Inventory of the Wet-laid Product System

Wet-laid product system includes the following major lifecycle stages:

- Raw materials production and processing. Wood harvesting (upstream)
- Intermediate materials conversion. Production of cellulosic wood pulp (upstream)
- Production of nonwoven fabrics by wetlaying process (core)

The flowchart of the Wet-laid nonwoven product system is presented in FIGURE 14.

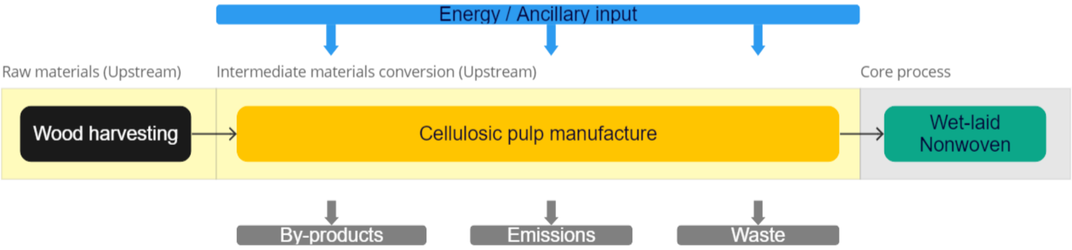


FIGURE 14. Wet-laid nonwoven product system

The main raw material used for wetlaid nonwoven production is wood pulp. The supply chain of raw materials for the wet-laid product system is shorter in comparison with the spunbound system. Virgin wood, after harvesting, is transported to the pulp mill where chip preparation, consistency refining, fractionation, treatment of long fibre fraction, bleaching and dewatering to baling for market pulp occurs in one cycle.

The nonwoven wet-laid production process resembles papermaking and, by contrast with the plastic extrusion process, is more energy-intensive. Also, due to the use of the hydroentanglement bonding technique, water consumption in the process is high. The phases of the wet-laid nonwoven production are depicted in FIGURE 15. First, the pulp with other fibres and water is mixed in the slurry tank to make a uniform body. Then through the feeding pump the mixture is dispersed in an inclined wire former and partially dewatered. After the web is formed, it is then transported to the bonding stage where the high-power water jets perform the entanglement to create the tension between fibres in the web structure and provide the nonwoven material with the required tearing resistance characteristics. The next phase of the process includes several hot rollers where excessive water evaporates from the product. Finally, the ready wet laid nonwoven web is winding up.

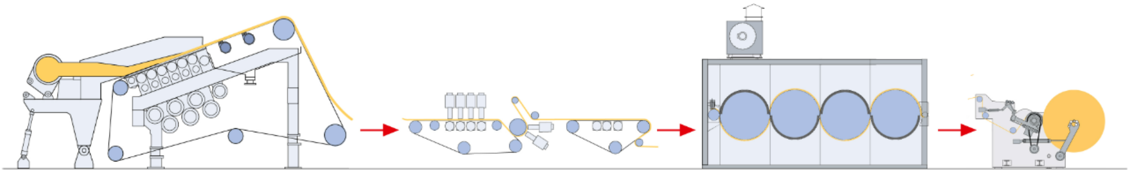


FIGURE 15. Wet-laid nonwoven process. (A.T.E. Private Limited, n.d.)

To model a wet-laid nonwoven process data provided by the CTMTC corporation for the CTMTC-HTHI Wet-Laid Spunlaced Nonwoven Line was used (CTMTC 2021), see TABLE 6.

TABLE 6. Energy and recourse consumption per ton of product CTMTC-HTHI

Recourse	Amount	Unit
Water	6-10	Ton
Electricity	1500-2000	kWh
Steam	3-5	Ton

In order to align the primary data to the studied functional unit and input units of the SimaPro software, the subsequent calculations and assumptions were made. The average amounts out of the ranges provided by the CTMTC corporation were set as consumed resources. Further to transform the amount of steam from mass to kWh units the next calculations were performed. It was assumed that the average temperature of the steam used in the wetlaid nonwoven process is approximately the same as in papermaking due to the high degree of similarity in these processes and is set to 150 ºC. With this temperature, the latent heat of steam – the amount of heat contained in steam released when steam condenses into the liquid state, according to the engineering calculator is 2.11367 MJ/kg (TLV Calculator, 2023). Knowing the total amount of energy transferred by steam converting it from SI units Megajoules to Kilowatt-hours using equation 1 kWh = 3.6 MJ. The calculated and converted data aligned with the functional unit presented in TABLE 7.

TABLE 7. Recourse consumption is expressed in terms of the functional unit.

Recourse	Amount	Unit
Water	8000	Kg
Electricity	1750	kWh
Steam	2349	kWh

Generalisation was made with the raw materials. According to Deng et al. (2018, 2), to produce hydroentangled wetlaid nonwoven for hygiene application, along with pulp fibres, a proportion of 20% of regenerated cellulose or dissolving wood pulp (lyocell-type) fibres is needed. For this study, it was assumed that the production of the regenerated cellulose in terms of energy, resources, and environmental impact is equal to the production of bleached wood pulp. It was also assumed an average of 20% of the water-evaporation rate, 50% of water recirculates in the system, and 30% of the water is directed to the wastewater treatment facility. Upstream unit process models for raw materials and intermediate materials conversion using unchanged data provided in the Ecoinvent LCI database. Transportation of materials and energy between production sites and the losses during that process accounted in the market category of inputs according to the Ecoinvent model. Sima Pro inputs into the product system B presented in TABLE 8.

TABLE 8. Input and output values of the product system B

Input/Output Product System B			
Outputs to technosphere: Products and co-products	**Amount**	**Unit**	**Category**
Textile, nonwoven cellulose {RER}| textile production, nonwoven cellulose, wetlaid | Cut-off, U	1	kg	Textiles/Transformation
Inputs from technosphere: materials/fuels	**Amount**	**Unit**	**Comment**
Building, hall {GLO}| market for | Cut-off, U	3.70E-05	m^2	m^2 of building / production per lifetime
Sulfate pulp, bleached {RER}| market for sulfate pulp, bleached | Cut-off, U	1	kg	No waste pulp generated
Tap water {RER}| market group for | Cut-off, U	8	kg	Slurry/Spunlace
Inputs from technosphere: electricity/heat	**Amount**	**Unit**	**Comment**
Electricity, medium voltage {RER}| market group for | Cut-off, U	1.75	kWh	Sum of electricity used
Heat, district or industrial, natural gas {RER}| market group for | Cut-off, U	7.6092048	MJ	Industrial heat 90.00%
Heat, district or industrial, other than natural gas {RER}| market group for | Cut-off, U	0.8454672	MJ	Industrial heat 10.00%
Emissions to air	**Amount**	**Unit**	**Comment**
Water/m3	0.0016	m^3	20% Dflt Evaporation
Emissions to water	**Amount**	**Unit**	**Comment**
Water, RER	0.004	m^3	50% Water reused
Outputs to technosphere: Waste treatment	**Amount**	**Unit**	**Comment**
Wastewater, average {Europe without Switzerland}| market for wastewater, average | Cut-off, U	0.0024	m^3	30% Default wastewater generation rate

The complete inventory analysis table, calculated in the SimaPro software based on the provided input values contains information about all inputs and outputs of the Wet-laid nonwoven product system in the form of elementary flows to and from the environment generated by unit processes included in the study boundaries and account for over 1800 units. The example of the inventory table for the Global warming impact category with applied cut-off criteria 1.00E-12% is presented in APPENDIX 2.

4 RESULTS AND DISCUSSION

4.1 Life Cycle Impact Assessment (LCIA)

Throughout the impact assessment step of an LCA study, all used raw materials and emissions during the life cycle of a product system are translated to environmental impacts. Life cycle impacts of the studied product systems were assessed according to the ReCiPe 2016 Midpoint (H) method in the SimaPro software. In the process called characterization, all substances identified in the LCI phase are multiplied by a factor which reflects their relative contribution to the environmental impact, quantifying how much impact a product system has in each impact category. The result of the characterization procedure in a graphic form is presented in APPENDIX 3. The chart shows the relative indicator results of the respective product system. For each indicator, the maximum sum is set to 100 per cent, and the result of the other variant is displayed in relation to this result. When creating a comparative LCA project in SimaPro software, the generated report contains consolidated inventory data. Therefore, additional individual calculations for each system were run to obtain more detailed and convenient data on the environmental impact of the product systems and analysed in the external Excel software. The impact assessment table for the Spunbound product system expressed in corresponding indicator units is presented in TABLE 9.

TABLE 9. Impact assessment results of the product system A

Product: 1 p Spunbond nonwoven textile from Polypropylene RER		
Method: ReCiPe 2016 Midpoint (H) V1.06 / World (2010) H		
Impact category	Unit	Total
Global warming	kg CO_2 eq	2741.130
Stratospheric ozone depletion	kg CFC11 eq	0.001
Ionizing radiation	kBq Co-60 eq	219.422
Ozone formation, Human health	kg NO_x eq	5.789
Fine particulate matter formation	kg PM2.5 eq	3.102
Ozone formation, Terrestrial ecosystems	kg NO_x eq	6.109
Terrestrial acidification	kg SO_2 eq	7.941
Freshwater eutrophication	kg P eq	0.861
Marine eutrophication	kg N eq	0.070
Terrestrial ecotoxicity	kg 1,4-DCB	6015.858
Freshwater ecotoxicity	kg 1,4-DCB	91.235
Marine ecotoxicity	kg 1,4-DCB	119.110

Human carcinogenic toxicity	kg 1,4-DCB	115.501
Human non-carcinogenic toxicity	kg 1,4-DCB	1732.351
Land use	m^2a crop eq	34.048
Mineral resource scarcity	kg Cu eq	5.730
Fossil resource scarcity	kg oil eq	1812.941
Water consumption	m^3	28.159

The chosen assessment method, ReCiPe 2016 Midpoint (H), also includes the optional step of the LCIA, referenced in the method's name as World (2010) H - normalization. As discussed later in the interpretation phase, this option provides a different perspective to the data analysed. In this procedure, the results are compared to a certain reference value. The selected method relates the contribution of different materials and processes in the product system to the average environmental impact of one person in the world per year. The impact assessment table for the Wetlaid product system with normalized scores according to the different midpoint impact categories is presented in TABLE 10. The unit of the values in the table is the impact caused by an average person per year.

TABLE 10. Impact assessment results of the product system B

Product: 1 p Wetlaid nonwoven textile from wood pulp RER		
Method: ReCiPe 2016 Midpoint (H) V1.06 / World (2010) H		
Impact category	Unit	Total
Global warming	H/A	0.185895
Stratospheric ozone depletion	H/A	0.011393
Ionizing radiation	H/A	0.861088
Ozone formation, Human health	H/A	0.201214
Fine particulate matter formation	H/A	0.087697
Ozone formation, Terrestrial ecosystems	H/A	0.236904
Terrestrial acidification	H/A	0.126718
Freshwater eutrophication	H/A	2.038366
Marine eutrophication	H/A	0.018679
Terrestrial ecotoxicity	H/A	0.240428
Freshwater ecotoxicity	H/A	1.829522
Marine ecotoxicity	H/A	1.453306
Human carcinogenic toxicity	H/A	8.979973
Human non-carcinogenic toxicity	H/A	0.042976
Land use	H/A	0.315843
Mineral resource scarcity	H/A	0.000021
Fossil resource scarcity	H/A	0.468625
Water consumption	H/A	0.216619

A summary of aggregated total impact assessment results of the product systems A and B expressed in corresponding indicator units is provided in APPENDIX 4.

The following section demonstrates the potential impacts of assessed product systems per chosen category and a comparison between the two systems. Moreover, the main contributors to the results are presented per each impact category within the respective systems.

Global warming

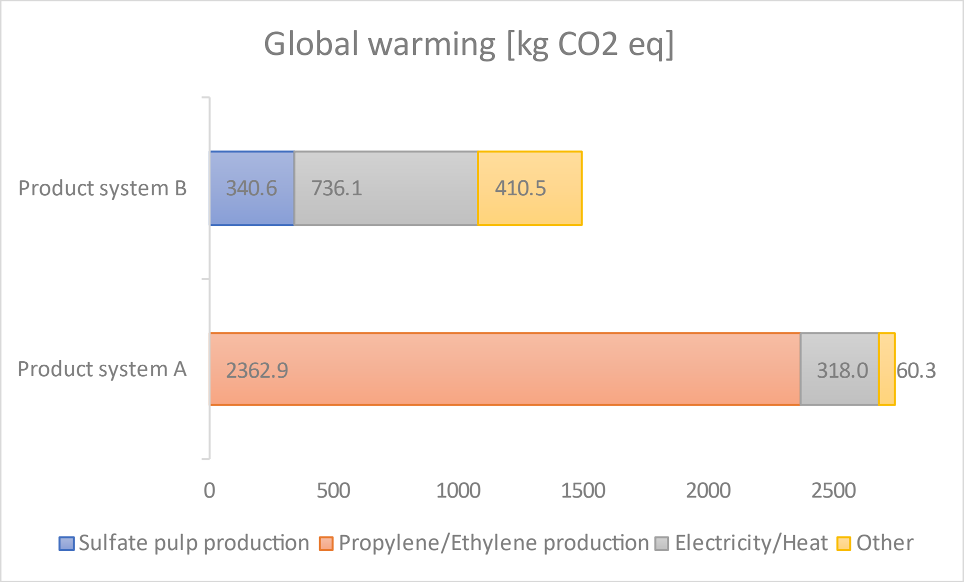


FIGURE 16. Global warming. Processes contribution

The potential climate change impact of product system A is largely driven by propylene manufacturing. Over 80 per cent of the aggregated total impact comes from raw material conversion upstream stages before the production of nonwovens. The electricity demand for the production of nonwovens plays a marginal role in this impact category. On the other hand, electricity and industrial heat contribute the most considerable portion of the total impact for system B, assuming the EU average grid mix, while the upstream product stage of raw material conversion into pulp generates only about 20 per cent of the total system's B effect. Overall, the Spunbound nonwoven product system brings almost twice the global warming load than the Wetlaid nonwoven system.

Fine particulate matter formation

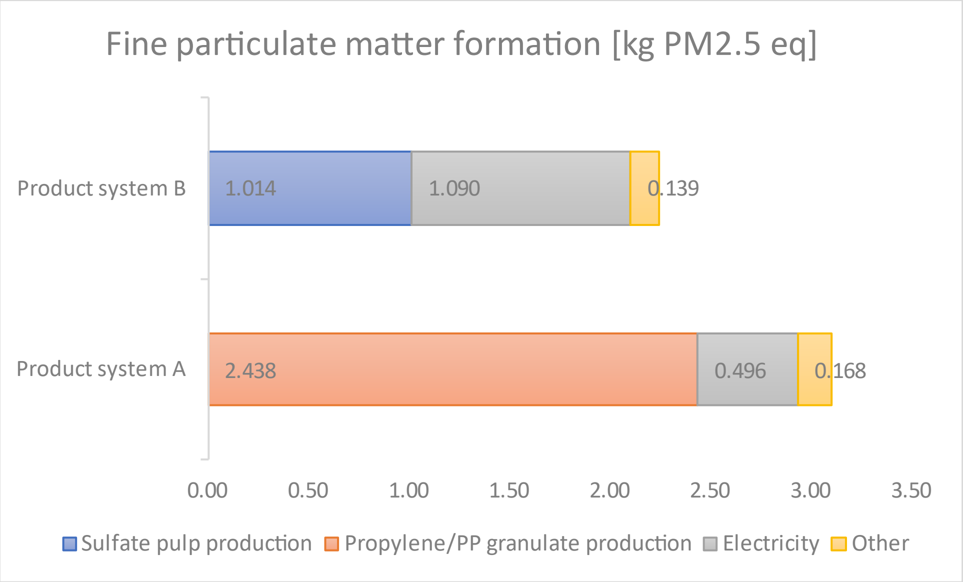


FIGURE 17. Fine particulate matter formation. Processes contribution

Both systems produce primary and secondary aerosols in the atmosphere that have a negative impact on human health. In product system B, over 90 per cent of indicator results are divided roughly equally between the production of the materials (bleached pulp) and energy generation required for the core nonwoven process. In contrast, product system A generates around 80 per cent of the total impact in this category through the cracking naphtha and polymerisation processes, while the energy demand for the production of the nonwoven web with spunbonding contributed only 16 per cent of the impact. As a whole, the Spunbound nonwoven system releases 40 per cent more harmful aerosols than the Wetlaid system.

Human carcinogenic toxicity

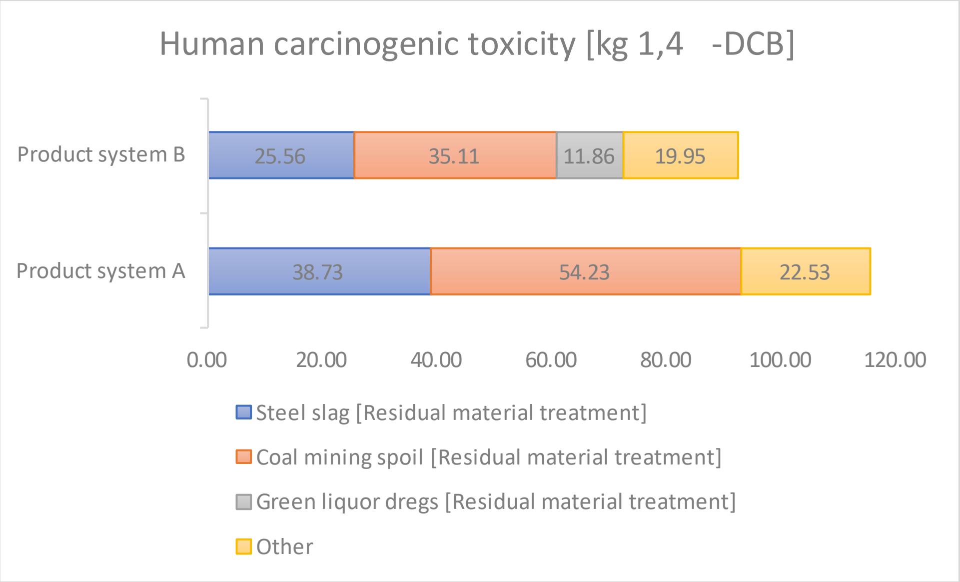


FIGURE 18. Human carcinogenic toxicity. Processes contribution

Most of the load on the human carcinogenic toxicity indicator accumulated from the early stages of the supply chains of both product systems and has a direct link to energy production. Steel and coal mining produces a lot of byproducts, such as basic oxygen furnace slag, spoil from lignite mining, electric arc furnace slag, etc., which are treated predominantly by surface landfilling. Notably, in the system B supply chain, almost 13 per cent of the toxicity impact comes from the green liquor dregs – a residual material of the pulp production process, while system A generates its impact mainly within the raw materials extraction phase. The difference between studied systems in this impact category is not considerable, with Spunbound nonwovens having a 25 per cent higher figure.

Land use

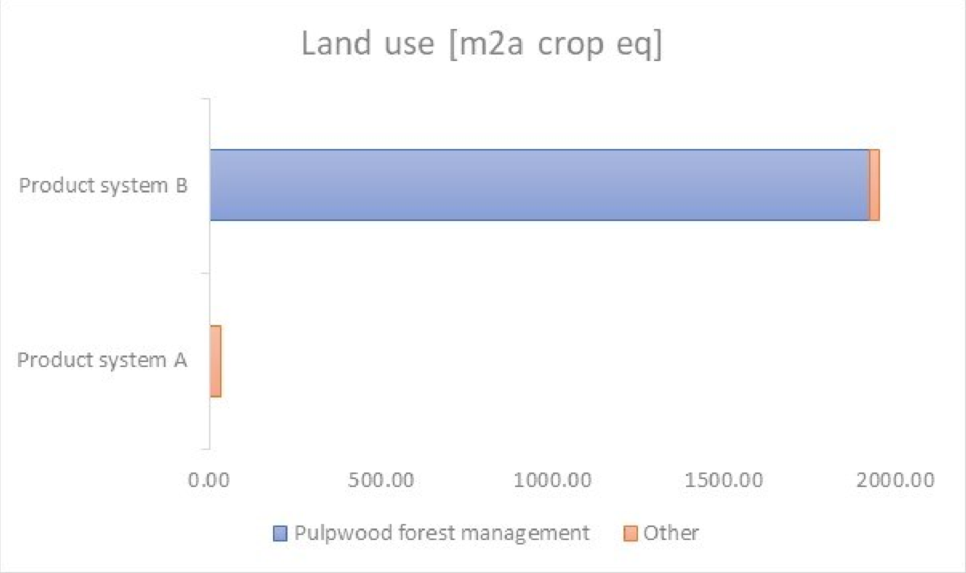


FIGURE 19. Land use. Processes contribution

The largest contributors to the land use impact category for system A are road construction, accounting for around 11 per cent of the input and onshore wells for oil and gas production, just under 7 per cent. The rest of the contributions are spread across all processes involved through the whole supply chain with minor shares of 3 per cent or less. The production of the wood for pulp in system B requires a massive amount of land to make raw material production sustainable and regenerate consumed natural resources. In this impact category, the Wetlaid system is responsible for 57 times more load than the Spunbound system.

Fossil resource scarcity

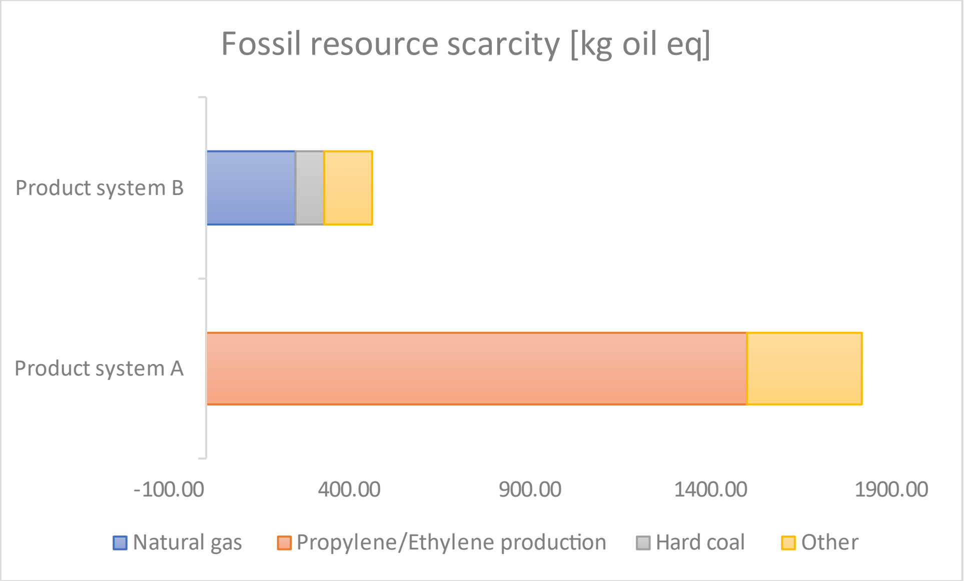


FIGURE 20. Fossil resource scarcity. Processes contribution

Fossil resource scarcity impact from product system B in its biggest share of over 70 per cent is attributed to the industrial heat and electricity production consumed in the core modelled process – the nonwoven manufacturing. An average EU electricity grid mix and industrial heating sources were assumed in the system. For system A, a paramount process contributing over 80 per cent to the indicator is refining naphtha with a fractional distillation process to obtain upstream raw materials such as propylene and ethylene. The Spunbound product system has a four times higher impact on a fossil resource scarcity indicator than the Wetlaid.

Water consumption

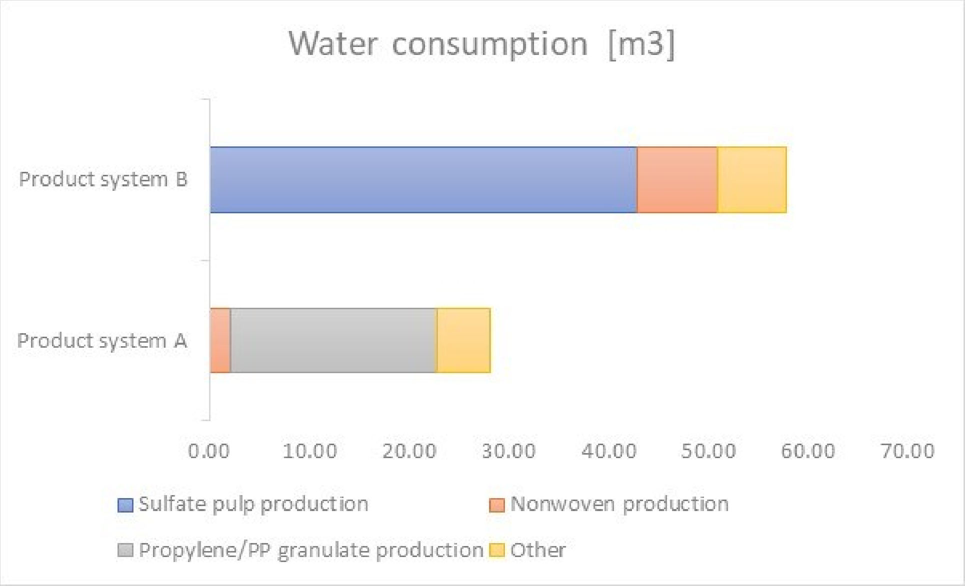


FIGURE 21. Water consumption. Processes contribution

Contrary to the initial hypothesis that the Wetlaid nonwoven technique would bear a prevailing impact on the water consumption indicator, the assessment shows the main consumer of water from the product system's B supply chain is the production of sulphate wood pulp, which brings around 75 per cent of the total impact; while the production of nonwovens accounts only 14 per cent of the contribution, partially due to positive effect of reusing water. Another revelation comes from system A. Although the production of polypropylene requires water input in all stages, during the material conversion phase, a chemical process produces unpolluted water as a by-product, which significantly affects the overall impact of the system on the water consumption indicator. The contribution network of the processes with positive effects of by-product water is illustrated in APPENDIX 5. Overall, the Wetlaid product system requires twice as much water as the Spunbound system.

4.2 LCA Interpretation

In order to identify the environmental hotspots of the studied systems, contribution analysis is performed. The contribution of each life cycle stage is reviewed for all assessed impact categories, and contributions to the total impact of the product systems are based on the normalized impact results.

Following this procedure, the results show that the environmental hotspots of the product systems A and B predominantly occur in different life cycle phases. Environmental impacts in the Spunbound product system (A) are primarily driven by the raw material extraction and intermediate material conversion life cycle stages, see FIGURE 22. The potential environmental impacts of product system A are largely affected by propylene and polypropylene manufacturing, which includes virgin material extraction, oil refining and polypropylene manufacturing. More than 70 per cent in all impact categories, apart from Land use.

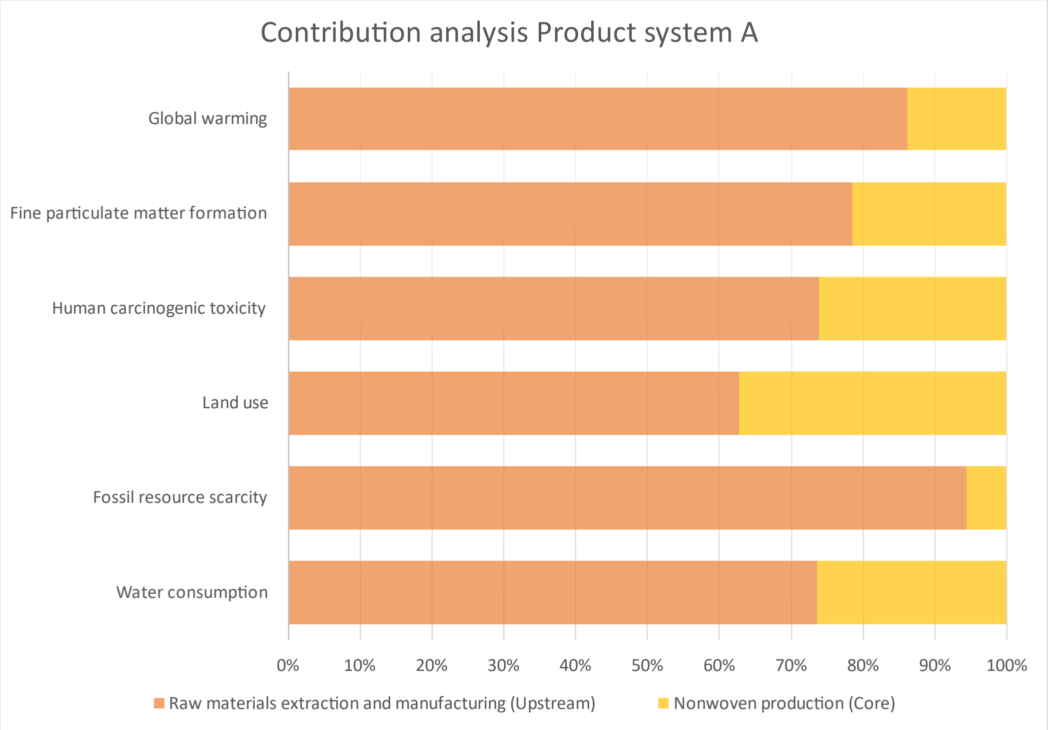


FIGURE 22. Contribution analysis Spunbound product system

The potential environmental impacts of the Wetlaid product system (B) are largely driven by the nonwoven production phase, with a contribution from 78 per cent in Fossil resource scarcity and Global warming categories to 25 per cent in the Water consumption category, with the exception of Land use, see FIGURE 23. This is linked to highly energy-intensive production processes, especially for running wetlaying nonwoven lines and the industrial heat required for drying the web.

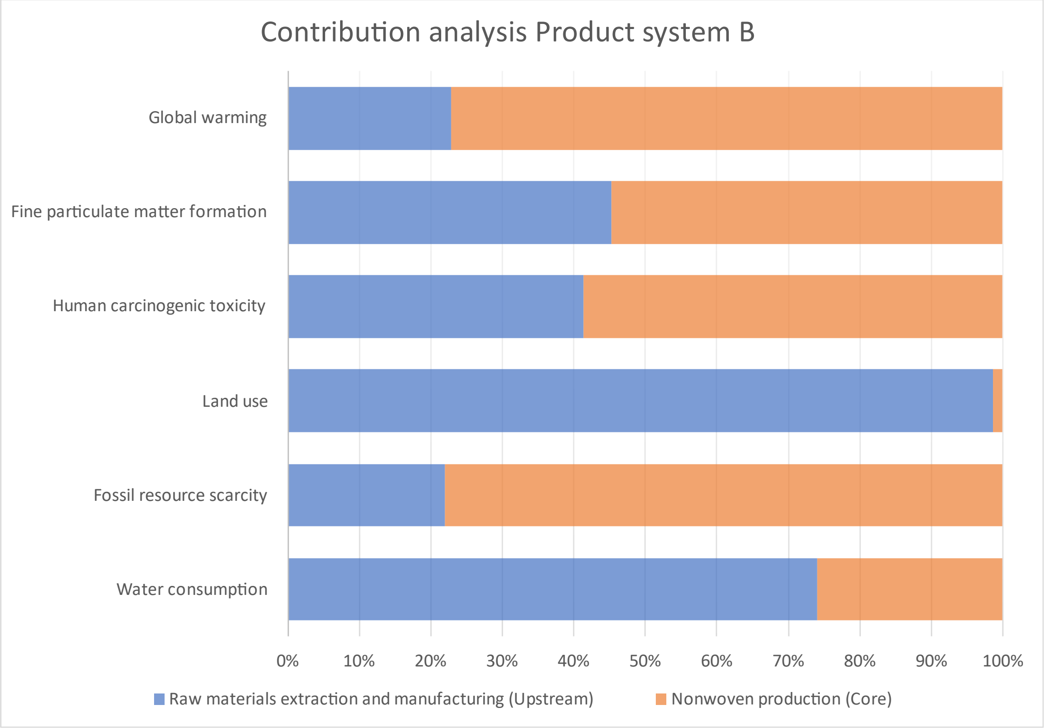


FIGURE 23. Contribution analysis Wetlaid product system

The normalization allows the identification of the most affected impact categories. Based on the normalized results, the most relevant impact categories are Human carcinogenic toxicity, Freshwater ecotoxicity, Freshwater eutrophication, Marine ecotoxicity, Fossil resource scarcity and Ionizing radiation, with a cumulative contribution of 91.9 per cent of the total impact for product system A, and 90.3 per cent for product system B. Impact categories contributing at least 90 per cent of the total environmental impact of both product systems are presented in TABLE 11. Most relevant categories common to both systems are indicated in the orange cells, while most relevant categories for only one system are indicated in green cells.

TABLE 11. Total environmental impact by impact category

Impact category	Contribution to the total impact (%)	
	Wetlaid system	Spunbond system
Global warming	1.1%	1.5%
Stratospheric ozone depletion	0.1%	0.0%
Ionizing radiation	**5.0%**	2.0%
Ozone formation, Human health	1.2%	1.2%
Fine particulate matter formation	0.5%	0.5%
Ozone formation, Terrestrial ecosystems	1.4%	1.5%
Terrestrial acidification	0.7%	0.8%
Freshwater eutrophication	**11.8%**	5.7%
Marine eutrophication	0.1%	0.1%
Terrestrial ecotoxicity	1.4%	1.7%
Freshwater ecotoxicity	10.6%	15.7%
Marine ecotoxicity	8.4%	11.9%
Human carcinogenic toxicity	51.9%	48.6%
Human non-carcinogenic toxicity	0.2%	0.2%
Land use	1.8%	0.0%
Mineral resource scarcity	0.0%	0.0%
Fossil resource scarcity	2.7%	**8.0%**
Water consumption	1.3%	0.5%

The calculated sum of total environmental impacts expressed in terms of normalized scores of Spunbond product system (A) is equal to the impact caused by 23.1 average persons per year, whereas the total environmental impact generated by the Wetlaid product system (B) is equal to the consequences caused by 17.3 average person’s activity during a year.

5 CONCLUSIONS

The chapters above provide background information and results for a comparative Life Cycle Assessment of Spunbound polypropylene and Wetlaid cellulosic options as a base for single-use nonwoven products in Europe (see description of goal and scope of the study in paragraph 3.1.1). A systems perspective is used to reflect both systems and compare equal functions of rolled nonwoven fabric sheets manufactured either from polypropylene granulate or cellulosic pulp with different technologies, which is then used to produce consumer single-use wipes. The LCA is conducted according to the relevant ISO 14040 series of standards and discusses the impacts on a set of chosen environmental impact categories. Regarding data quality and completeness for the goal and scope of this assessment, it is important to acknowledge the limitations of primary and secondary data used. Due to the data availability issues this LCA should be interpreted as simplified research.

Overall, results of the comparative assessment of Spunbound and Wetlaid systems show that the environmental hotspots refer to different life cycle phases in the two systems: the main contributors to the impacts in the Spunbound system are the raw material production and manufacturing stages, whereas the main contributor in the Wetlaid system is the core nonwoven manufacturing stage. It can be concluded that the Wetlaid product system shows lower impacts in 12 impact categories with a relative percentage difference ranging between 20 per cent for the human carcinogenic toxicity category to 75 per cent for the fossil resource scarcity category and higher impacts in 6 impact categories with a relative percentage difference ranging between 19 per cent for the marine eutrophication category to 98 per cent for the land use category.

Performed contribution analysis shows that most of the environmental impacts in the Spunbound product system (A) primarily come from virgin material extraction, oil refining and polypropylene manufacturing while in the Wetlaid product system (B) the dominant contributor to the impacts is the production of the energy required for running wetlaying nonwoven line. The limited level of impact from the materials conversion stage can be attributed to the maturity of technology for wood pulp production and a relatively short supply chain. Since the normalized indicator results show that for both product systems, at least half of the total environmental impact is attributed to the human carcinogenic toxicity category and directly linked to energy production, it can be stated that the improvement in this particular part of the supply chain of both product systems would greatly improve the overall sustainability of the products. For example, the exclusion of nuclear energy from the energy mix used for the production processes would lead to a decrease in the carcinogenic toxicity and ionizing radiation impact categories, while the substitution of coal and gas generation with renewables such as wind or geothermal can also decrease the contributions to the fossil resource scarcity and global warming categories.

The results of the study also point to further need for research and investigation. Including other life cycle stages in the study, like usage and end-of-life treatment would add to the full understanding of the environmental impact of nonwoven products made from different materials. While discarded polypropylene-based single-use nonwoven items are clearly more problematic waste to handle than cellulosic waste the gap between these product systems is expected to grow even more. Also, separate modelling of the transportation phase of the life cycle would add more clarity to the assessment.

This research highlighted that one of the most significant limitations for the wider implementation of the LCA method is data availability. From the experience of communicating with the nonwoven industry representatives, it could be declared that they are very reserved regarding the disclosure of any information even aggregated and generalized for research purposes. This is creating obstacles to those attempting to understand and research the environmental burden of the products they are using. The legislation regarding the publication of sustainability information comes into force recently but more needs to be done also to promote the LCA method and life cycle thinking together with data disclosure requirements.

Reflecting the secondary goal of this thesis it can be argued that the utilization of the Life Cycle Assessment as an instrument for analysing the environmental burden of a product or service and improvement of the product's sustainability proved to be of high value. The tool helps to reveal the weak points of the current supply chain and provide a holistic comprehension of the products, including the effects arising outside the enterprise border.

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APPENDICES

Appendix 1. Mineral resource scarcity Inventory. System A 1(2)

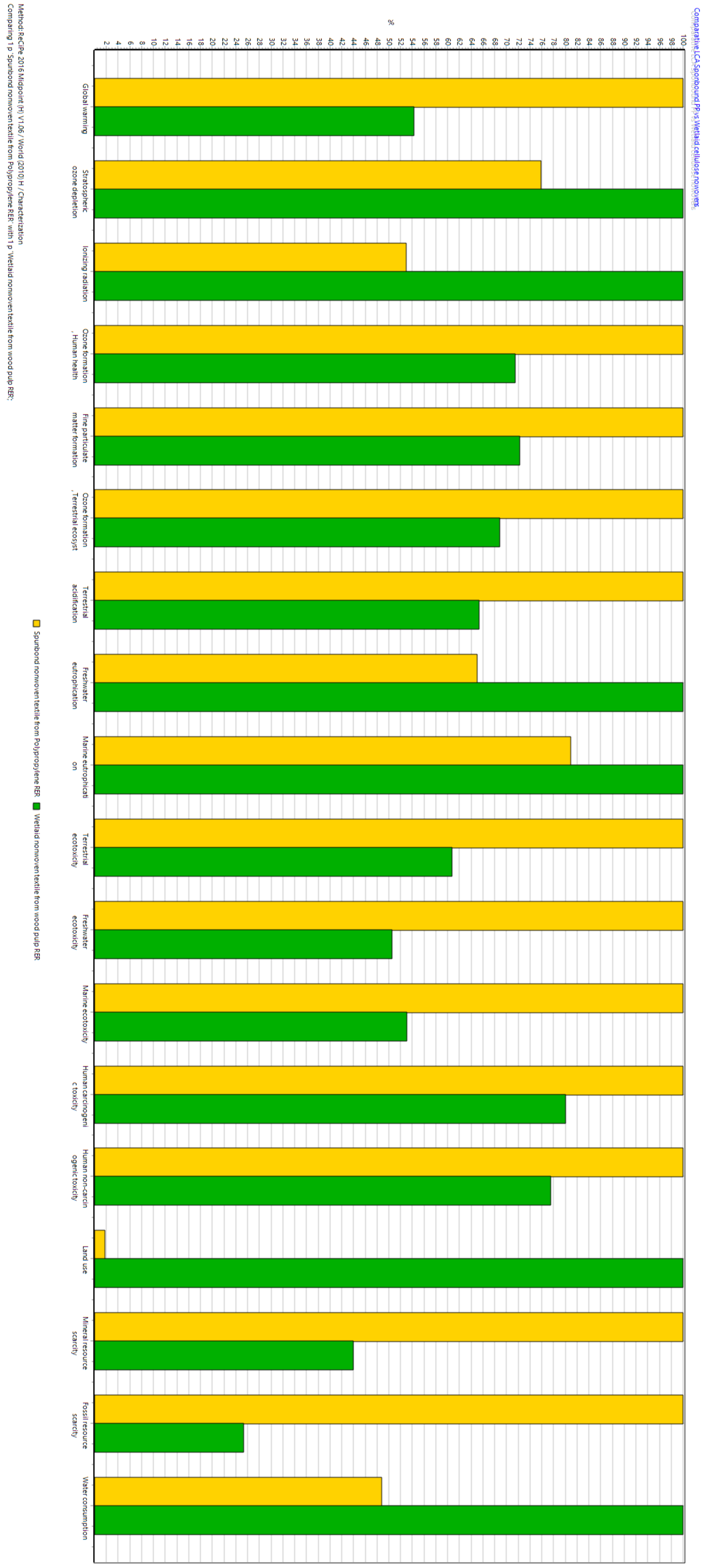
Results:	Inventory			
Product:	1 p Spunbond nonwoven textile from Polypropylene RER (of project Nonwovens)			
Method:	ReCiPe 2016 Midpoint (H) V1.06 / World (2010) H			
Indicator:	Characterization			
Category:	Mineral resource scarcity			
Cut-off:	1.00E-12			
No	Substance	Compartment	Unit	Amount
1	Nickel	Raw	kg Cu eq	9.69E-01
2	Copper	Raw	kg Cu eq	8.92E-01
3	Iron	Raw	kg Cu eq	8.34E-01
4	Titanium	Raw	kg Cu eq	7.69E-01
5	Molybdenum	Raw	kg Cu eq	5.84E-01
6	Hafnium	Raw	kg Cu eq	3.43E-01
7	Clay, unspecified	Raw	kg Cu eq	2.70E-01
8	Uranium	Raw	kg Cu eq	2.62E-01
9	Gold	Raw	kg Cu eq	1.79E-01
10	Aluminium	Raw	kg Cu eq	1.62E-01
11	Silver	Raw	kg Cu eq	9.72E-02
12	Silicon	Raw	kg Cu eq	5.76E-02
13	Zinc	Raw	kg Cu eq	4.79E-02
14	Magnesium	Raw	kg Cu eq	4.57E-02
15	Lead	Raw	kg Cu eq	3.36E-02
16	Chromium	Raw	kg Cu eq	3.34E-02
17	Phosphorus	Raw	kg Cu eq	2.70E-02
18	Gallium	Raw	kg Cu eq	2.45E-02
19	Selenium	Raw	kg Cu eq	2.10E-02
20	Tin	Raw	kg Cu eq	1.38E-02
21	Manganese	Raw	kg Cu eq	1.27E-02
22	Platinum	Raw	kg Cu eq	1.11E-02
23	Tantalum	Raw	kg Cu eq	1.02E-02
24	Cobalt	Raw	kg Cu eq	9.95E-03
25	Palladium	Raw	kg Cu eq	7.54E-03
26	Tellurium	Raw	kg Cu eq	5.42E-03
27	Clay, bentonite	Raw	kg Cu eq	2.39E-03
28	Gypsum	Raw	kg Cu eq	2.02E-03
29	Rhenium	Raw	kg Cu eq	1.10E-03
30	Rhodium	Raw	kg Cu eq	9.81E-04
31	Niobium	Raw	kg Cu eq	7.80E-04
32	Chrysotile	Raw	kg Cu eq	5.33E-04
33	Lithium	Raw	kg Cu eq	9.93E-05
34	Iodine	Raw	kg Cu eq	5.72E-05
35	Mercury	Raw	kg Cu eq	4.22E-05
36	Talc	Raw	kg Cu eq	2.13E-05

37	Cadmium	Raw	kg Cu eq	1.16E-05
38	Strontium	Raw	kg Cu eq	8.44E-06
39	Vanadium	Raw	kg Cu eq	5.60E-06
40	Arsenic	Raw	kg Cu eq	4.16E-06
41	Perlite	Raw	kg Cu eq	1.45E-06
42	Antimony	Raw	kg Cu eq	9.29E-07
43	Feldspar	Raw	kg Cu eq	9.76E-09
44	Diatomite	Raw	kg Cu eq	3.77E-09

Appendix 2. Global warming Inventory. System B

Results:	Inventory			
Product 2:	1 p Wetlaid nonwoven textile from wood pulp RER (of project Nonwovens)			
Method:	ReCiPe 2016 Midpoint (H) V1.06 / World (2010) H			
Indicator:	Characterization			
Category:	Global warming			
Cut-off:	1.00E-12			
No	Substance	Compartment	Unit	Amount
1	Carbon dioxide, fossil	Air	kg CO_2 eq	1.37E+03
2	Methane, fossil	Air	kg CO_2 eq	8.67E+01
3	Dinitrogen monoxide	Air	kg CO_2 eq	1.34E+01
4	Methane, biogenic	Air	kg CO_2 eq	8.23E+00
5	Sulfur hexafluoride	Air	kg CO_2 eq	5.40E+00
6	Carbon dioxide, land transformation	Air	kg CO_2 eq	3.02E+00
7	Methane, tetrafluoro-, CFC-14	Air	kg CO_2 eq	1.89E-01
8	Methane, chlorodifluoro-, HCFC-22	Air	kg CO_2 eq	1.21E-01
9	Methane, tetrachloro-, CFC-10	Air	kg CO_2 eq	5.07E-02
10	Ethane, hexafluoro-, HFC-116	Air	kg CO_2 eq	3.56E-02
11	Methane, bromochlorodifluoro-, Halon 1211	Air	kg CO_2 eq	2.72E-02
12	Methane, bromotrifluoro-, Halon 1301	Air	kg CO_2 eq	2.32E-02
13	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Air	kg CO_2 eq	1.41E-02
14	Methane, land transformation	Air	kg CO_2 eq	1.33E-02
15	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	kg CO_2 eq	3.03E-03
16	Methane, trifluoro-, HFC-23	Air	kg CO_2 eq	2.05E-03
17	Methane, dichlorodifluoro-, CFC-12	Air	kg CO_2 eq	1.54E-03
18	Ethane, 1,1-difluoro-, HFC-152a	Air	kg CO_2 eq	1.52E-03
19	Hydrocarbons, chlorinated	Air	kg CO_2 eq	7.20E-04
20	Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	Air	kg CO_2 eq	2.79E-04
21	Ethane, 1,2-dichloro-	Air	kg CO_2 eq	2.58E-04
22	Methane	Air	kg CO_2 eq	1.76E-04
23	Methane, monochloro-, R-40	Air	kg CO_2 eq	4.92E-05
24	Chloroform	Air	kg CO_2 eq	4.51E-05
25	Methane, dichloro-, HCC-30	Air	kg CO_2 eq	2.64E-05
26	Ethane, 1,1,1-trichloro-, HCFC-140	Air	kg CO_2 eq	2.39E-05
27	Methane, trichlorofluoro-, CFC-11	Air	kg CO_2 eq	2.74E-06
28	Nitrogen fluoride	Air	kg CO_2 eq	9.51E-08
29	Methane, dichlorofluoro-, HCFC-21	Air	kg CO_2 eq	8.31E-08
30	Methane, bromo-, Halon 1001	Air	kg CO_2 eq	1.19E-08

Appendix 3. Impact Assessment Comparison



Appendix 4. Summary of aggregated total impacts

Method: ReCiPe 2016 Midpoint (H) V1.06 / World (2010) H		Product system A	Product system B
Impact category	Unit	Total	Total
Global warming	kg CO_2 eq	2741.1302000	1487.1635000
Stratospheric ozone depletion	kg CFC11 eq	0.0005177	0.0006822
Ionizing radiation	kBq Co-60 eq	219.4222100	413.9846900
Ozone formation, Human health	kg NO_x eq	5.7886710	4.1402070
Fine particulate matter formation	kg PM2.5 eq	3.1023792	2.2428894
Ozone formation, Terrestrial ecosystems	kg NO_x eq	6.1092442	4.2078896
Terrestrial acidification	kg SO_2 eq	7.9410308	5.1933581
Freshwater eutrophication	kg P eq	0.8612954	1.3236141
Marine eutrophication	kg N eq	0.0696149	0.0860775
Terrestrial ecotoxicity	kg 1,4-DCB	6015.8576000	3653.9214000
Freshwater ecotoxicity	kg 1,4-DCB	91.2354130	46.0836800
Marine ecotoxicity	kg 1,4-DCB	119.1100200	63.1872310
Human carcinogenic toxicity	kg 1,4-DCB	115.5012100	92.4817030
Human non-carcinogenic toxicity	kg 1,4-DCB	1732.3505000	1343.0102000
Land use	m^2a crop eq	34.0484310	1949.6501000
Mineral resource scarcity	kg Cu eq	5.7297958	2.5214995
Fossil resource scarcity	kg oil eq	1812.9414000	459.4365600
Water consumption	m^3	28.1589960	57.7650670

Appendix 5. Water consumption indicator. Contribution network.