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Supporting Green Supply Chain Strategy of Bottled Water: A Scenario-Based Life Cycle Assessment of Packaging and Logistics

A Scenario-Based Life Cycle Assessment

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ABSTRACT:

The aim of this thesis is to evaluate the potential of using Life Cycle Assessment (LCA) in the field of bottled water sector as a method of green supply chain strategy. The study focused on packaging and logistics, given that they contribute significantly to the environmental impact of the raw materials used, to the production of bottles as well as to the transport and end-of-life treatment of the bottles. The main goals are to define the environmental hotspots and to benchmark a baseline bottled water supply chain against other scenarios (recycling PET bottles, logistics improvements, end-of-life changes).

The study uses a scenario approach and a system boundary from cradle to grave, as per ISO 14040 standard, with a functional unit of 1 000 liters of bottled water delivered to the consumer. The analysis is based on secondary data, where foreground data are taken from previous research and reports, and background data are taken from ecoinvent database based on the ReCiPe 2016 Midpoint (H) method and modelled in openLCA. All environmental impact categories are computed, with special attention paid to climate change as packaging and transportation of bottled water are closely linked to greenhouse gas emissions and energy consumption.

The electricity produced during manufacture of the plastic bottles is the biggest hotspot, accounting for 87 % of the total baseline climate change impact of 21789 kg CO_2-eq, with virgin PET resin accounting for a further 10%, transport 1.2% and waste management 0.5%. The use of recycled PET material instead of virgin material, on its own, reduces the climate change impact by 7.0%to 20264 kg CO_2-eq, while the improvement of logistics contributes only 1.0% to 21565 kg CO_2-eq. The combination of the two strategies provides the greatest reduction of 8.0%, with a result of 20040 kg CO_2-eq. There is no burden shifting, that is, the strategies that benefit climate change also help with other categories like fossil resource use, acidification and toxicity.

The study illustrates that LCA can deliver clear and concrete evidence for making decisions in supply chains. It identifies the most critical environmental hot spots, discusses the options before implementing them and ensures that improvements in one place do not bring problems to another. The most effective single lever to reduce the carbon footprint is to use 100% recycled PET, this should be considered first. Optimizing logistics can be used as an ancillary value-added service for other purposes, but at a lower level. The thesis shows how LCA is a useful and useful tool to facilitate more sustainable choices in bottled water supply chain packaging and logistics.

KEYWORDS: Green supply chain management, Life Cycle Assessment, Bottled water packaging, openLCA software and ecoinvent database, Sustainability

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Abbreviations

ADP	Abiotic Depletion Potential
AP	Acidification Potential
EP	Eutrophication Potential
EPD	Environmental Product Declaration
FEP	Freshwater Eutrophication
FRS	Fossil Resource Scarcity
FU	Functional Unit
GHG	Greenhouse Gas
GSCM	Green Supply Chain Management
GWP	Global Warming Potential
HTPc	Human Toxicity, carcinogenic
HTPnc	Human Toxicity, non carcinogenic
ILCD	International Reference Life Cycle Data System
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LDPE	Low density polyethylene
MEP	Marine Eutrophication
OAT	One at a time
ODP	Ozone Depletion Potential
PET	Polyethylene terephthalate
PP	Polypropylene
rPET	Recycled polyethylene terephthalate
SC	Sensitivity Coefficient
SETAC	Society of Environmental Toxicology and Chemistry
SR	Sensitivity Ratio
TAP	Terrestrial Acidification
UNEP	United Nations Environment Program

1 Introduction

1.1 Background

One of the most significant global issues of the twenty-first century is environmental sustainability. There is growing concern among governments, industries, and consumers regarding climate change, depletion of resources, and plastic pollution (Schwarz et al., 2019). Some of the observable environmental problems include the increasing rate of plastic packaging, particularly food and beverage products. Bottled water is among the most rapidly expanding categories of beverages across the world as a result of urbanization, changing lifestyles, and consumer beliefs about their safety and convenience (Gleick and Cooley, 2009).

However, even though bottled water has increased in commercial growth, it has brought forth a lot of concerns regarding the environment. The studies indicate that bottled water systems need energy and bottling materials to treat water, package in bottles, transport, and dispose of waste (Garfi et al., 2016). Bottled water typically has more negative environmental effects than tap water systems due to packaging sources and transportation (Horowitz et al., 2018).

The majority of the containers of bottled water are manufactured of polyethylene terephthalate (PET), which is a light and strong plastic made out of fossil materials (Plastics Europe, 2019). PET is highly applied due to its transparency, strength, and food contact inspection. Nevertheless, the manufacture of regular PET consumes a lot of energy and fossil-based raw materials which increase the emission of greenhouse gases and the consumption of resources (Wernet et al., 2016). Moreover, the world has not yet developed efficient plastic waste management systems, and some of the plastic waste materials are deposited in landfills or nature (Geyer, Jambeck and Law, 2017).

Packaging material is not the only factor affecting environmental impacts of bottled water rather it is a product of the whole supply chain. This covers the extraction of raw materials, the production of polymer, the bottles, filling, logistics of distribution and the treatment of end-of-life (ISO, 2006a). The environmental performance can be greatly affected by decisions that can be made at various levels in the supply chain. Examples of these include reducing the content of recycled PET, decreasing the weight of bottles, enhancing transportation routes, or enhancing the rate of recycling to decrease greenhouse gas emissions (Tamburini et al., 2021).

Green supply chain strategies have been embraced by companies as a result of environmental awareness. Green supply chain management incorporates the ecological aspect in the sourcing, production, distribution and wastes management activities (Srivastava, 2007; Mota et al., 2017). The strategies in the bottled water industry can involve recycled material, use of renewable energy in the industry, optimized logistics, and better recycling systems (Sazdovski et al., 2021).

Nevertheless, to implement green supply chain strategies, effective and scientific assessment tools are needed. The companies should be aware of where they have environmental impacts and the effects of alternative decisions on the overall performance. Life Cycle Assessment (LCA) is the standardized approach which analyzes the environmental effects of the entire life cycle of a product, including the extraction of raw materials and its disposal (ISO, 2006a; Finkbeiner et al., 2006). LCA offers quantitative data to assist the identification of environmental hotspots and compare alternative situations using the assumptions that are consistent (Finnveden et al., 2009).

During recent years, LCA software programs like OpenLCA have increased the quality of transparency and access of environmental modelling. OpenLCA enables users to assemble product systems and compute effects with existing databases, which include ecoinvent (Ecoinvent Center, 2021). Ecoinvent is a global LCI database that is among the most comprehensive and widely used. It offers detailed and standardized information about a broad spectrum of processes, such as material production, energy supply, transportation, and waste management. The openLCA and ecoinvent database can be used to analyze bottled water supply chains in a systematic and consistent way. It also assists in making evidence-based decisions as it offers comparable and dependable environmental impact outcomes.

1.2 Problem Statement

Despite the fact that sustainability has emerged as a strategic focus of a significant number of companies, it is difficult to convert environmental objectives into supply chain operations. Marketing statements like eco-friendly packaging, low carbon footprint, etc., are becoming more popular, but they do not always have any systematic environmental evaluation (Sazdovski et al., 2021).

The past studies demonstrate that the significant contribution to the environmental footprint of the bottled water is production and transportation of the packaging (Horowitz et al., 2018). But the comparisons between alternative strategies are not always clear and quantitative, which is why companies do not always have such. As an illustration, the state of the environment of virgin PET versus recycled PET or local versus long-distance distribution is not necessarily comprehended (Tamburini et al., 2021).
Most of the current LCA research has been conducted to compare the bottled water and tap water instead of assisting in internal strategy formulation in the bottled water supply chain (Gleick and Cooley, 2009). As a result, there is limited research that directly related to the LCA modelling and the design of green supply chain strategies through scenario-based methodologies.

A company can implement measures that limit impacts in a certain area of the supply chain without structured analysis and have unintended effects that escalate impacts in other areas. As an example, light packaging can use less material. However, using less plastic makes the bottles much thinner and weaker. These thin bottles are breakable and likely to break easily during travel. Companies should use heavy protective cardboard to prevent such damage. This additional cardboard makes for a heavy load for delivery trucks. In the end, the more weight that the trucks have, the more fuel that they consume and the increased emissions that are generated. Likewise, the change of materials can also help to decrease emissions but also resource depletion.

Thus, an alternative packaging and logistics strategy requires a scenario-based Life Cycle Assessment study that evaluates the alternative strategies with transparent data and a consistent approach to the study. This type of study can be used to aid in managerial decision-making and add academic knowledge on the integration of LCA in the development of green supply chain strategies.

1.3 Research Question and Objectives

The core aim of the thesis is to analyze that green supply chain strategy development can be facilitated using Life Cycle Assessment of bottled water packaging and logistics.

The supply chains of bottled water involve the extraction of raw materials, the packaging, filling, transport, and end life management. All the stages have environmental impacts like greenhouse gas emission and energy consumption (ISO, 2006a). Companies need effective tools to enhances sustainability performance, tools that help them gain clear picture of the impacts of these companies throughout the life cycle (Wolf et al., 2010).

The primary research question of the thesis is:

How can the development of green supply chain strategy be supported by Life Cycle Assessment in bottled water packaging and logistics?

In order to respond to this research question, the following objectives are formulated:

a) To identify the environmental hotspots of bottled water packaging production, distribution, and end-of-life waste management.
b) To develop and compare a baseline supply chain scenario with alternative green supply chain scenarios such as recycled materials, energy mix, logistics modifications, and end-of-life modifications.
c) To assist the managerial decision making based on LCA results.

The identification of environmental hotspots is crucial as it helps to show those life cycle stages which have the greatest share of overall impacts (Finnveden et al., 2009). Scenario modelling allows systematic comparison between traditional and enhanced supply chain designs (Rebitzer et al., 2004). Comparative LCA is a quantitative evidence that can assist in determining trade-offs across alternative approaches (Curran, 2015).

1.4 Scope and Limitations

To remain non-partisan and transparent, this thesis examines a generic product of a bottled water. The functional unit is as follows: 1,000 liters of bottled water delivered to the consumer.

The research adheres to ISO 14040 standards of a cradle-to-grave system boundary (ISO, 2006a). This involves the extraction of raw materials, packaging production, water treatment and bottling, transportation and waste management at the end of life.

The analysis is based on the secondary data, with background data from databases:

ecoinvent (Ecoinvent Center, 2021) and foreground data from previous studies, reports. There is no primary company data gathered. As such, results are generic supply chain arrangements and not company operations.

All the categories of impacts resulting from the impact assessment method are included in the environmental assessment. But special attention is given to the impact on climate change (kg CO2-equivalent). This is because the production and transportation of packaged water is closely linked to GHGs and energy consumption (Rosenbaum et al., 2018).

Life Cycle Assessment entails modelling assumptions and methodological decisions. The outcomes should therefore be viewed as comparative and strategic as opposed to being precise projections. The results are designed to facilitate strategic knowledge on green supply chain possibilities as opposed to operational planning.

1.5 Structure of the Thesis

This thesis is divided into five chapters. Chapter 2 is a literature review on green supply chain management, Life Cycle Assessment technique, bottled water systems, and sustainability strategies. Chapter 3 outlines the research methodology, comprising of system boundaries, source of data, scenario design and impact assessment means. The findings of the Life Cycle Assessment are provided and discussed in Chapter 4. In Chapter 5, the findings are discussed, conclusions reached and recommendations given to the managers and future research.

2 Literature Review

2.1 Green Supply Chain Management

2.1.1 Green Supply Chain Management Concept and Definition

Green Supply Chain Management (GSCM) can be described as a combination of environmental concerns in the conventional practices of supply chain management. These activities are; green purchasing, cleaner production, sustainable logistics, eco-design, and end-of-life management (Srivastava, 2007). The key aim of GSCM is to minimize negative effects to the environment and remain economically competitive and efficient in operations (Seuring and Muller, 2008).

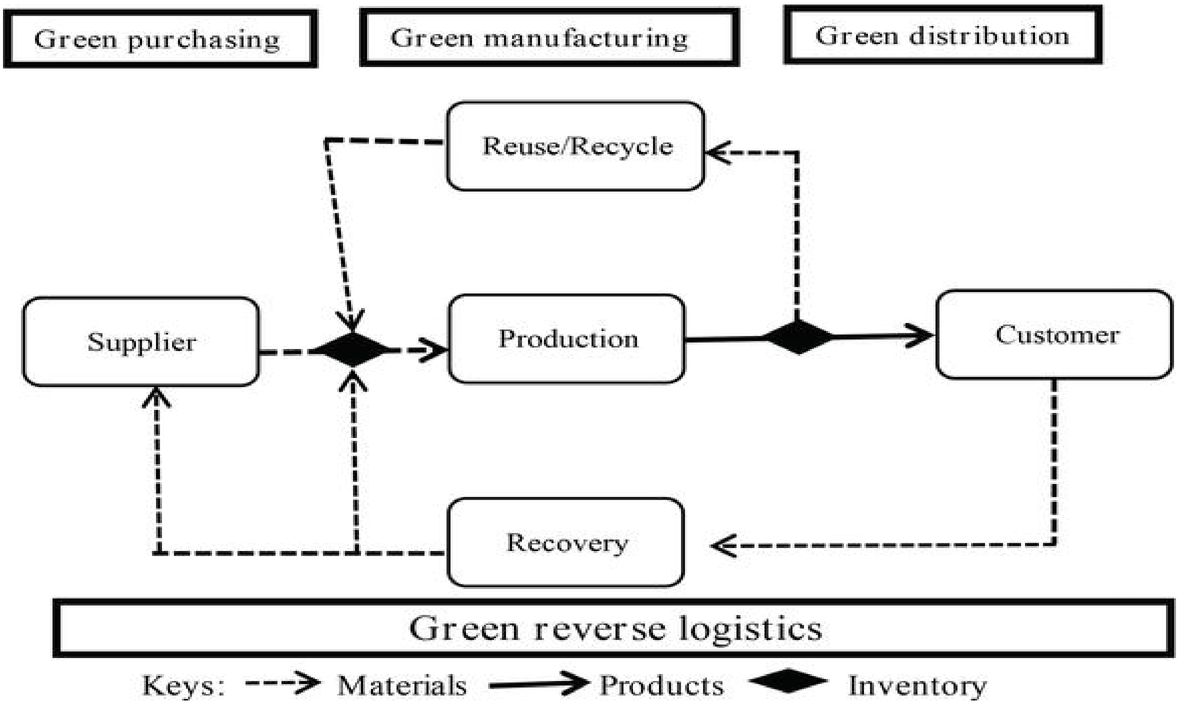

Figure1. Green Supply Chain Management Model (from Khan, 2018)

Cost, quality, and performance of delivery are the primary concerns of the traditional supply chain. Green supply chains, on the other hand, include environmental performance as a strategic goal (Zhu and Sarkis, 2004). This change has been influenced by growing regulatory pressure, expectations of stakeholders and

consumer sensitivity to sustainability matters (Carter and Rogers, 2008). Consequently, environmental performance is no longer considered as a constraint but rather as a possible source of competitive advantage.
A number of authors state that GSCM must have a life-cycle perspective i.e. the environments effects must be taken into account not only during extraction of raw materials but also during final disposal (Srivastava, 2007). This view is especially significant in case of products that have complicated international supply chains like bottled beverages wherein its effects are experienced in diverse levels and various geographical locations.

2.1.2 Important Components of Green Supply Chain Management

Green supply chain management is a combination of a number of interconnected elements. Green sourcing aims at finding suppliers who offer materials and processes that are environmentally desirable, including low impact or recycled raw materials (Zhu & Sarkis, 2004). In manufacturing, cleaner production focuses on minimizing energy consumption, emissions and waste in manufacturing processes (Porter and van der Linde, 1995).

Green logistics deals with the environmental effects of transportation, warehousing and distribution. Key measures to reduce emission in a logistics system are transport mode choice, distance reduction and load optimization. Eco-design refers to the design of products and packaging in such a way that the material consumption is minimized, recyclability is enhanced, and environmental performance in the product life cycle is improved (Bocken et al., 2016).

End-of-life management and reverse logistics are also important elements of GSCM. Such activities consist of, collecting, recycling, and disposal of used products and packaging (Guide & Van Wassenhove, 2009). In the case of bottled water, PET bottle recycling systems are highly significant in minimizing the environmental footprint and contributing to the circular economy objectives (Ellen MacArthur Foundation, 2016).

2.1.3 The importance of Packaging in Green Supply Chains

In the context of Green Supply Chain Management (GSCM), packaging is a crucial issue as environmental consideration should be incorporated in the design of products, choice of materials, distribution process, and end life disposal (Srivastava, 2007). The packaging influences the level of raw material, the weight of the product after the process, the efficiency of transporting the product, and the level of waste that is produced after the use. The role of packaging is even more critical in the food and beverage industry which needs to ensure product protection, hygiene, shelf life support as well as corporate environmental objectives (Verghese & Lewis, 2007). It is based on this reason that packaging decisions are not only those of technical design but also are strategic supply chain decisions.

Polyethylene terephthalate (PET) plastic packaging is very common in bottled water supply chains due to its light weight, durability and relatively low cost. The operational advantages of PET include these properties, which support the handling cost and transport burden associated with the process of transport. Nevertheless, the alternative packaging PET also poses serious environmental impacts, such as excessive levels of greenhouse gases released during its manufacturing process, which are fossil-fueled, and extreme pollution of plastic waste post-disposal (Geyer et al., 2017). Due to these effects, more and more interest is paid by researchers and companies to lightweighting and material reduction in packaging and the application of recycled PET content (rPET) as a means of reducing the environmental footprint.

According to green supply chain perspective, the packaging decisions have a great impact on the life cycle performance of a product. The choice of material, weight of the bottle, and recycled content can decrease the demand in raw materials, reduce emissions, and increase the end-of-life performance (Franklin Associates, 2009). In addition, the design of packaging has a direct effect on the efficiency of logistics. Well-designed and lightweight bottles can lead to better utilization of transport volume and lower fuel consumption per volume of products (Garcia-Arca et al., 2014). The transport impact however depends on the functional unit, the transport distance and the total product volume. Thus, it is necessary to consider packaging as a strategic sustainability challenge within bottled water supply chains, not only as a design aspect of products.

2.1.4 Importance of Logistics in Green Supply Chain

Another important component of GSCM is logistics since it regulates the flow of products between suppliers and producers, retailers and final consumers. The environmental management in green supply chain literature does not only refer to factory production but also to delivery, distribution networks and reverse flows after the products are used (Hervani et al., 2005). This implies that the transport activities, the network structure, and the efficiency of the distribution are significant in considering the environmental performance of a supply chain. In the case of heavy and high volume goods such as bottled water, logistics operations are particularly important since the transportation costs a significant percentage of the total energy used in the product life cycle (Gleick and Cooley, 2009).

There are a number of practical issues such as transport distance, type of vehicle, fuel consumption, route structure and load factor, that influence the environmental impact of the logistics. Long routes consume more fuel and result in more carbon emission. On the same note, low vehicle use raises the number of environmental burden per unit of product delivered. A significant number of traditional supply chains have empty returns, indirect delivery routes, and discontinuous systems of transportation, which lower logistics performance and cause unnecessary emissions. Consequently, enhancement of green logistics usually relates to shortening the transportation routes, maximizing the use of the truck load, making routes simpler, and bringing the facilities of production nearer to the target market (Hellstrom and Nilsson, 2011).

Logistics decisions in the bottled water supply chains may determine the sustainability performance of the product. Although a company may invest in very sustainable packaging, the positive impact on the environment may be completely neutralized in case the product is delivered to customers over long distances via inefficient distribution channels (Gleick and Cooley, 2009). That is why, GSCM frameworks highlight the necessity to consider packaging and logistics as interconnected rather than as independent operation (Garcia-Arca et al., 2014). Finally, a more sustainable bottled water system demands not only environmentally friendly packaging materials but also an exceptionally efficient and localized logistic system.

2.2 Sustainability Problems in Bottled Water Supply Chains

The bottled water supply chains pose complicated sustainability issues as they are highly dependent on raw materials that are extracted to be used in the packaging, packaging manufacturing processes which are energy-demanding, and complex transportation systems. Environmental thinking in modern green supply chain management should be holistic, that is, it should include all the processes of a product life cycle, such as material sourcing, factory processes, distribution, and waste disposal at the end of the life cycle (Srivastava, 2007).

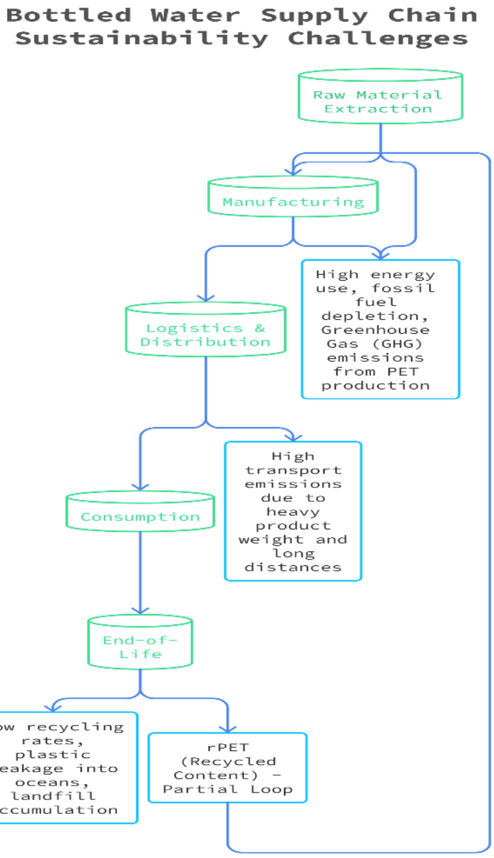

Figure 2. Sustainability issues and environmental hotspots in the bottled water supply chain.

The five processes of bottled water supply chain have major sustainability issues and environmental hotspots, as depicted in figure 2. The flowchart follows the life cycle of the product, starting with the extraction of raw materials and manufacturing to logistics and distribution, consumption, and life-end. As indicated in the diagram, raw material mining and production processes are characterized by high-energy consumption, fossil fuel consumption, and greenhouse gas (GHG) emissions due to normal production of PET plastics. Another important hot-spot is the logistics and distribution step, whereby transportation emissions are high owing to the excessive weight of the water and long distance of transportation. In the end-of-life phase, the diagram presents extreme environmental risks of low recycling rates including plastic leakage into oceans and landfill. Lastly, the figure shows a reverse loop that the use of recycled PET (rPET) generates a partial circular economy that can alleviate the effects related to the extraction of virgin plastics and the production of waste.

2.2.1 Bottled Water consumption growth

Bottled water consumption has increased remarkably in the last two decades globally as one of the biggest segments in the commercial beverage industry (Gleick and Cooley, 2009). Several global trends, such as the rapid urbanization, changing consumer lifestyles, and the safety and taste concerns of municipal tap water systems in different regions are the drivers behind this rising demand (Fact.MR, 2025). Moreover, in the developed markets, bottled water among other products is also becoming a convenient and healthy substitute of sugary soft drinks, which has further boosted the growth of markets.

Nevertheless, the ongoing increase in the use of bottled water has prompted extensive environmental questioning. As opposed to the local tap water, which is distributed via municipal pipelines, bottled water needs to be physically packed and physically transported to the consumer (Gleick and Cooley, 2009). Such demands imply that the environmental footprint of bottled water is naturally much greater than that of tap water which requires much more energy and fossil resources to deliver a litter of water (Franklin Associates, 2009).

In countries with already safe, well-maintained infrastructure of public drinking water, these environmental issues are especially acute. Under such circumstances, critics claim that mass production of bottled water is the ineffective utilization of natural resources and poses unnecessary environmental costs (Gleick and Cooley, 2009). Therefore, regulatory and social pressure on bottled water producers is growing to keep its environmental footprint as low as possible through redesigning supply chains, switching to eco-friendly materials, and streamlining logistics operations (Fact.MR, 2025).

2.2.2 Plastic Packaging and its Environmental Effects

Packaging is regarded as one of the most significant areas of sustainability hotspots in the bottled water supply chain. Polyethylene terephthalate (PET) plastic is essential to the industry due to its high durability, transparency, low cost of production, and low weight. Operationally, lightweight PET helps to decrease the weight of the shipment, and consequently, it decreases transport and handling expenses (Garcia-Arca et al., 2014). Nevertheless, regardless of these logistic benefits, PET plastic creates serious environmental issues. Regular PET resin manufacturing is an energy-intensive industry that relies directly on the extraction of petroleum, leading to high concentrations of greenhouse gas emissions and fossil fuel uses (Franklin Associates, 2009).

After the manufacturing process, another significant challenge in the world is the end of life management of plastic containers. Unless plastic waste is collected or recycled, it often finds its way into natural ecosystems and marine environments, where it may take centuries to disappear, with a vast destruction of the ecological environment as a result (Geyer et al., 2017). Even though PET is technically a highly recyclable material in reality, the recycling rates can differ drastically with the local infrastructure and consumer behavior of various countries.

Green supply chain approaches to the packaging industry aim to counter these effects, paying much attention to material recovery and enhancement of its recycling. The major trends in the industry are called lightweighting, i.e. re-engineering bottles with the use of slimmer plastic walls, and replacing virgin plastic with post-consumer recycled PET (rPET) (Fact.MR, 2025; Knowledge Sourcing Intelligence, 2026). Even though substituting regular PET with rPET can considerably reduce the amount of carbon footprint that the packaging causes, the changes should be calculated with the help of Life Cycle Assessment (LCA) so that the recycling processes themselves do not inadvertently raise the energy consumption and water consumption in the rest of the system (Franklin Associates, 2009).

2.2.3 Logistics and its role in Bottled Water Sustainability

The aspect of logistics plays a vital role in the sustainability of bottled water because water is a heavy good that is normally shipped in large quantities. In green supply chain thinking, distribution, delivery and post use reverse flows is part of the environmental responsibility besides production (Srivastava, 2007). This implies that all of these factors can affect the overall environmental impact of bottled water systems; transport distance, vehicle use, route design, and transport mode.

Transportation-based emissions may get particularly critical whenever bottled water is transported over a long distance or even international boundaries. It has been established through the studies of bottled water that the packaging and transport requirements have a strong influence on energy consumption and emissions, especially in cases where the goods are distributed across a large territory rather than locally (Franklin Associates, 2009; Gleick and Cooley, 2009). The effects of high transport distances are generally more fuel consumption and it is also possible that low load factors and empty returns can raise further the amount of emissions per unit delivered.

Due to this reason, the enhancement of logistics is a significant approach in the greener bottled water supply chain. The possible measures that can be relevant are to bring the transport distance shorter, to raise the truck load factor, to make the route more direct, to relocate the production or filling activities towards the target market. This way, the environmental benefits of better packaging can be either supported or undermined by the logistics decisions, hence packaging and logistics should be considered jointly in the context of the sustainability of bottled water.

2.3 Life Cycle Assessment (LCA)

2.3.1 History, Development and Background of Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) has now become the best and most complete approach in the assessment of the environmental impacts of products, processes and supply chains. Nevertheless, LCA did not come out all of a sudden as the complete scientific technique. Its methodology has been a constant process, and which started as the basic energy calculations evolved to a highly standardized framework over the world that is utilized by governments, researchers, and industries (Guinee et al., 2011). It is significant to study the historical evolution of LCA since it will shed light on the reasons why modern standards, databases and software tools were developed.

Life cycle thinking can be traced to the late 1960s and early 1970s. Surprisingly, the earliest uses of this technique were directly related to the beverage packaging sector, so, it is very relevant to the research of bottled water. In 1969, The Coca-Cola Company commissioned the Midwest Research Institute (MRI) to carry out a study that was done on the comparison of various beverage container, in particular, glass and plastic (Bjorn et al., 2018). This was aimed at finding out which package used less natural resource and produced less solid waste.

The approach was not then known as LCA. This analytical method was called Resource and Environmental Profile Analysis (REPA) in the United States and "Ecobalances" in parallel efforts happening in Europe (Klopffer and Grahl, 2014; Curran, 2015).

The theme of these initial evaluations dramatically changed with the world oil crisis of 1973. These sudden energy shortages made the consumption of fuel the major concern of industries and governments. Thus, the REPAs and Ecobalances of the 1970s were mainly applied to monitor the energy efficiency and fossil fuel loss within manufacturing processes and minimal emphasis was put on the ecological effects in general, such as toxicity or climate change (Guinee et al., 2011).

In the 1980s, there was a growing interest in environmental awareness on the global environment as opposed to solid waste and energy consumption. The general population and the scientific community were more upset about the intricate problems like acid rain, ozone holes, and greenhouse gases. Businesses started to apply life cycle research by publicly stating that their product was eco-friendly.

There however were no standardized principles on how these should be done in the 1980s. Various researchers and companies had different system boundaries, computing, and data (Curran, 2015). Due to this, two separate pieces of research on the same product may deliver completely opposing findings. Such discrepancy brought about a lot of skepticism. The society and the environmental groups started to perceive these initial studies as biased marketing instruments or greenwashing other than objective science (Guinee et al., 2011). It was revealed that in case life cycle studies were to be taken in serious consideration the method is to be harmonized strictly.

The 1990s was a decade of scientific cooperation in order to address the issue of inconsistency. Organizing the international workshops where scientists and practitioners gathered was a crucial role played by the Society of Environmental Toxicology and Chemistry (SETAC) and by the environmental protection agencies such as the US EPA (Curran, 2015).

Life Cycle Assessment (LCA) was coined by SETAC. More to the point, SETAC has introduced the four-stage conceptual framework that is at the heart of the modern LCA, namely, (1) Goal and Scope Definition, (2) Life Cycle Inventory (LCI), (3) Life Cycle Impact Assessment (LCIA), and (4) Interpretation (Klopffer and Grahl, 2014). SETAC was able to provide a reasonable, transparent framework, which could be easily universalized, by breaking down the data collection (Inventory) and the environmental modeling (Impact Assessment).

Although SETAC contributed to the scientific model, the most important step in the history of LCA was its standardization. To create global transparency, the International Organization for Standardization (ISO) created a series of ISO 14040 which was first introduced in the late 1990s.

These standards have been updated in 2006 and have been merged into two main documents, the ISO 14040 (Principles and framework) and the ISO 14044 (Requirements and guidelines) documents (ISO, 2006a; ISO, 2006b). These standards offered rigid guidelines to the definition of system boundaries, co-products (allocation) and critical peer review (Finkbeiner et al., 2006). With the introduction of ISO 14040 and 14044, LCA was made to be a powerful, internationally recognized, and legally defendable instrument. Simultaneously, in 2002, the United Nations Environment Program (UNEP) and SETAC introduced the Life Cycle Initiative to spread the concept of life cycle thinking on a global level and enhance the quality of LCA data.

LCA is no longer an esoteric academic game in the contemporary world, but has become a common business practice. This shift has been motivated by the creation of huge, quality Life Cycle Inventory (LCI) databases. During the initial years of LCA, scholars were forced to inquire data on each and every individual background process, including electricity production or transportation. Of the background processes, today, there are comprehensive databases, such as ecoinvent (global) and the AGRIBALYSE (specific to French agriculture and food) which provide standardized data on thousands of background processes, resulting in LCA being highly efficient (Wolf et al., 2010).

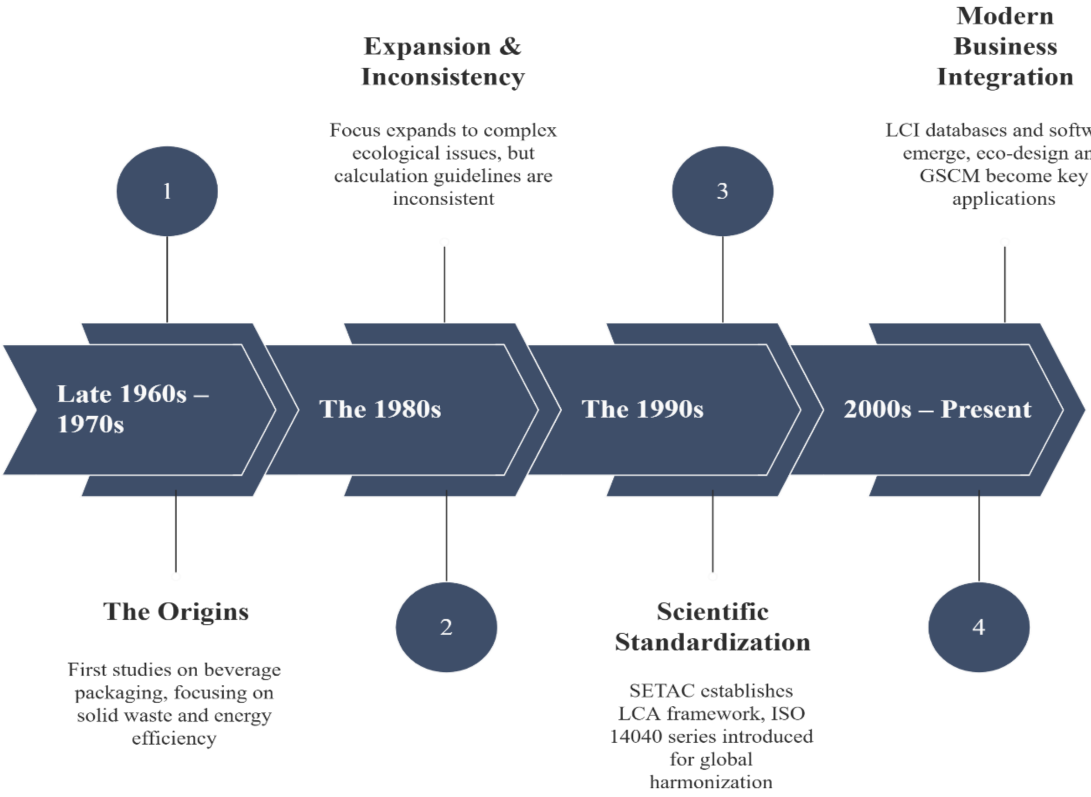

Figure 3. Historical development of Life Cycle Assessment (LCA)

Moreover, life cycle modeling has become much more accessible due to the presence of sophisticated modeling software both commercial and open-source such as openLCA (Curran, 2015). Nowadays, LCA is not the instrument to compute the past effects anymore, it is the future-oriented instrument that can be utilized in green supply chain management, eco-design, and strategic corporate decision-making. Enabling decision-makers to simulate alternative supply chain conditions, say the packaging material is not regular PET but is recycled PET, or the logistics routes are adjusted, modern LCA will ensure that environmental damages are actually avoided, and not transferred to another supply chain segment.

2.3.2 Principles, Framework, and Guidelines of Life Cycle Assessment (LCA)

In order to make environmental assessments scientifically valid, objective and comparable across industries and to make certain that they will be applicable in various industries, Life Cycle Assessment (LCA) is dictated by stringent international standards. The International Organization of Standardization (ISO) specifies the main principles, structure, and methodological guidelines of LCA in two documents, including ISO 14040 (Environmental management - Life cycle assessment - Principles and framework) and ISO 14044 (Environmental management - Life cycle assessment - Requirements and guidelines) (ISO, 2006a; ISO, 2006b). Combined, these standards form a constitutional basis behind any environmental impact assessment in modern times (Finkbeiner, 2014).

The basic idea behind the LCA approach is the so-called life cycle thinking (Curran, 2015). This involves assessing a service, process, or product in its entirety i.e. cradle to grave. An actual cradle-to-grave analysis does not simply consider what occurs within the confines of a manufacturing factory. Rather, it covers each and every product stage. It starts with the process of the raw materials extraction out of the earth (the "cradle"), moves onto the material processing and core manufacturing, goes on to the distribution logistics and consumer use, and finally ends with the disposal of the end-of-life, its recyclability, or energy recovery (the "grave"-processing) (Klopffer & Grahl, 2014).

The importance of this holistic approach lies in the fact that it avoids a frequent environmental issue, which is commonly called burden shifting (Curran, 2015). Burden shifting is associated with the situation when an environmental improvement in one product stage of the life cycle unintentionally alters the environmental issue to another one, or transfers the harm in one environmental category to another (Matthews, Hendrickson and Matthews, 2014).

As an example, a company could opt to adopt the use of a lightweight plastic bottle as an alternative to the heavy glass beverage bottle. This may apparently drastically decrease the amount of environmental effects that transportation fuel has due to the fewer weight being carried by the trucks. But, a closer look at it, which may be conducted by means of an LCA can provide the revelation that the new plastic bottle has a serious effect on the effects of the extraction of fossil-based raw materials and the end-of-life contamination of microplastic. LCA guarantees that the overall environmental impact of the entire supply chain is truly diminished as opposed to being transferred elsewhere to another geography or even the environmental group (Klopffer and Grahl, 2014).

The structure of a Life Cycle Assessment (LCA) is founded on two essential international standards, that is, ISO 14040 and ISO 14044. These standards are general principles and methodological guidelines of conducting LCA studies. This framework of LCA as presented in these standards is very common in environmental research and industrial practice (Curran, 2015; Wolf et al., 2010).

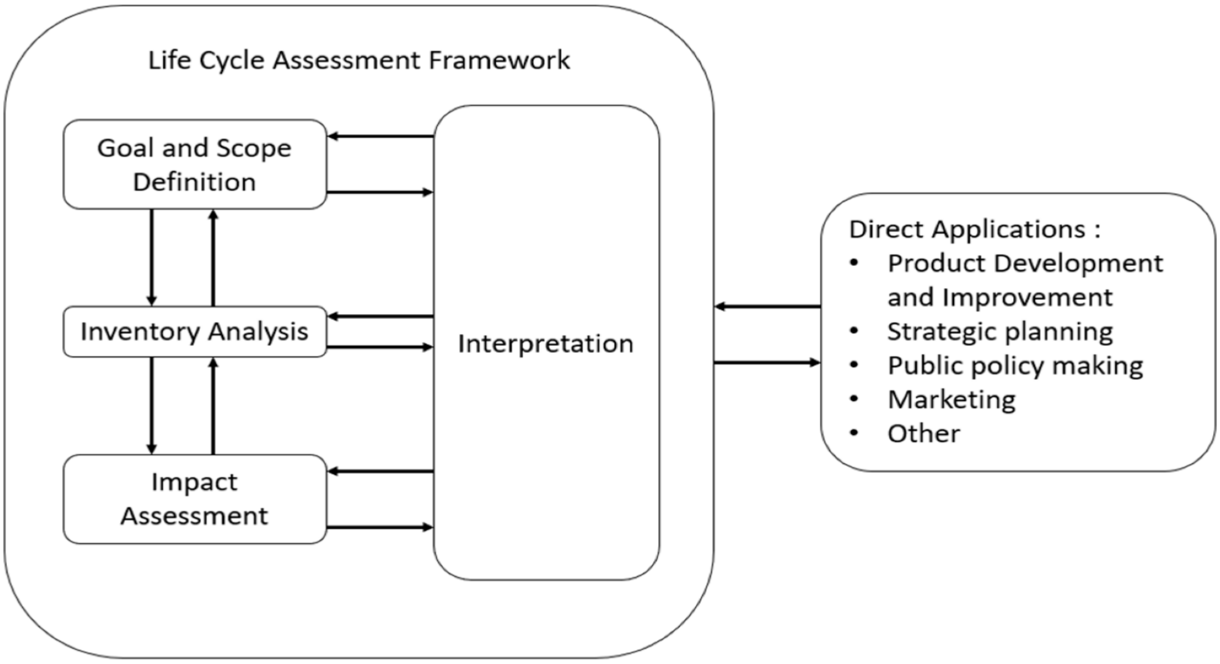

Figure 4. The structure of LCA based on ISO 14040:2006

ISO 14040 identifies four phases namely: 1) Goal and Scope Definition, 2) Life Cycle Inventory (LCI) Analysis, 3) Life Cycle Impact Assessment (LCIA), and 4) Interpretation. Figure 4 illustrates that the four phases identified by ISO 14040 include: Goal and

Scope Definition, Life Cycle Inventory Analysis, Life Cycle Impact Assessment and Interpretation. All of the stages are significant in determining environmental effects of a product or process in its life cycle.

The first phase is the goal and scope definition, which defines the aim of the research and establishes the scope of the assessment. The second phase is inventory analysis that gathers information on the material utilization, energy, emissions, and waste during the life cycle. The third stage is impact assessment which measures the environmental impact of these inputs and outputs. Lastly, the results are analyzed and conclusions and recommendations are given in the interpretation stage.

LCA can have numerous applications such as to enhance product design, minimize environmental impacts of the product or create more environmentally friendly production processes. Strategic planning, marketing decisions and the development of the environmental policy can also be supported by LCA findings.

The general aim of LCA is to enhance the environmental performances in the whole life cycle of a product. Once the improvements are done one can repeat that analysis and see whether the changes have minimized the environmental impacts. The new opportunities of further improvement can also be identified in this process.

Accordingly, LCA model on the basis of ISO standards is viewed as an iterative and dynamic process. It assists the researcher and organizations to systematically examine the effects of the environment and how it can be made more sustainable. LCA helps in the achievement of sustainable development by offering a systematic way of assessing the performance of the environment.

2.3.2.1 Phase 1 Goal and Scope Defining

The initial stage of an LCA sets the absolute grounding, working logistics, and confines of the whole research. Since the ISO standards fail to specify a single mathematical formula, which one should use to perform an LCA, the result of the analysis is heavily reliant on the decisions and assumptions taken at this first stage (ISO, 2006b).

The definition of the goals clearly defines the specific aim of the study. The ISO 14044 defines the aim by stating that four key components must be defined: the purpose of the study, the reasons why the study is to be conducted, with whom the studies will be shared, and whether the study results will be utilized in the comparative claim that will be presented publicly (ISO, 2006b).

The objective determines the rigorousness, openness and profundity of the following stages. As an example, internal LCA could be useful to enable a supply chain manager to recognize environmental hotspots and enhance product eco-design. In the present instance, the guidelines may be a little lax since the information remains in the business. Otherwise, LCA could be done outside in order to develop an Environmental Product Declaration (EPD) to be used in marketing. When the aim is to establish a comparison with others in the market or to create EPDs, the ISO guidelines impose very high standards of strictness, the critical analysis of third-parties, and very transparent reporting on data (More, Galindro & Soares, 2022).

Scope definition identifies what is going to be in the life cycle assessment and what will not be in the assessment. This will be done to make sure that the study is manageable and that it is focused on the most relevant process. It also assists researchers on where to base their attention to the kind of data that should be gathered and the extent of the analysis that would be done to each part of the product life cycle.

Besides, scope definition will help to determine what phases of the life cycle are going to be analyzed. To illustrate, the evaluation can examine the whole life cycle of a product, or can be limited to certain stages of the life cycle e.g. production, transportation, or disposal (ISO 14040:2006).

The other significant scope definition aspect is the establishment of time boundaries. The time period involved in the assessment is determined by the temporal boundaries. This implies the identification of the start of the life cycle and the end of the life cycle in the study (ISO 14040:2006). Having explicit time frames can assist in trying to make the analysis consistent and in fact the results are useful to the research goals.

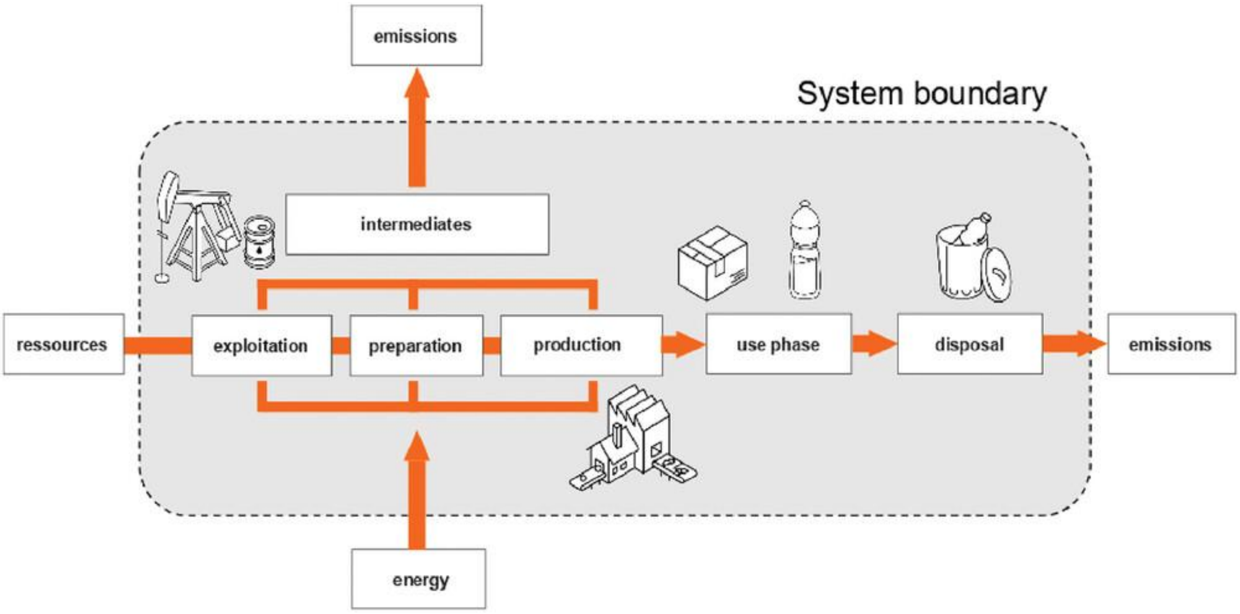

Figure 5. LCA System Boundary (from Mudersbach et al., 2023)

When determining the boundaries of a study, a diagram is useful in showing the boundaries of the system. This is clearly demonstrated in figure 5 that indicates what components are covered in the analysis and what components are not covered. It assists the readers in identifying study limits. The diagram normally points out the key phases of the life cycle of the product. These stages may involve a production process, delivery, usage of the product and its ultimate disposal. The system would be easier to comprehend through the demonstration of these steps.

Setting System Boundaries

System boundaries define what types of stages of the life cycle, transport routes, and unit processes are to be considered as part of the mathematical assessment and which are not to be considered (Curran, 2015). The boundary should be set in such a manner that it covers all the processes which have a large contribution to the environmental impact and leaves out the insignificant ones. There are various types of system boundaries that can be defined depending on what the goal of the study is:

- Cradle-to-Grave: The best all round boundary. It covers the entire process of the extraction of the raw materials, production, distribution, and end-users, until the ultimate disposal or recycling of the product at the end of its life (Klopffer and Grahl, 2014).

- Cradle-to-Gate: This point is the extraction of raw materials until the finished good comes out of the factory gate. It is common to business-to-business (B2B) supply chains, where the manufacturer has no ability to foresee or regulate how the ultimate consumer will utilize or discard the product (More et al., 2022).

- Gate-to-Gate: This is a thin boundary that dwells upon the fundamental manufacturing processes in a single plant. It is normally applied to internal process optimization as opposed to complete product declarations (Curran, 2015).

The Functional Unit and Reference Flows

It is generally understood that the functional unit is the most crucial notion in the entire LCA methodology (Klopffer and Grahl, 2014). Since LCA is a relative tool, it has to have a quantified, mathematical reference point on which all physical inputs and environmental outputs would be set (Wolf et al., 2010). The functional unit will guarantee that various items or systems will be compared with each other fairly in relation to the actual task they carry out and not just their physical weight or volume.

As an example, considering the environmental influence of packaging, the functional unit cannot be merely a single plastic container. Rather, it should specify the particular service that is offered, e.g., the safe transportation and supply of 1 liter of liquid to a customer within a shelf-life of more than 6 months (Mendes da Luz et al., 2018). The calculations that follow, the amount of petroleum that is extracted, the amount of electricity that is used, the amount of carbon dioxide that is released, all this is then adjusted to the production of that particular functional unit. This will enable the entirely level, apples-to-apples, comparison of a PET plastic bottle, an aluminum can, and a reusable glass system as they all serve the purpose of the same thing (Matthews et al., 2014).

The flow of references is highly associated with the functional unit. It is the amount of product that is necessary to complete the functional unit in terms of specificity and the physical form (ISO, 2006a). Assuming that the functional unit is providing 1 liter of liquid, a company produces 0.5 liter bottle, then the reference flow of the particular product system is precisely 2 of 0.5 liter bottles.

2.3.2.2 Phase 2 Life Cycle Inventory (LCI) Analysis

The second stage of Life Cycle Assessment is Life Cycle Inventory (LCI). This stage is aimed at gathering and systematizing the data regarding all inputs and outputs of the system within the system boundary that was identified in the Goal and Scope phase. The LCI stage is generally regarded as the most complicated and the most time-consuming phase in an LCA study due to the necessity to provide the information about materials, energy consumption, emission, and waste in the whole lifecycle of the product (Curran, 2015). The key aim of this stage is to develop a detailed list of all physical flows in and out of the product system.

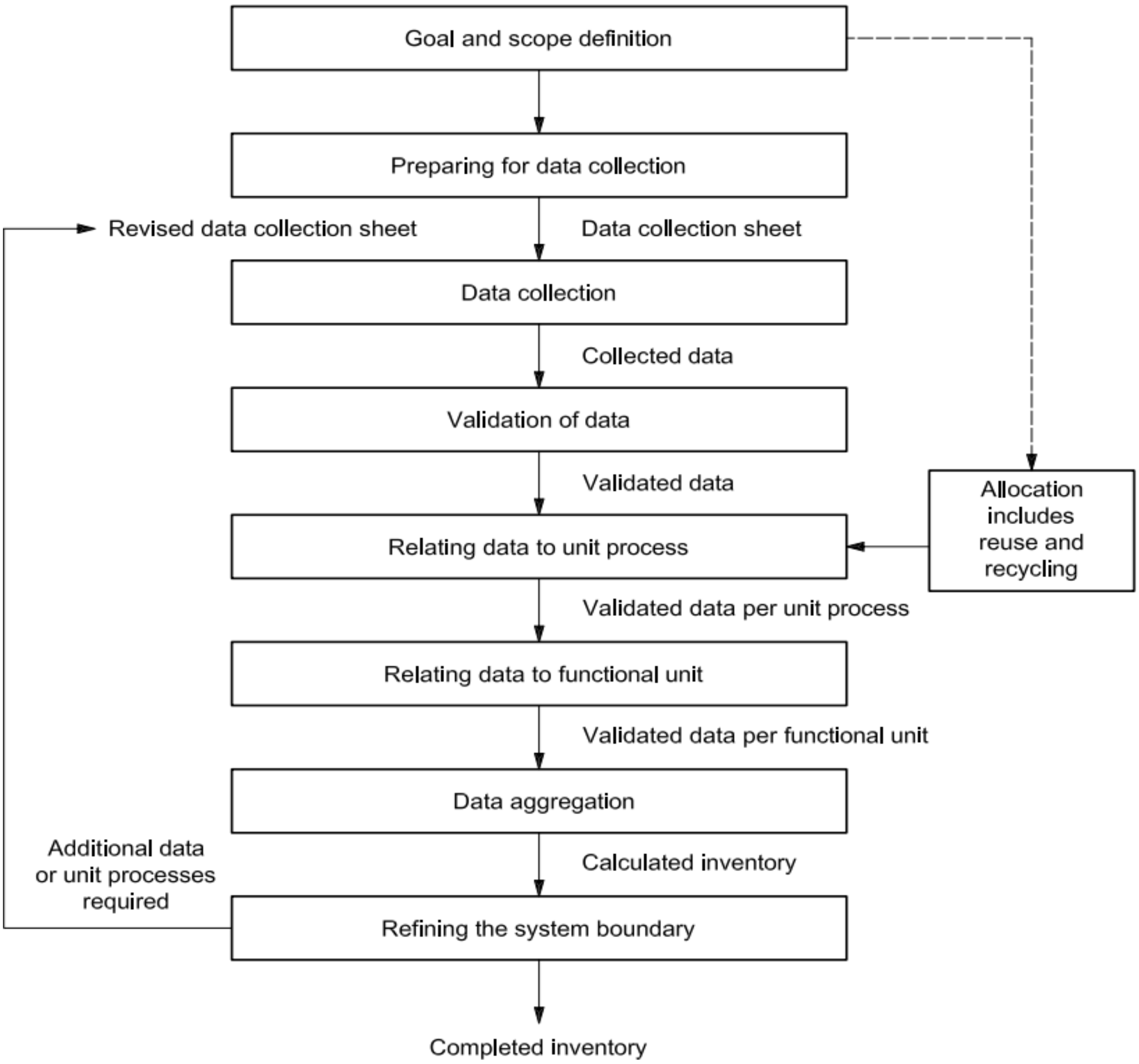

Figure 6. Procedures for Inventory analysis (from ISO 14044:2006)

Process flow diagrams should be used to describe the whole product system before a numerical data collection is done. These charts depict the chronological order of activities and processes to take place in the life cycle of the product. The life cycle is broken down into small manageable processes which are known as unit processes. The smallest part of a product system whose data are gathered and examined is referred to as a unit process (ISO 14040:2006). Splitting the system into unit processes will make the process of data collection more organized and will contribute to the fact that no significant environmental flows will be missed. Some of the common operations that can be included in the diagrams are extraction of raw materials, transportation, production, assembling, packaging and distribution, usage of the products, and disposing the products.

Data applied during the phase of Life Cycle Inventory is normally derived out of two primary sources: primary data and secondary data. Primary data are the special data that has been gathered at the production plants, suppliers or systems of operations. Such data can be electricity used, fuel used, direct emissions, water used, and quantities of materials used during manufacturing operations (Klopffer and Grahl, 2014). Primary data are usually most preferred as they reflect the real performance of the processes being studied in the environment. They are especially important for foreground processes. However, when primary data are not available, secondary data from previous studies, industry reports, or published sources can also be used for foreground modelling.

Nevertheless, it is not always possible to get detailed primary data on all the stages of a complex supply chain. Secondary data in such situations are employed. The secondary data are average data produced by scientific research, governmental or environmental databases (Wolf et al., 2010). These data are the ones that are generally used in the background processes; processes that are not directly controlled by the system that is under study. They are the extraction of raw materials, electricity generation on the national grids, or the international transport systems emission (Mendes da Luz et al., 2018). In numerous LCA analyses, standardized environmental data on thousands of industrial processes is compiled in internationally standardized databases like the ecoinvent database. These databases are usually managed using specialized LCA software tools like openLCA, and they are used to calculate inventory.

The other significant problem in Life Cycle Inventory stage is the multi-output processes. A real industrial system can have multiple products manufactured by a single production process simultaneously (Curran, 2015). In particular, oil refineries are used to obtain a number of products including gasoline, diesel and other petroleum products using the same raw. In this case, environmental effects of the process would have to be apportioned to the various products. This is referred to as allocation (ISO 14044:2006).

The ISO principles state that in any case, should it be possible, one should avoid allocation since it may lead to uncertainty in the outcomes. The allocation may be avoided by breaking the process into smaller sub-processes in order to allocate the environmental flows more directly. The other approach is system expansion, whereby system boundary is also extended to incorporate alternative production systems of the co-products (Finkbeiner, 2014).

In case the allocation is inevitable, the environmental impacts should be distributed with some rules. Physical allocation is one of such common approaches since the impacts are apportioned based on physical properties i.e. mass or volume. The example of this is that when product is 80 percent of the total output weight and product is 20 percent, the environmental effects of the process will be split in the same proportion (Klopffer and Grahl, 2014). The other process is economic allocation whereby impacts are shared as per the economic worth of the products. The most lucrative product gets the most significant share of environmental impacts in this instance (Curran, 2015).

Further analysis of recycling and end-of-life processes also involves allocation as a significant issue. There are closed-loop recycling and open-loop recycling. Closed-loop recycling takes place whereby a product is recycled into the same product. As an illustration, a glass bottle can be recycled and it can be utilized in producing a glass bottle again. The environmental benefits in this case lie within the same product system and therefore makes the calculation process simple to carry out(ISO 14044:2006).

In open-loop recycling, a material is recycled and reused in the production of another product. An example of this is that plastic bottle can be recycled to produce synthetic textile fibres in clothing. In this case, environments should be allocated between the new system of the product and the original product system (Matthews et al., 2014). This can be done using different methodological approaches. The cut-off approach attributes all the environmental impact of production of raw materials to the initial system of production products and makes no provision of recycling credits. The other one is the substitution method, where the credits of the environmental reduction of the production of virgin materials in the second system is given to the first product system (Wolf et al., 2010).

2.3.2.3 Phase 3 Life cycle Impact Assessment (LCIA)

The phase of Life Cycle Inventory (LCI) generates a great deal of information related to resources consumed and emissions emitted in the life cycle of a product. There are numerous substances that can be included in these data, including methane, carbon dioxide, sulfur dioxide, metals and other materials. The findings are normally reported as a measure of the materials and emissions and may be expressed in grams, milligrams or kilograms of materials. Nevertheless, this long list of thousands of chemicals can hardly be comprehended when it comes to assessing the overall environmental performance of a product. Thus, Life Cycle Impact Assessment (LCIA) is the third stage of the Life Cycle Assessment transforming this unstructured inventory data into easily understandable environmental impact indicators (Rosenbaum et al., 2018). This step assists in clarifying the impact that the utilization of resources and emissions can have on the environment.

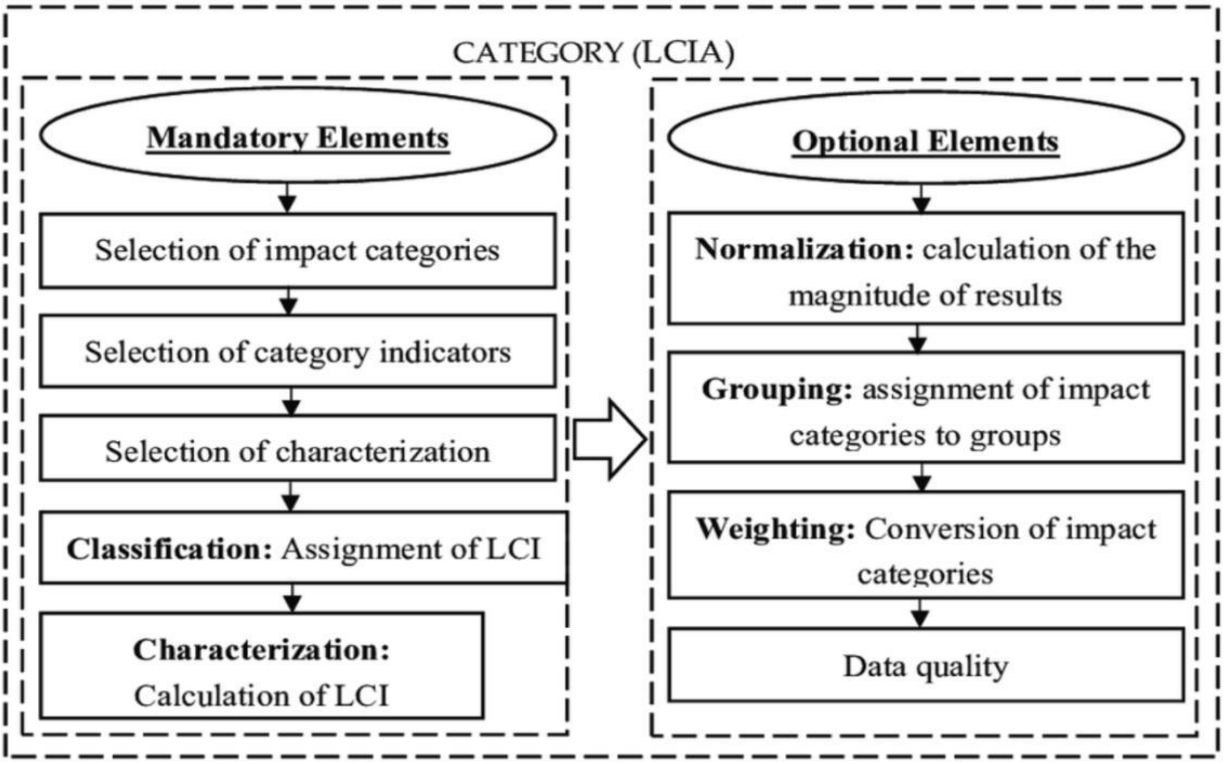

Figure 7. Life cycle impact assessment (LCIA) structure from Piotrowska et al.,2019

In the international standard, ISO 14044, the LCIA phase consists of three key steps that are mainly mandatory: selection, classification and characterization (ISO, 2006). These measures are to make sure that environmental effects are assessed with the help of the same scientific method.

The first step is selection. Under this step, the right environmental impact categories, indicators and scientific models are identified depending on the scope and objective of the study. The chosen categories are to reflect the most significant issues concerning the environment connected with the product system. Among the impact categories that are frequently used, climate change, acidification, eutrophication, resource depletion, and toxicity must be mentioned (Rosenbaum et al., 2018). The choice of appropriate categories will be used to make sure that environmental impacts of the product system will be evaluated in a holistic manner.

The second one is classification. In the classification, the LCI phase result is put under the corresponding environmental impact groups based on their impact on the environment. As an example, the greenhouse gasses like the methane and the carbon dioxide fall under the category of climate change. Gases like sulfur dioxide and nitrogen oxide belong to the acidification sector since they cause acid rain (Klopffer & Grahl, 2014). There are also emissions that can be the cause of multiple environmental issues. Under these situations, the emission is attributed to several impact categories that are of concern.

The third stage is characterization. This is a step in which the various emissions are standardized in a standard measurement unit using scientific characterization factors. These are the relative environmental impact of each substance. To illustrate, methane has an extremely high impact on climate change compared to carbon dioxide. Thus, a characterization factor is used to multiply the methane emissions to reflect the effects in carbon dioxide equivalents (CO2-eq). This enables the combination of the entire greenhouse gas emissions into one value of the Global Warming Potential (GWP) of the product system (Rosenbaum et al., 2018). This is achievable through characterization that enables comparison and summarization of environmental effects of an enormous number of substances.

Contemporary LCIA techniques consider various types of environmental impacts with a view of presenting an overall picture of the environmental performance. Some of the widely applied methods in LCA studies include ReCiPe, CML, and TRACI (Wolf et al., 2010). It is of high importance to consider various categories since concentrating on a single indicator, i.e. carbon emissions, can conceal other environmental issues (Curran, 2015). Given that the environment is commonly hit in several categories, these are as follows.

The contribution of the greenhouse gas emissions to the climate change is measured by Global Warming Potential (GWP). The findings are presented in kilograms of carbon dioxide equivalents (kg CO2-eq).

The Potential (AP) is a measure of the emissions that lead to acid rain, including sulfur oxides and nitrogen oxides. There are forests, soil, water bodies, and buildings that acid rain can destroy. The amount of results is normally reported in kilograms of sulfur dioxide equivalents (kg SO2-eq).

Eutrophication Potential (EP) considers the excessive discharge of the nutrients like nitrogen and phosphorus into water bodies. These nutrients may lead to the development of algae, which decreases the supply of oxygen in water and damages aquatic animals. The outcomes are usually determined in kilograms of phosphate equivalents (kg PO4-eq) (Rosenbaum et al., 2018).

The Ozone Depletion Potential (ODP) is a measure of substances that destroy the ozone layer in the high atmosphere like chlorofluorocarbons. The findings are presented in kilograms of the CFC-11 equivalents.

Abiotic Depletion Potential (ADP) considers the use of non renewable resources e.g. fossil fuels and mineral substances. The category contributes to making it clear that there are long-term natural resources depletion.

Human Toxicity and Ecotoxicity assess the possible adverse impact of the toxic substances on human health and the environment. These consequences can be caused by heavy metals, chemical pollutants, and industrial elements that are emitted to nature (Rosenbaum et al., 2018).

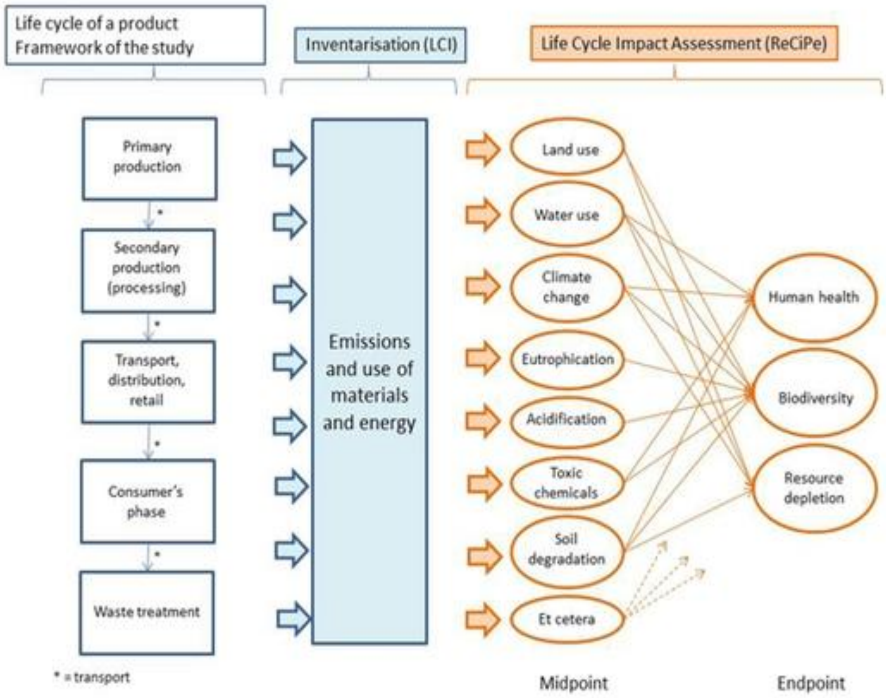

Figure 8. Life Cycle Impact Assessment (LCIA)at both midpoint and endpoint level (from Huvepharma article)

In LCIA stage, one can present the results using midpoint indicators or endpoint indicators. Midpoint indicators are indicators that are concerned with the environmental issues being faced earlier in the cause-effect chain. As an illustration, the emissions of greenhouse gases expressed in terms of global warming potential are midpoint indicators. The midpoint indicators tend to be more preferable within the scientific LCA research due to their better reliability and less uncertainty (Rosenbaum et al., 2018).

The end point indicators are the ultimate harm occasioned by environmental issues. Examples of impacts estimated by these indicators include destroyed human health or a destroyed ecosystem quality. As an example, the effect on human health can be measured in disability-adjusted life years (DALYs), and the degradation of the ecosystem might be measured in species loss (Klopffer and Grahl, 2014). The endpoint indicators are simpler to comprehend by the non-expert, but have more complex modelling and greater levels of uncertainty.

Besides the mandatory steps, the LCIA step could consist of a number of optional steps necessary to simplify and interpret the results. These are optional procedures namely the normalization, grouping, and weighting.

Normalization is used to compare the estimated environmental impacts to some reference value, e.g., the average environmental impact of a region or a population. The comparison can be used to explain the relative proportion of the impacts (ISO, 2006).

Organization Grouping brings the various categories of impacts together into more general themes of the environment e.g. human health, quality of the ecosystem or depletion of resources.

Weighting gives the various categories of environmental impact relative importance. Indicatively, the effects of climate change can be regarded to be more significant compared to other categories in some policy situations. Weighting enables various environmental measures to be amalgamated into a unitary environmental measure (Curran, 2015). Nevertheless, weighting includes value judgments and can bring in subjectivity. This is why the ISO standards insist on a clear transparency in case of weighting and do not permit weighting in the public comparative LCA studies (ISO, 2006; Finkbeiner, 2014).

2.3.2.4 Phase 4 Interpretation of Results

The fourth and last step in the Life Cycle Assessment (LCA) is the Interpretation phase. During this stage, the findings of the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) are critically examined and checked. This stage will be used to describe the findings in a straightforward and relate them to the study goals stipulated in stage one of this study. The step aids in converting the numerical findings into the sensible conclusions and practical implications of making a decision

(Klopffer and Grahl, 2014). The interpretation phase does not only concentrate on how to present the results but also responding to the research questions and offering practical recommendations on how the environment can be improved.

Identification of important environmental issues commonly known as a hotspots is one of the significant steps in this phase (ISO, 2006b). Hot spot analysis assists in identifying those life cycle areas of the product that are the most significant contributors to the environmental effects. These phases can be the extraction of raw materials, production, transportation, consumption or disposal. As an illustration, an LCA study can indicate that the manufacturing process has comparately low energy consumption, whereas raw materials extraction and transportation activities take a significantly bigger portion of the total effect on the environment. In other instances, it can be seen that these phases can contribute to a significant part of greenhouse gas emissions (Curran, 2015). The need to identify these hotspots is essential to green supply chain management since it assists the organizations to know where the improvements need to be focused on. This enables organizations to devote resources to those areas that would contribute the most to the benefits of the environment (Mendes da Luz et al., 2018).

The results evaluation and validation is also part of the interpretation phase. The LCA studies usually base on database, assumption as well as estimations. Thus, the findings should be scrutinized with due care to make them reliable and accurate (Matthews et al., 2014). This stage has a number of checks that must be made according to ISO 14044.

The former is the completeness check, which will make sure that all the pertinent data, materials, and environmental flows were taken into consideration in the inventory analysis. This measure is used to ensure that no valuable data has been left out in the collection procedure and that data available are enough to justify the findings (ISO, 2006b).

The other significant process is the sensitivity analysis. Sensitivity analysis is performed to determine the way in which the results change in case of modifications in the major assumptions or variables (Finkbeiner, 2014). As an illustration, transportation distance can be varied to 500 kilometers to 2,000 kilometers or the recycling rate can be varied to 20 percent to 80 percent. In case any slight variation in these assumptions leads to significant discrepancies in the outcomes, the study is regarded as very sensitive and the findings should be interpreted with caution (Klopffer and Grahl, 2014). Conversely, when the results are the same irrespective of such changes, the results are deemed to be more valid.

The interpretation phase is also performed in order to check the consistency. This step will make sure that the same procedures, assumptions, rules on allocation, and boundaries of the system were used all through the study. At least the consistency is vital in comparative research whereby the various products or systems are compared. Adhering to the same methods can contribute to the occurrence of fair and unbiased outcomes (ISO, 2006b).

The last step in the interpretation stage is making conclusions, finding limitations and offering recommendations. The results of the analysis are explored to make definite conclusions basing on the collected data (Wolf et al., 2010). The conclusions may be used in advancing the product design, manufacturing or the supply chain management practices. An example is that the findings might propose to utilize recycled raw materials rather than virgin raw materials, enhance the efficiency of transportation, or use renewable energy sources like wind power or solar power in manufacturing plants (More et al., 2022).

Simultaneously, the weaknesses of the study should also be mentioned explicitly. All of the LCA studies possess some constraints that can influence the outcomes. Such constraints can be the average database data used like ecoinvent or small scope geographical data, or unknowns in terms of environmental impact modeling (Klopffer

& Grahl, 2014). These limitations are important to be recognized and make the results more transparent and understandable by the readers. The results of LCA are not the measurements of environmental damage but estimates of potential environmental impact (Curran, 2015).

2.4 Tools and Databases

Not all sophisticated software was always in aid of Life Cycle Assessment (LCA). During the early history of LCA, it was common to do such calculations by hand or using simple spreadsheets due to the lack of data and other digital tools. With the increase in the use of LCA since the 1960s, an increase in the size of systems, data about inventory, and categories of impacts began being studied. This further complicated the management of the assessment process, which was not possible without specific tools (Curran, 2015; Klopffer and Grahl, 2014). That is why LCA software was created to assist the researcher in arranging the information, modeling the product systems, implementing the impact assessment techniques, and computing the outcomes in a more systematic manner.

The LCA software has quickly become a central component of the majority of the environmental assessment research since LCA deals with numerous inter-related processes, material flows, assumptions, and calculations. Software assists the users organize the product system, interrelate unit processes, aggregate inventory information and compute the environmental impacts in a uniform manner. It also enhances transparency since the data, assumptions and modeling decisions can be saved and checked in a better way than the manual calculations. Moreover, software may aid in scenario analysis, sensitivity analysis, and graphical presentation of results, which will simplify comparison of the alternatives and report findings to stakeholders (Curran, 2015; Klopffer and Grahl, 2014). Nevertheless, even when it is done with the help of software, there is still no need to eliminate methodological knowledge and prudent attention on the part of the practitioner.

Various LCA software programs can be used in academics and industries. Some of the best-known are SimaPro, GaBi and openLCA. SimaPro and GaBi are mature business applications and frequently utilized in the research of sustainability in practice. In comparison, OpenLCA is an open-source and freely available software that has gained more and more popularity in the academic research community due to its flexibility, transparency, and the ability to be compatible with various other databases and impact assessment methods (Ciroth, 2007). openLCA is the primary modeling tool in this thesis. OpenLCA is the right choice to make as it enables to create product systems, incorporate external databases and compare different scenarios of the supply chain of bottled water in an open and transparent manner that can be reproducible.

The other major strength of current LCA software is that it enables users apply pre-calculated life cycle impact assessment techniques. One can connect those methods and the data of the life cycle inventory so as to establish the environmental indicators of climate change, acidification, eutrophication, and use of fossil resources. This assists in enhancing similarity among the researches and minimizes the chances of error in calculation. Meanwhile, software, database, and LCIA method can determine the ultimate outcomes and therefore, such decisions should be well explained in the research design (Curran, 2015; Klopffer and Grahl, 2014). Hence, the role of the researcher is also quite significant. The meaning of software should be perceived as a support tool, instead of automatic decision-making system.

Besides software, databases are core component of LCA since it offers inventory data to model the processes in the supply chain. In LCA, a draw line is usually drawn between the foreground data and the background data. Foreground data is the information that is directly connected to the system under study of a product(like the number of materials to use, transport distances, package weights, or assumptions about a situation). Background data are more generic data to support processes, including electricity production, fuel production, extraction of raw materials, or the average transport services (Curran, 2015; International Organization for Standardization [ISO], 2006). This is a significant difference since the foreground data tends to indicate the peculiarities of the case study, whereas background data tend to be borrowed in existing databases.

In the case of this thesis, the foreground data is informed by past research work, scientific literature and technical reports. This method is appropriate since the thesis is based on scenario-based modeling as opposed to the use of direct primary data collection of a particular bottled water company. Those assumptions pertaining to the material of the bottle, recycling content, transportation distance, the efficiency of logistics, and the scenarios of waste management are thus incorporated into the foreground data. Published studies and reports as foreground data are also typical of LCA when no direct industrial data is available, but again must also be approached with care as to the quality of data, geographical relevance and consistency with the goal and scope of the study (ISO, 2006). Because of this reason, all major assumptions must be stated in a clear manner and be associated with trustworthy sources.

The databases used to obtain the background data of this thesis are like ecoinvent. One of the most popular databases of LCA research and practice is the ecoinvent database. It has numerous datasets of energy systems, transport processes, materials production, waste treatment, among many other background activities. One significant benefit of ecoinvent is that its approach is open and is currently well-known in the LCA academic community, which enhances comparability and reliability of the findings (Wernet et al., 2016). Ecoinvent in the context of this thesis will give the background processes required to model the environmental effects of the production of PETs, recycled PETs, electricity supply, transport services, and end-of-life treatments.

This thesis is based on the combination of the openLCA, ecoinvent background data, and foreground data of the previous works and reports and is a practical and academically valid basis. The comparison and modeling of bottled water scenarios is possible with OpenLCA and the standardized background processes required to produce robust calculations is available with ecoinvent. Simultaneously, literature-based foreground data allow realizing realistic Nordic supply chain scenarios even in the cases, when the primary data of the companies are not available. However, the accuracy of the final results remains to be based on the quality of the assumptions, the appropriateness of the chosen datasets, and the accuracy of the model structure. Thus, the application of software and databases should be always backed by the critical interpretation and the disclosure of limitations (Curran, 2015; ISO, 2006; Klopffer and Grahl, 2014).

2.5 Bottled Water and Packaging Studies of LCA

Life Cycle Assessment (LCA) is an established science with the ability to quantify the environmental effects of the products cradle to grave. The researchers in the beverage industry use LCA to assess complicated supply chains and avert greenwashing. Greenwashing occurs when any company makes claims that a product is sustainable even in the absence of scientific evidence. Through LCA, the researchers will be able to determine the hot spots within a life cycle of a product. One of the phases that is the most damaging to the environment is a hot spot. The actual LCA studies conducted in the real world always indicate that the drinking water itself extraction and treatment have extremely low environmental impacts. Rather, two sources of carbon footprint are huge and include production of the packaging materials and the movement of the heavy product to the market (Garfi et al., 2016; Papong et al., 2014).

A significant number of LCA research studies in the bottled water industry are concerned with polyethylene terephthalate (PET) plastic. The industry prefers using PET due to its cheapness, transparency and lightweight. Nonetheless, the study on LCA demonstrates that the energy consumption needed to manufacture regular PET using fossil fuels is enormous and the greenhouse gas emission is significant (Franklin Associates, 2009). In order to devise more suitable solutions, scientists apply LCA regularly in order to compare normal PET with other types of packaging materials, including glass, aluminum or recycled PET (rPET).

Interestingly, LCA research indicates that there is no assurance that alternative materials are superior. Consider, as an example, glass bottles which can be easily recycled, but they are much heavier in comparison to plastic. Research indicates that glass is too heavy to transport without the consumption of a lot of fuel and release of carbon dioxide into the atmosphere (Fantin et al., 2014). Due to this transport penalty, one of the most effective strategies that have been strongly proposed by the academic literature is to substitute regular PET with 100 percent recycled PET (rPET). rPET makes the bottle lightweight to carry around but significantly decreases the amount of fossil fuel that has to be extracted and minimizes the total effects of climate change (Simon et al., 2016; Zheng and Suh, 2019).

Although packaging is essential, it is also mentioned in the LCA literature that transportation logistics can entirely change the environmental performance of bottled water. Bottled water is a high volume and a heavy weight product. This implies that it consumes much diesel fuel and truck space to move it. A multiple case-study analysis of bottled water supply chains carried out by Misopoulos et al. (2019) revealed that in instances where the water is imported over long distances the transportation process may in fact produce more carbon emissions than the plastic bottle around the production process.

There is a stress on the efficiency of transport by other researchers. According to Gleick and Cooley (2009), inefficient logistics like trucks driving with half-full loads or empty trucks returning to the depot after making a delivery results in wastage of energy, and emission allocated to each bottle increases. Hence, LCA research findings show that the localization of production and the optimization of truck loads factors are the steps that should be implemented in order to make the supply chain truly sustainable. The analysis of a plastic bottle will not result in complete environmental analysis without considering the distance and efficiency of their transportation.

Due to the close interrelation of the environmental impacts of packaging and logistics, scenarios-based comparative LCA is frequently used by modern researchers. The method makes it possible to develop hypothetical what-if models which are used to test various decisions in supply chains prior to their application in the real world. As an example, one can model a standard situation (e.g., regular PET shipped over 1,000 kilometers) and compare it with a better one (e.g., rPET shipped over 200 kilometers). This comparative approach contributes to providing supply chain managers with a view of the particular combination of the material and transport operations that has the minimal environmental footprint (Garfi et al., 2016; Papong et al., 2014).

This is the practice of this scholar thesis. This research extends the literature to investigate the performance of certain packaging and logistics solutions (specifically, the improvement of packaging, namely regular PET versus rPET, and improvement of logistics, namely, transport distance, and load factor) in a Nordic Nordic bottled water supply chain, with the help of the scenario-based LCA approach.

2.6 LCA integration in Green Supply Chain Strategy

The concept of Green Supply Chain Management (GSCM) is a strategic business model, which incorporates environmental considerations in each step of a supply chain including sourcing of raw materials, distribution and disposal of the end-of-life product (Srivastava, 2007). The main aim of GSCM is to reduce environmental footprint of a company but at the same time to ensure its economic effectiveness. Nevertheless, a green strategy can be successfully applied to a company only when it is capable of measuring its environmental performance. In the absence of proper measurement, sustainability policies tend to be based on guesses or marketing rhetoric, and may be propagated to ineffective policy or greenwashed. To address this issue, scholars and practitioners in the industry are increasingly incorporating directly into GSCM strategies, Life Cycle Assessment (LCA). Whereas GSCM offers the general management model and business objectives, LCA offers the hard, scientific data now needed to assess whether the latter are effectively fulfilled (Yun et al., 2024).

Environmental decision-making in the supply chain management is very complicated. Supply chains are characterized by numerous organizations that are intertwined, such as suppliers, manufactories, logistics, and waste management facilities. Any change done at a node will have an implication on the others. Hence, supply chains managers need quantifiable means by which they can test the impact of the decisions they are making before they can implement them. LCA is a necessary strategic decision-support measure in that it goes further to offer quantifiable, verifiable information about the environmental impact of a product (Seuring & Muller, 2008).

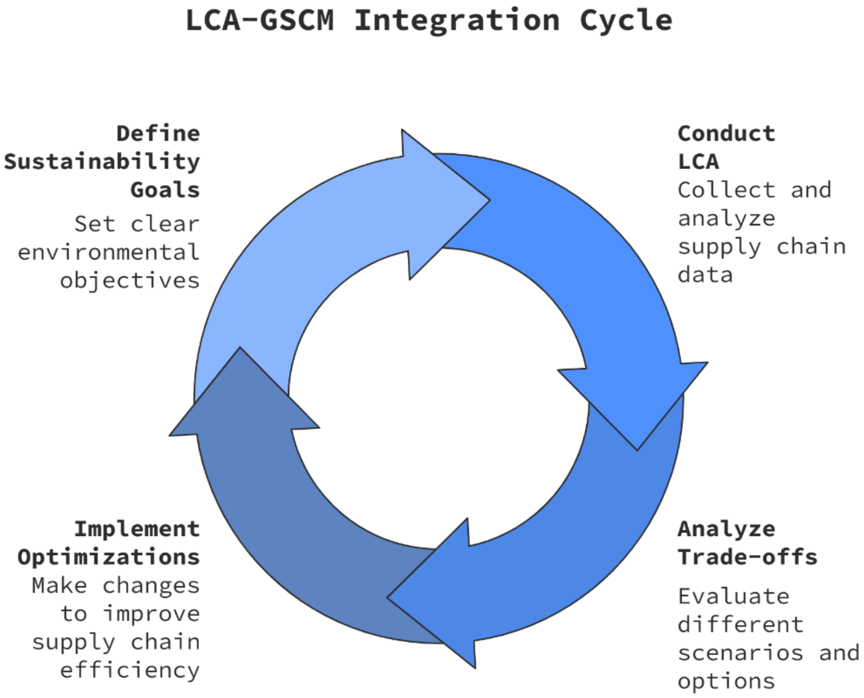

Figure 9. The continuous cycle of integrating Life Cycle Assessment as a decision-support tool

within Green Supply Chain Management.

Using LCA as part of the decision-making process, managers are able to scientifically experiment with different scenarios in the supply chain. One such example is when a firm can employ LCA to determine the environmental performance of sourcing its raw materials within a local area as compared to sourcing outside the country. LCA information enables managers to properly balance the amount of carbon emissions produced by transport with the amount of carbon emissions produced during the extraction of the materials. By integrating LCA into GSCM, environmental performance is applied as an operational objective to measure, like financial costs or product quality or delivery speed. It is a data-driven strategy that is necessary to show the actual sustainability to stakeholders, investors, and regulatory agencies (Wognum et al., 2011; Yun et al., 2024).

In addition, LCA aids in green procurement and selection of suppliers. The procurement departments may force suppliers to supply the LCA information about the environmental footprint of that material. Through the incorporation of such data into their internal systems, companies will be able to choose the partners of a supply chain according to objective environmental standards, and not on the basis of the price or hypothetical statements only. This resource sharing LCA creates a common sustainability objective among the whole system of supply chain (Hervani et al., 2005).

Problem shifting or in the academic literature, burdens shifting is one of the most critical challenges in Green Supply Chain Management. Burden shifting happens when an intended environmental improvement of one part of the supply chain leads to another part to develop a greater environmental issue (Genovese et al., 2017). An example is a beverage company that may choose to launch a new bottle model that is ultralight with plastic material in order to minimize the use of material at the production level. But in case this new bottle is not as strong, it will need a weightier protective cardboard wrapping to be transported. The increased weight of the secondary packaging may lead to a rise in the consumption of fuel and transportation emissions, that is, it merely transferred the environmental cost burden to the logistics stage.

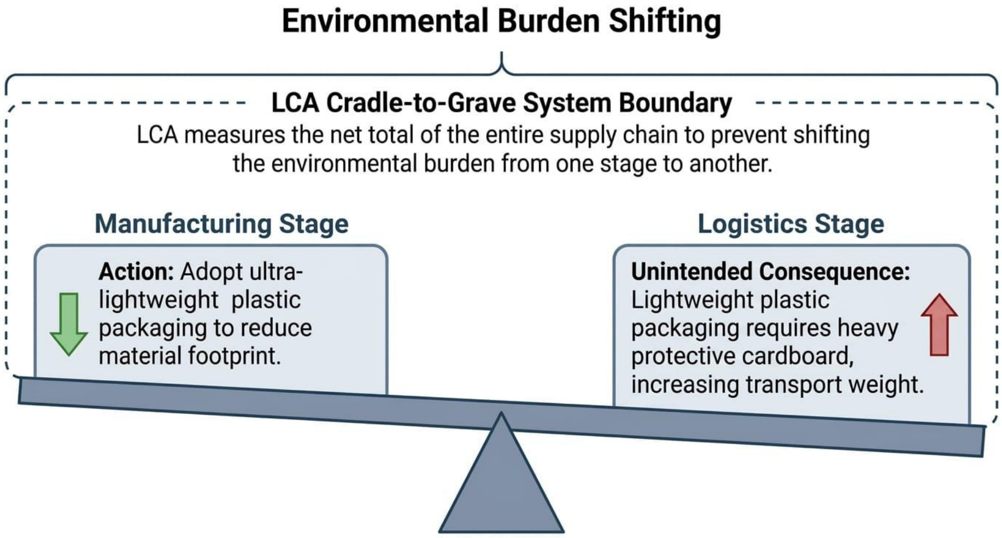

Figure 10. Environmental burden shifting across the supply chain.

Likewise, the possible burden shifting may be on inter-environmental impact groups. Another company may go to a new production method that may be effective in reduction of carbon dioxide emissions (Global Warming Potential) but very high levels of fresh water are used thus exacerbating the problem of water shortage in the area (Seuring and Muller, 2008).

The best approach to avoid problem shifting is the integration of LCA into the supply chain strategy. LCA looks at the whole life cycle of a product taken into consideration the cradle to grave hence it enables managers to have the big picture. It logically reveals trade-offs between the various activities in the supply chain and in the various categories of the environment (Srivastava, 2007). Through such trade-offs, the supply chain planners will be able to address all these trade-offs mathematically and optimize the entire system and not just the isolated problems that cause ripple effects in other parts.

The idea of the Circular Economy (CE) has emerged as one of the key pillars of Green Supply Chain Management over the past several years. In the case of traditional supply chains, the supply chain model is linear, based on the principles of take- make-discard, and it depletes natural resources and produces significant quantities of waste continuously. Contrarily, the circular economy encourages closed-loop supply chains through the concepts of reduction, reuse, and recycling materials (Genovese et al., 2017). In the case of the bottled water sector, the incorporation of the principles of the circular economy would probably consist of switching the usual PET to recycled (rPET) and deploying reverse logistics systems, with which the company will collect the empty bottles.

Researchers, however, warn that not all scenarios of the circular economy are sustainable. Recycling activities need energy, fresh water and chemicals. Also, the transportation of empty bottles to recycling plants to perform the reverse logistics that ensures the recycling takes place burns fuel and creates emission by its own. Thus, the United Nations Environment Program (UNEP) Life Cycle Initiative emphasizes the fact that circular supply chain strategies should be regularly justified by the LCA (UNEP, 2020).

LCA is made in such a way that the energy and resources used to recycle a product do not surpass the environmental advantages that the product would achieve through the lack of virgin materials. When LCA is incorporated into the circular supply planning, managers will be able to identify the point at which recycling will give back to the environment. It helps organizations answer critical questions, such as whether it is more sustainable to recycle a bottle locally using an energy-intensive process or to transport the waste to a highly efficient recycling facility in another country (Genovese et al., 2017; UNEP, 2020).

It is evident in the scholarly literature that LCA and GSCM are closely related fields.

GSCM offers the strategic vision of the reduction of the environmental impacts, whereas LCA offers the mathematical evidence necessary to verify the strategic vision. Studies indicate that the combination of packaging redesign and logistics optimization is much more effective in generating environmental benefits than either of the two steps taken separately (Yun et al., 2024).

This is the integrated approach that is applied directly to this thesis. This study can be used as a strategic decision-support tool because it involves a scenario-based comparative LCA methodology. It assesses the impact of particular Green Supply Chain Management choices like the shift to the use of recycled packaging materials (rPET) and the relocation of logistics systems on the overall environmental performance of a supply chain of Nordic bottled water. With the help of such integration, the thesis is going to set the optimum balance between packaging sustainability and distribution efficiency so that the supply chain design in the future will be economically feasible and scientific.

3 Research Methodology

3.1 Research Design and Approach

The research design used in this thesis is quantitative research. A quantitative approach uses numbers and mathematical calculations instead of quantitative observations. The main goal is to assess the environmental impacts in terms of certain and standardized units like, for example, kg CO_2-eq for climate change. The approach is very appropriate for Life Cycle Assessment (LCA), since the concept of LCA is to quantify material flows, energy use and emissions during a product's life cycle (Curran, 2015). The study is based on quantitative approach which provides objective and repeatable results. The research methodology does not include qualitative techniques like interviews or surveys. Rather, it builds a computational model of the bottled water supply chain and simulates potential environmental impacts of different strategic decisions for the supply chain.

Comparative Life Cycle Assessment is the main method adopted in this study. LCA is a scientific standardized approach for assessing the environmental impacts of a product throughout its entire life cycle, from the raw materials stage of a product's life cycle, through its use and maintenance, to its reuse, recycling and final disposal (ISO, 2006a). Comparative LCA (Klöpffer & Grahl, 2014) builds on this by comparing two or more systems with the same functional unit and the same assumptions. This is useful for Green Supply Chain Management (GSCM) as it enables managers to make comparisons between various strategic options. It could, for instance, indicate whether recycled packaging or shorter transport distance would be better for the environment. The study is conducted according to the ISO 14044 requirements for comparative LCA studies to be reported publicly (ISO 2006b). This will make the comparison fair, transparent and scientifically sound.

The study is based on scenario-based modelling for investigating different green supply chain strategies. From the point of view of this research, a scenario is a certain arrangement of the bottled water supply chain. The different scenarios developed vary in important parameters. These parameters include material composition of the packaging, place of manufacturing, distance of transport and loading/unloading efficiency of the vehicles. For instance, the baseline scenario is based on the assumption of virgin PET bottles sold from Nordic origin and used in Nordic countries, generally as a cross-border supply chain model. The distance of the transport is 800 km, and a load factor of 60 per cent is assumed for the truck. Alternative scenarios consider using 100 per cent recycled PET, shifting the production to Finland, shortening transport distance to 200 km and enhancing the load factor to 85 per cent. By using scenario modelling, the researcher can run these scenarios and see what the quantitative results are. This approach is particularly applicable in the context of GSCM as the Supply Chain is an interconnected system. An impact reduction in one stage could lead to an increase in another. This is referred to as burden shifting (Srivastava, 2007). The study can be used to determine which supply chain option provides the maximum overall environmental performance by modelling entire scenarios.

This thesis is based on secondary data. Secondary data are data that have already been gathered and published by other researchers or organizations. Journal articles, technical reports, and databases are all types of them. No data on the primary companies were gathered for this study. This decision was taken due to two reasons. The first thing is that the research is not about one particular company but to build general knowledge about a typical Nordic bottled water supply chain. Second, if the publicly available data are used it will make the study transparent and can be replicated by other researchers. The data provided in the foreground section of the study, such as bottle weight, transport distance, and the scenario assumptions, have been taken from previous LCA studies and reports, such as Horowitz et al., 2018 and Gleick & Cooley (2009). The background data, such as electricity production and fuel supply, are taken from the ecoinvent database version 3 (Ecoinvent Center, 2021). Ecoinvent is a very common tool used in LCA studies, due to the fact that it offers standardized and consistent data for many industrial processes (Wernet et al., 2016).

The geographic and temporal aspects are also part of the research design. The geographic scope is the Nordic part of Europe. As such, the computational model makes use of background data in the regions as much as possible. For instance, the electricity use at the bottling plant is simulated with the Nordics electricity grid mix, represented by electricity mix in Sweden. This grid mix includes a much higher percentage of renewable energy sources than the European average (hydro and wind power). Likewise, the transport processes and end-of-life waste treatment parameters are defined based on typical practice in the Nordic countries, namely in Sweden and Finland. Time frame for the study matches the present day. The model is based on the most recent version of the ecoinvent database and some recent scientific publications. It is not trying to predict future technological developments or future changes in the energy system. The results therefore give an overview of the environmental performance of the industries and the supply chain in a comparative way using the current industrial technologies.

3.2 Goal and Scope Definition

The goal and scope definition is the first and most basic stage of any LCA. The ISO 14040 standard states that this phase will provide a context for the analysis and ensure that the study is focused, consistent and scientifically valid (ISO, 2006a). The large amounts of data needed later in the inventory and impact evaluation stages of carrying out an LCA are effectively managed by setting clear goals and boundaries (Rebitzer et al., 2004). The purpose of the research, the intended audience of the research and the practical reasons for conducting the research are clearly outlined in the goal definition (Curran, 2015). The main aim of this thesis is the assessment and comparison of the environmental performance of a conventional water supply chain with multiple cross-border operations with alternative localized green water supply chain configurations. In particular, the research objective is to answer the question of how the change of packaging materials (e.g. virgin PET to recycled PET) and logistics optimization (e.g. shorter transportation distances, better vehicle load factors) can influence the overall environmental impact. This research is targeted towards a variety of supply chain managers, sustainability officers and academic researchers of Green Supply Chain Management (GSCM). The study is a quantitative decision support tool that differentiates on the environmental trade-offs needed for strategic logistics and packaging decisions.

The scope of the study needs to be elaborated since it gives the breadth and depth for the assessment, whereas the goal statement is brief. The scope explains exactly what the goal is likely to be done in practice in the computational model (Klöpffer & Grahl, 2014). The scope must be clearly specified in terms of what is being assessed, what is excluded, and how the environment impacts will be measured, as outlined by the ISO 14044 standard (ISO, 2006b). The product system under study in this research is the supply chain of drinking water in single-use polyethylene terephthalate (PET) bottles, for the Nordic region. LCA software allows to compute a number of environmental indicators, but the focus of the present study is mainly on climate change impacts. This focus is well warranted since manufacturing plastic and using heavy transport logistics is highly fossil fuel intensive, and carbon emissions are the greatest environmental concern in the bottled water industry. Lastly, the scope will define what the functional unit is (the actual measurement that will be used to make comparisons) and the boundaries of the system (the specific stages of the life cycle that will be included in the model). In the following independent subsections, the functional unit and system boundaries are discussed in detail, which are the most important technical parameters in comparative LCA modelling.

3.3 Functional Unit

One of the most important parts of an LCA is its functional unit. It is the point of reference for all the data gathered and calculated throughout the study (ISO, 2006a). Comparing different products is difficult without a common base since the sizes, life spans, and packaging weight vary. Functional unit is a solution to this problem where it defines the exact service or performance that the product system offers (Curran, 2015). For a comparative LCA, as this thesis, the functional unit must be the same for all the scenarios under investigation to make it a fair comparison of the scenarios, known as "apples to apples" (Klöpffer & Grahl, 2014).

The quantity, duration and quality of the service to be provided must be specified by the well-defined functional unit, as per standard LCA practice (Finnveden et al., 2009). Primary role of the supply chain for this research is to safeguard the drinking water in a safe package and transport it to the consumers. Hence the functional unit in this thesis is: "1,000 liters of bottled water delivered to the consumer in a Nordic market".

This particular functional unit was chosen for various reasons. The first benefit is that a volume-based measure (liters) provides a meaningful measure of the primary purpose of the product system (Garfí et al., 2016). Secondly, the unit is scaled up to 1000 liters (or 0.5 Liter bottle) making the impacts on the environment, such as carbon emissions, readily understood and measurable by managers in the supply chain.

Table 1. Functional unit (FU) for bottled water for Life Cycle Assessment (LCA).

Category	Description
Function	Bottled water delivered to the consumer in a Nordic market.
Functional Unit	1,000 liters of bottled water.

From a practical aspect, the reference flow means that exactly 2,000 bottles, the bottle caps, labels and secondary cardboard packaging are needed to fulfil this functional unit using standard 0.5 liter PET bottles.

The functional unit also sets the location as a "Nordic market" which also determines the geographic context for the logistics modelling. Every input (like raw materials and electricity) and every output (like transport emissions) of the following steps of the LCA will be mathematically scaled to the production and transport of these 2,000 bottles (Garfi et al., 2016). This functional unit is the basis of the system boundary, which is shown and described in the next section (see Figure 11 in Section 3.4).

3.4 System Boundaries

The system boundary of a LCA specifies exactly what processes and life cycle are studied and what are not. The definition of system boundaries is necessary as it dictates the depth of analysis and the fact that the data collection should be manageable, relevant and consistent with the functional unit (ISO, 2006a; Curran, 2015). The ISO 14040 standard suggests that the system boundary should define all the physical processes involved in providing the function of the product system, from the extraction of resources from natural systems to the ultimate disposal of the waste (Klöpffer & Grahl, 2014).

This thesis uses the "Cradle to grave" system boundary. Cradle to cradle is the most thorough LCA as it measures the environmental effects of a product throughout its entire life cycle. The system boundary for this study is selected to include the supply chain of single-use PET bottled water, from the raw material extraction through to waste management in a Nordic market. Figure 11 shows the processes that are included from this boundary.

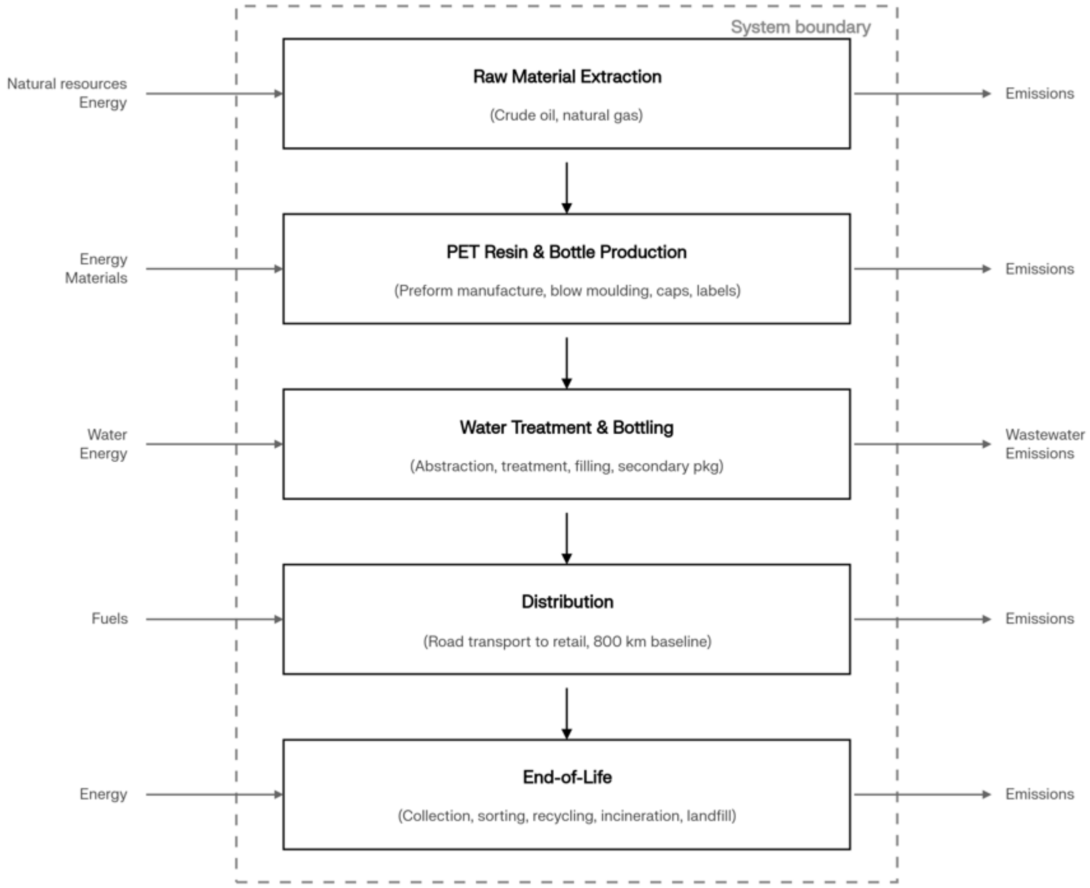

Figure 11. Cradle to Grave system boundary and life cycle of single-use PET bottled water.

The figure illustrates the five main stages of the life cycle of a system:

1. Raw Material Extraction: This involves the extraction and processing of natural resources such as crude oil and natural gas that are used to make virgin plastic materials and energy.

2. PET Resin and Bottle Production: This part relates to the industrial production of the actual packaging. It involves the manufacture of PET preforms, blow moulding of the bottles and the production of plastic caps and paper/plastic labels.

3. Water Treatment and Bottling: This phase involves the extraction of the

water, the industrial treatment processes, the filling of the bottles and the secondary packaging that needs to be applied to the bottles for transport (e.g. cardboard trays or shrink plastic).

4. Distribution: This step simulates the logistics and transport that would be necessary to take the finished, packaged good from the bottling facility to the retail market. For the purpose of this thesis this means to model an 800 km road transport route between Sweden and Finland.

5. End-of-Life: This is the final stage and refers to what happens to the packaging after consumption of the water. It represents the gathering, sorting and end treatment process of primary and secondary packaging waste. This can be material recycling (recycling of PET bottles to new PET), incineration with energy recovery and landfilling, depending on the scenario.

3.5 Data Sources and Databases

The quality and transparency of data used for the development of the model directly influence the credibility and reproducibility of any Life Cycle Assessment (LCA). In order to correctly interpret the LCA results and replicate them in future studies, it is important that the sources, types, and quality of the data provided in the LCA are clearly documented following ISO 14044 (ISO, 2006b). Typically, LCA data is split into two categories, namely, Foreground and Background. The foreground data refers to the particular process(es) under study (e.g., the exact weight of the bottle). Background data refers to the thousands of supporting industrial processes behind the product system, e.g., electricity generation, fuel refining etc. (Curran, 2015).

The data in this study are compiled from literature and technical reports published by other groups that have been peer reviewed and verified (foreground data) and from the ecoinvent life cycle inventory database (version 3.11) (background data). All modelling is done in the openLCA software platform (Ciroth, 2007; Wernet et al., 2016).

For this thesis, the most detailed foreground inventory was compiled from Horowitz, Frago, and Mu (2018), which did a comprehensive LCA on all products in the Green2O bottled water product category. They conduct a detailed analysis of all the direct material and energy consumption involved in the manufacture of one unit of bottled water, which includes the PET bottle, the cap, the label, the secondary packaging and the water itself. Table 2 shows the direct inputs and outputs of a regular PET (100% virgin) bottle and a 100% recycled PET (rPET) bottle as reported by Horowitz et al. (2018). These data are particularly relevant as they include all the physical components and directly compare virgin and recycled PET bottles made with the same bottle design and filling process. For the baseline scenario the value for regular PET is used and for the material-strategy scenario the value for recycled PET is used.

Table 2. Direct inputs and outputs per bottle for regular PET and recycled PET (Horowitz et al., 2018, adapted)

Parameter	Unit	Regular PET (Virgin)	Recycled PET (100% rPET)
Direct Inputs			
PET (bottle body)	kg	0.278	0.278
Packaging Film	kg	0.0184	0.0184
LDPE (cap seal)	kg	0.0156	0.0156
PP (cap)	kg	0.0216	0.0216
Cardboard (secondary packaging)	kg	0.0599	0.0599

Parameter	Unit	Regular PET (Virgin)	Recycled PET (100% rPET)
Water (filled product)	kg	0.479	0.479
Direct Discharges / Waste			
Waste Stream	kg	0.334	0.0556

As seen in Table 2, the same amount of PET is required for the bottle body (0.278 kg per bottle) with virgin PET as with recycled PET (0.278 kg per bottle). The secondary packaging components (LDPE seal, PP cap and cardboard tray) are also the same in both cases. The most significant difference is in the waste stream; the regular PET bottle contributes 0.334 kg of waste per unit whereas the recycled PET bottle contributes only 0.0556 kg of waste per unit. The six fold reduction is due to the fact that the recycled PET system saves and reuses material that is diverted away from landfill and incineration.

(Note about transport data in Table 2: The transport distances in the original Horowitz et al. study were 3,292 km for regular PET and 3,156 km for recycled PET.) The distances used in this study are not the ones used directly in the study, since the distances measured in this study are redefined in the Nordic scenario logic, with 800 km for the baseline and 200 km for the local scenario. In principle, however, the Horowitz et al. values are useful for reference to the large scale of transport associated with global supply chains).

3.6 Impact Assessment Method

Life Cycle Impact Assessment (LCIA) is the third step of the LCA framework after inventory analysis. Its goal is to take the large inventory of material extractions, energy consumption, and emissions that are gathered in the lengthy list and create a smaller list of environmental impact scores that can be understood easily and compared. The ISO 14044 standard sets out 3 required steps for the LCIA phase as follows: selection, classification and characterization (ISO, 2006b). The following steps make the environmental relevance of the raw data clearly visible systematically and scientifically defensibly.

The impact categories are selected depending on the purpose of the study in the selection step. Each emission is categorized as impacting which impact categories, for example, carbon dioxide and methane are categorized to climate change. Last, during the characterization step, the emissions are weighted by scientific factors to represent their relative potency and a single indicator score is then calculated for that category (Curran, 2015).

The impact assessment is conducted according to the ReCiPe 2016 Midpoint (H) method, for this study. ReCiPe 2016 is a worldwide accepted LCIA methodology that is widely used in up-to-date research and industrial LCA (Huijbregts et al., 2017). The "Midpoint" designation refers to the fact that the results are presented as specific environmental issues (climate change, acidification, etc.) instead of as broad end-point damages (human health, ecosystem extinction etc.). Modelling uncertainties are lower for midpoint indicators and these indicators are a very strong basis for comparative statements. The "H" is the Hierarchist perspective, the scientific mainstream view on the temporal perspective, and strongly advised for policy and management purposes (Huijbregts et al., 2017).

All impact categories as defined in the ReCiPe 2016 Midpoint (H) method are determined and presented for the baseline as well as for the three alternative scenarios. This detailed reporting is essential to make sure the environmental assessment is transparent and to make sure that so called "burden shifting" (solving one environmental problem while unintentionally creating another) can be detected (Klöpffer & Grahl, 2014).

Table 3. The following is a list of key impact categories assessed by the ReCiPe 2016 Midpoint (H) method (Huijbregts et al., 2017).

Name of the impact	**Abbreviation**	**Unit**	**Key contributing flows to the impact**
Climate change (Global Warming)	GWP	kg CO_2-eq	CO_2, CH_4, N_2O from transport and plastic resin production
Fossil resource scarcity	FRS	kg oil-eq	Extraction of crude oil and natural gas for virgin PET
Terrestrial acidification	TAP	kg SO_2-eq	SO_2, NO_x from diesel transport trucks and energy generation
Freshwater eutrophication	FEP	kg P-eq	Phosphate added to freshwater in waste handling processes
Fine particulate matter formation	PMFP	kg PM2.5-eq	Dust and particulates from PET cooling and diesel transport
Water consumption	WCP	m^3	Water used for cooling bottles and filling product
Stratospheric ozone depletion	ODP	kg CFC-11-eq	Halocarbons and cooling agents used

Name of the impact	**Abbreviation**	**Unit**	**Key contributing flows to the impact**
			in shaping processes
Human Toxicity (cancer and non-cancer)	HTPc, HTPnc	CTUh	Heavy metals, organic pollutants

All these categories have been calculated but the main emphasis of the comparative analysis and interpretation is on Climate Change (Global Warming Potential). This particular focus makes sense, given the known pattern of environmental hotspots in the supply chains of bottled water. PET plastic is produced using fossil feedstocks and is an energy intensive process, which produces significant amounts of GHG. There is a transport related carbon footprint associated with the distribution of bottled water, as a heavy product, which is typically carried by trucks using diesel fuel, which is used in direct proportion to the distance travelled and the weight carried. Bottled water production and long-distance transportation have been consistently identified as the main sources of carbon footprint in previous LCA studies (Garfi et al., 2016). All the green supply chain strategies considered in this thesis have a direct impact on the use of fossil fuels and transport efficiency, and this is why Climate Change is the most decision-relevant indicator.

The impact assessment is applied fully in the openLCA software. The ReCiPe 2016 method package is used for the product system which has been created with the ecoinvent background data and the foreground scenario parameters. All results are automatically classified and characterized and scaled to the functional unit by the software.

3.7 Interpretation Framework

The fourth and last phase of the Life Cycle Assessment (LCA) framework is the interpretation phase. At this stage, the researcher should systematically summarize and interpret the entire results of the research. For this thesis, the interpretation takes place continuously over the course of this study. As it is a continuous review, data quality, assumptions and models will be reliable. It also guarantees that data stays aligned to the goal and area of study of the research. The primary function of this framework is to be able to clearly answer the research questions. To do this, the interpretation phase identifies the biggest environmental impacts, which are known as hotspots. It also conducts sensitivity analysis to demonstrate the scientific soundness and reliability of the study.

The detailed results of the LCA are provided in Chapter 4: Results and Analysis. In this chapter, the significance, reliability and validity of the findings are also analyzed. Lastly, Chapter 5: Discussions, Conclusion and Recommendations discusses the major findings and the study's limitations. It also provides actionable insights for developing sustainable bottled water supply chains.

3.7.1 Scenario Analysis

In this thesis four different scenarios are defined and compared with each other, all of which represent different green supply chain strategies for the packaging and logistics of bottled water. The bottle-specific inventory provided by Horowitz et al. (2018), there are a number of peer-reviewed publications that provide important foreground parameters. Gleick and Cooley (2009) offer information about energy intensities for all production steps of bottled water. They state that UV disinfection would need about 10 kWh per million liters of water (0.00001 kWh/L) compared to about 100 kWh per million liters of water (0.0001 kWh/L) for the conventional method. Cleaning, filling, sealing and labelling one PET bottle requires about 0.014 MJ of energy. In addition, the energy that is required to produce PET resin and to make it into a finished bottle is approximately 100 MJ/kg. The important parameters of the foreground, which represent the general structure of the supply chain, are presented in Table 4. All values are extracted from the referenced literature and/or specific scenario assumptions.

Table 4. A summary of the foreground data parameters that are scenario defining.

Parameter	Unit	Baseline	Scenario 1	Scenario 2	Scenario 3	Sources & Comments
PET bottle mass	kg	0.278	0.278	0.278	0.278	Horowitz et al. (2018)
Recycled PET Content	%	0%	100%	0%	100%	Scenario definition
PP (cap)	kg	0.0216	0.0216	0.0216	0.0216	Horowitz et al. (2018)
LDPE (cap seal)	kg	0.0156	0.0156	0.0156	0.0156	Horowitz et al. (2018)
Packaging Film	kg	0.0184	0.0184	0.0184	0.0184	Horowitz et al. (2018)
Cardboard (secondary packaging)	kg	0.0599	0.0599	0.0599	0.0599	Horowitz et al. (2018)
Water (filled product)	kg	0.479	0.479	0.479	0.479	Horowitz et al. (2018)
Waste Stream	kg	0.334	0.0556	0.334	0.0556	Horowitz et al. (2018)
Water treatment energy (UV disinfection)	kWh	0.00001	0.00001	0.00001	0.00001	Gleick & Cooley (2009); best-case treatment
Bottling energy (clean, fill, seal, label)	MJ	0.014	0.014	0.014	0.014	Gleick & Cooley (2009); best-case treatment
PET bottle manufacturing energy	MJ	100	100	100	100	Gleick & Cooley (2009); production and conversion of resin
Transport Distance	km	800	800	200	200	800km-Estimate based on typical Sweden–Finland route; 200km-Estimate for domestic Finnish distribution(Localized production)
Truck Load Factor	%	60%	60%	85%	85%	60%-Ecoinvent default (includes empty returns

						and partial loads); 85%-improved logistics.
Bottle production & filling location		Sweden	Sweden	Finland	Finland	Scenario definition

All background data are taken from ecoinvent database (version 3.11), which is the most widely used and well documented LCI database worldwide (Wernet et al., 2016). The fossil resource, electricity and fuels production and use, transport vehicles, basic materials production, and waste treatment unit-process level data are standardized in Ecoinvent.

The following key background processes from ecoinvent were used for this study: crude oil and natural gas production (PET feedstocks); virgin and recycled PET granulate production; European and Nordic electricity grid mixes; diesel fuel production; heavy duty lorry operation (16-32 metric tons, Euro 5/6); polypropylene and low density polyethylene production for caps and seals; cardboard production; and municipal solid waste treatment processes (material recycling, incineration with energy recovery, and landfill).

The average load factor of the standard road freight ecoinvent datasets can be assumed as a typical 18-36% load factor, where empty returns and partially loaded trips are taken into account (Ecoinvent Center, 2021). The default assumption (which corresponds to an average volume load factor of approximately 60%) is maintained in the base case, as the current average performance of logistics. In the better logistics scenario, a higher load factor of 85 % is needed. Since there are no existing ecoinvent datasets available for high-load factors, the impact of the load factor improvement is applied as a correction factor in a mathematical way in openLCA. The baseline load factor is divided by the improved load factor to adjust the transport emissions.

3.7.2 Sensitivity Analysis

LCA outcomes are not actual measures of environmental harm; they are projections based on models, assumptions and data which always involve some uncertainty. The international standard ISO 14044 acknowledges this, and specifies that a sensitivity analysis should be part of the interpretation stage of an LCA study (ISO, 2006b). The aim of a sensitivity analysis is to systematically explore the sensitivity of the final conclusions of the study to the variation of the main input parameters, assumptions, and methodological options within realistic ranges.

This analysis can be used to determine which parameters are most important and provides a means to assess the general validity of the conclusions. The more important an assumption is modified and still the overall ranking of the supply chain scenarios is the same, the more confident one can be about the final results. However, when significant variations in the results occur due to small changes in the input, the result of the LCA is deemed to be highly sensitive and should be treated with caution (Curran, 2015).

The main comparative results of this study are based on the foreground parameters set out in Chapter 3.5. There are some parameters for which the uncertainty arises due to being literature averages, estimated from typical Nordic conditions, or being scenario assumptions. The sensitivity analysis is thus designed to evaluate a subset of the most sensitive parameters in a systematic way to see how they influence the key impact parameter, Global Warming Potential (GWP).

For this purpose, the study uses a perturbation analysis approach called "one-at-a-time" (OAT) and is conducted in line with the methodology for uncertainty in waste management LCAs developed by Clavreul et al. (2012). With an OAT approach the variation is conducted over one parameter, whereas all other parameters are maintained strictly at its baseline values. The advantage of this method is that it enables the researcher to determine the effect that each specific factor has exerted.

These changes are quantified by calculating two particular parameters for each of the tested parameters (Clavreul et al., 2012).

The Sensitivity Coefficient (SC): Ratio of the absolute change in the result to absolute change in the parameter.

Sensitivity Ratio (SR): Ratio of the relative changes. If a parameter has an SR of 2, then a 10% increase in the input parameter will result in a 20% increase in the resulting environmental impact. The SR is especially convenient for comparing the relative importance of completely different parameters.

Three main parameters with high potential uncertainty and high environmental importance were identified based on the known environmental hotspots of the bottled water industry. The three parameters will be tested in the sensitivity analysis, as listed in Table 5.

Table 5. Parameters test in Sensitivity Analysis

Tested Parameter	**Baseline Value**	**Sensitivity Variation Tested**
Amount of PET Bottle	0.278 kg/bottle	±10% (0.2502 kg and 0.3058 kg)
Transport Distance	800 km (approx. Sweden to Finland)	± 20% (640 km, 960 km)
End-of-Life Recycling Rate	60% (Nordic average)	40% (Low), 90% (High)

These values will be changed and the openLCA results will again be calculated with these values as well as the Sensitivity Ratios that will be computed, in order to see if the main results of this thesis hold true even when the real world supply chains will vary. The last recommendations to the industry can be considered scientifically sound if the scenario using 100% recycled PET (rPET) and short transport distances continues to have the lowest Global Warming Potential for all OAT sensitivity tests.

4 Results and Analysis

4.1 Environmental impact results

The environmental impact results shown in this section are for the Baseline scenario (virgin PET, 60 % load factor, 800 km transport). As a baseline scenario, the current supply chain of bottled water to the Nordic market is represented. The results are based on the openLCA software and the ecoinvent 3.11 database. The functional unit for the assessment is 1,000 liters of bottled water.

Table 6 presents the summary of environmental impacts of the baseline scenario. Values are total potential environmental impacts per functional unit.

Table 6. Total environmental impacts for the baseline scenario.

Name	Impact assessment result	Unit
Acidification: terrestrial	71.12	kg SO2-Eq
Climate change	21788.84	kg CO2-Eq
Ecotoxicity: freshwater	1024.05	kg 1,4-DCB-Eq
Ecotoxicity: marine	1359.45	kg 1,4-DCB-Eq
Ecotoxicity: terrestrial	34023.47	kg 1,4-DCB-Eq
Energy resources: non-renewable, fossil	6350.09	kg oil-Eq
Eutrophication: freshwater	17.70	kg P-Eq
Eutrophication: marine	1.52	kg N-Eq
Human toxicity: carcinogenic	2983.53	kg 1,4-DCB-Eq
Human toxicity: non-carcinogenic	28722.58	kg 1,4-DCB-Eq
Ionising radiation	11430.81	kBq Co-60-Eq

Land use	635.22	m2*a crop-Eq
Material resources: metals/minerals	229.82	kg Cu-Eq
Ozone depletion	0.02	kg CFC-11-Eq
Particulate matter formation	29.19	kg PM2.5-Eq
Photochemical oxidant formation: human health	38.99	kg NOx-Eq
Photochemical oxidant formation: terrestrial ecosystems	40.63	kg NOx-Eq
Water use	276.06	m3

From the baseline scenario, as described in Table 6, there are substantial burdens in several areas. highest values are observed for terrestrial ecotoxicity and non-carcinogenic human toxicity. One of the most important categories for this thesis is, however, climate change. The total climate change impact for the baseline scenario is 21,788.84 kg CO_2-Eq. This suggests that the existing value chain is very carbon intensive.

In order to identify the sources of these environmental impacts, a contribution analysis was carried out. The overall results are then divided into five life cycle stages: Production, Packaging, Transportation, Electricity and Waste Management.

The breakdown of the contributions is shown graphically in Figure 12 and numerically in Table 7.

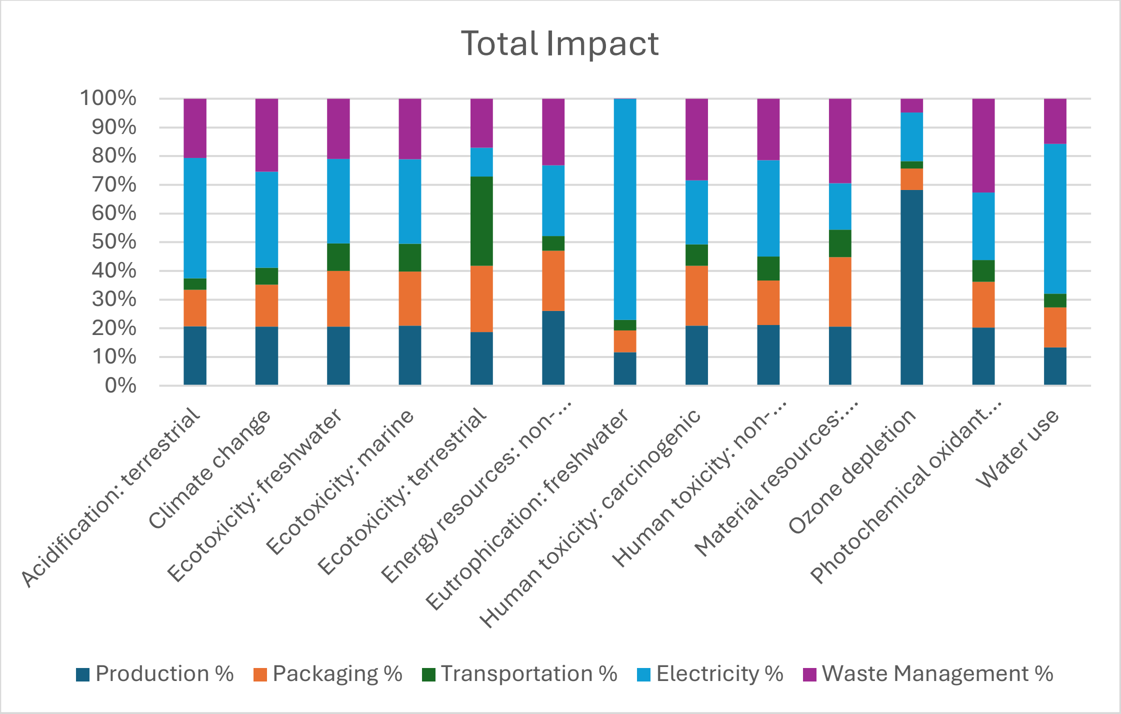

Figure 12. Contribution of different life cycle stages to the total environmental impacts.

Table 7. Life Cycle stages contribution to selected impact categories

Impact Category	Production	Packaging	Transportation	Electricity	Waste Management
Acidification: terrestrial	6.14	0.61	0.50	63.64	0.23
Climate change	2267.99	262.53	271.34	18879.43	107.26
Ecotoxicity: freshwater	117.34	17.98	22.81	861.35	4.56
Ecotoxicity: marine	157.93	23.22	30.52	1141.69	6.09
Ecotoxicity: terrestrial	7231.46	1450.15	5035.52	20054.64	251.21
Energy resources: non-renewable, fossil	1042.51	135.90	85.24	5050.89	35.48
Eutrophication: freshwater	0.50	0.05	0.07	17.06	0.00
Human toxicity: carcinogenic	436.62	70.81	66.30	2386.95	22.70
Human toxicity: non-carcinogenic	3033.63	360.62	504.13	24706.61	117.33

Material resources: metals/minerals	41.88	7.99	8.18	169.47	2.28
Ozone depletion	0.01	0.00	0.00	0.01	0.00
Photochemical oxidant formation: terrestrial ecosystems	5.56	0.71	0.87	33.15	0.34
Water use	12.93	2.18	1.95	258.41	0.58

The contribution analysis clearly shows a hotspot. In nearly every category, Electricity is the leading cause of environmental impacts. In the category of climate change for instance, electricity contributes 18,879.43 kg CO_2-Eq. The results are most notably, the impact of the Electricity stage is responsible for around 87 % of the total climate change impact. This is because the baseline modelling assumed that all energy use for manufacturing the bottles (resin conversion) and for the bottling line was used as electricity. Nordic grid is relatively clean, but high energy consumption of 7.7 kWh manufacturing and bottling drives up the impact.

The GWP is increased by an additional 11 % in the Production stage (mostly water treatment). Only about 1.2 % of transportation (271.34 kg CO_2-eq) and Packaging (262.525 kg CO_2-eq) contribute, the long-distance lorry transport is relatively efficient per ton-km and the impacts of the virgin PET resin production are already covered in the “Electricity” stage, where the manufacturing electricity is added as a separate input to the ecoinvent PET granulate dataset. This modelling option results in a small Packaging stage. The amount of waste management waste that contributes to the results (107.258 kg CO_2-Eq) is quite small (0.5 %).

The result of the hotspot analysis thus clearly indicates that electricity consumption is the main contributor to climate change in this baseline model. This is quite a contrary result to some published studies where packaging production and transport are dominant. The difference is explained by the assumption that the energy for the manufacturing of the bottles is provided as electricity and that the electricity portfolio is not completely renewable. This effect would be significantly lowered if it were possible to use a 100 % renewable electricity contract for a real Nordic supply chain or to use the actual Nordic grid mix, which has a very low carbon intensity.

4.2 Scenario comparison

This section compares the effects of the baseline scenario to three alternative supply chain scenarios. The main purpose of this comparison is to investigate the effect of various green supply chain strategies (use of recycled materials and optimized logistics) on the overall environmental footprint of bottled water.

As outlined in the methodology chapter, comparisons made in this analysis are between the following scenarios:

Baseline Scenario: Virgin PET, 800 km transport, 60 % load factor, Waste Management (60 % recycling, 30 % incineration and 10 % landfill).

Scenario 1 (Material strategy): 100 % recycled PET, 800 km transport, 60 % load factor, Waste Management (60 % recycling, 30 % incineration and 10 % landfill).

Scenario 2 (Improved Logistics strategy): Virgin PET, 200 km transport, 85 % load factor, Waste Management (60 % recycling, 30 % incineration and 10 % landfill).

Scenario 3 (Combined strategy): 100 % recycled PET, 200 km transport, 85 % load factor, Waste Management (60 % recycling, 30 % incineration and 10 % landfill).

All impacts are reported per functional unit. The comparison is first made on the primary indicator, Climate change (kg CO_2-eq) and then broken down by each life cycle stage.

Climate change (kg CO_2-eq) is the focus environmental indicator in this study. Each scenario's total climate change and percentage reduction from the baseline is given in Table 8. The same data are visualized in Figure 13.

Table 8. Climate change (kg CO_2-eq) and reduction relative to baseline

Scenario	Climate change (kg CO_2-eq)	Reduction compared to baseline
Baseline (virgin PET, 800 km, 60% load factor)	21788.843	0
Scenario 1 (rPET, 800 km, 60% load factor)	20263.883	6.999
Scenario 2 (virgin PET, 200 km, 85% load factor)	21565.385	1.026
Scenario 3 (rPET, 200 km, 85% load factor)	20040.424	8.024

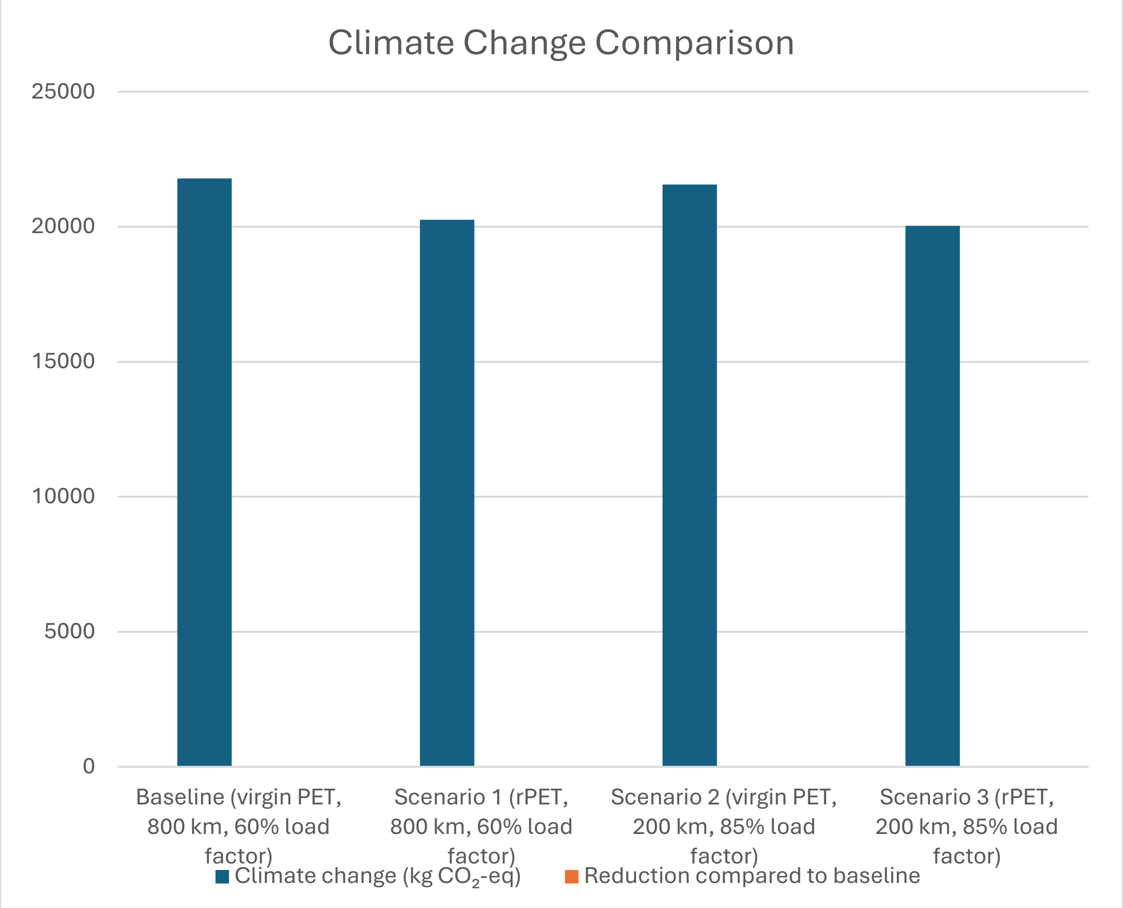

Figure 13. The total climate change impacts and the percentage reduction from baseline.

There are four vertical bars on the chart. The baseline bar is the tallest (21788.84348 kg CO_2-eq). Scenario 1 and Scenario 3 are clearly shorter, with Scenario

2 being just slightly lower than the baseline.

The material strategy in scenario 1 offers a very powerful environmentally beneficial strategy. The total climate change impact is reduced to 20,263.88 kg CO_2-Eq, when using 100% rPET packaging materials. This is a 7% decrease (6.99% actual) from the baseline GHGs.

The logistics strategy tested in Scenario 2, on the other hand, shows a far smaller climate change burden reduction. Transporting water locally reduced transport distance by a great deal, and improved the load factor of the water trucks. In scenario 2, as the supply chain is still completely virgin PET packaging, the overall footprint of the supply chain is reduced only to 21,565.39 kg CO_2-Eq. The logistical improvement just by itself makes an approximate 1% reduction, which is 1.02% in the total climate change impact.

Lastly, it shows that Scenario 3 is the most environmentally friendly. With 100% recycled packaging and optimized logistics, the overall climate change impact in Scenario 3 is 20,040.42 kgs of CO_2-Eq. This is the most effective overall emission reduction, and strategies work best if layered.

To determine the reasons for the success of Scenario 1 compared to Scenario 2, and why Scenario 3 was the most successful, a contribution analysis was carried out. The total climate change score is divided into the separate life cycle stages (Production, Packaging, Transportation, Electricity, Waste Management). The contributions are presented in Table 9 and illustrated in Figure 14.

Table 9. Life cycle stage contribution to Climate change (kg CO_2-eq) for all scenarios.

Life Cycle Stage	Baseline	Scenario 1	Scenario 2	Scenario 3
Production	2267.99	832.44	2267.99	832.44
Packaging	262.53	262.53	262.53	262.53
Transportation	271.34	271.34	47.88	47.88

Electricity	18878.43	18879.43	18879.43	18879.43
Waste Management	107.26	17.85	107.26	17.85

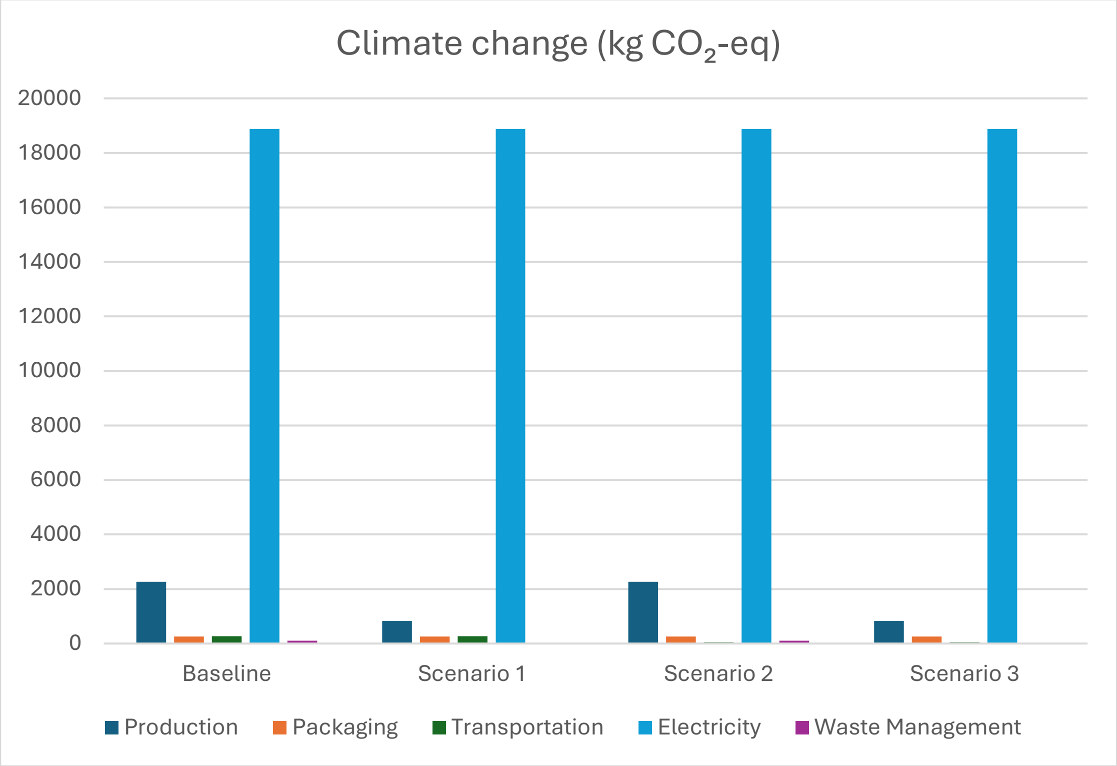

Figure 14. Contribution of specific life cycle stages to the total climate change impact by scenario.

Electricity and Production are the two main drivers of high emissions in the baseline scenario as observed in Table 9 and Figure 14. The total electricity consumption for the bottling processes are the same in all four scenarios at about 18,879 kg CO_2-Eq. Because this electricity consumption does not change, the emission reductions must come from other stages.

The table shows a huge decrease in "Production" emissions for analysis of Scenario 1. This reduction in emissions is achieved by switching the production material from virgin PET to recycled PET, and is calculated to be 2,267.99 kg CO_2-Eq compared to 832.44 kg CO_2-Eq. This is because crude oil extraction and refining is a very energy-intensive process, and recycling can help to save energy. In addition, the use of rPET results in a significant reduction of the Waste Management emissions from 107.26 kg CO_2-Eq to 17.85 kg CO_2-Eq in the end-of-life stage under the ecoinvent cut-off approach.

The table for Scenario 2 indicates that the transport emissions decrease significantly from 271.34 kg CO_2-Eq to 47.88 kg CO_2-Eq. This is a good example of the effectiveness of reducing the supply chain from 800 km to 200 km, and thereby the amount of diesel fuel used. With the virgin plastic the production emissions are still very high (2267.99 kg CO2-Eq) due to virgin plastic, however, the overall benefit of the shorter transport route is being offset by the material impact. This is what makes the results of the overall reduction in Scenario 2 just a 1%.

Both benefits are well achieved in scenario 3. It keeps the reduction of production emissions (832.44 kg CO_2-Eq) of rPET and the reduction of transportation emissions (47.88 kg CO_2-Eq) due to local sourcing. It addresses multiple hotspots at once, thus realizing the lowest possible carbon footprint in the supply chain.

Climate change is the main concern, but a strong LCA should also avoid unintended environmental trade-offs in the reduction of carbon emissions.

Table 10. Impact assessment results other than Climate Change in all scenarios.

Name	Unit	Baseline	Scenario 1	Scenario 2	Scenario 3
Acidification: terrestrial	kg SO2-Eq	71.12	67.18	70.71	66.76
Ecotoxicity: freshwater	kg 1,4-DCB-Eq	1024.05	977.91	1017.73	971.59
Ecotoxicity: marine	kg 1,4-DCB-Eq	1359.45	1299.27	1348.67	1288.49
Ecotoxicity: terrestrial	kg 1,4-DCB-Eq	34023.47	30578.86	29876.57	26431.96

Energy resources: non-renewable, fossil	kg oil-Eq	6350.09	5512.84	6279.89	5442.64
Eutrophication: freshwater	kg P-Eq	17.70	17.40	17.69	17.38
Eutrophication: marine	kg N-Eq	1.52	1.54	1.52	1.54
Human toxicity: carcinogenic	kg 1,4-DCB-Eq	2983.53	2706.66	2943.39	2666.52
Human toxicity: non-carcinogenic	kg 1,4-DCB-Eq	28722.58	27407.51	28527.17	27212.10
Ionising radiation	kBq Co-60-Eq	11430.81	11370.23	11427.56	11366.98
Land use	m2*a crop-Eq	635.22	622.45	626.89	614.13
Material resources: metals/minerals	kg Cu-Eq	229.82	205.04	223.08	198.30
Ozone depletion	kg CFC-11-Eq	0.02	0.01	0.02	0.01
Particulate matter formation	kg PM2.5-Eq	29.19	27.53	28.99	27.34
Photochemical oxidant formation: human health	kg NOx-Eq	38.99	35.69	38.32	35.02
Photochemical oxidant formation: terrestrial ecosystems	kg NOx-Eq	40.63	36.89	39.91	36.17
Water use	m3	276.06	266.30	275.68	265.92

The data of Table 10 confirms that the green supply chain strategies do not cause significant burden shifting. The trend seen in the climate change analysis is still quite similar in other critical impact categories.

In the Energy resources: non-renewable, fossil category, for instance, the baseline scenario has the greatest fossil energy consumption (6,350.09 kg oil-Eq). In scenario 1, this is reduced to 5,512.84 kg oil-Eq due to the reduced amount of oil needed to produce recycled plastic. There is a slight decrease (6,279.89 kg oil-Eq) in scenario 2, because of the lower consumption of diesel fuel in transportation. Finally, the total fossil energy use for Scenario 3 is the lowest (5,442.64 kg oil-Eq).

The pattern is the same in the Ecotoxicity: terrestrial and Human toxicity: non-carcinogenic categories. The long blue bars in Figure 16 indicate the most severe impacts to the environment in both of these toxicity-related categories in the baseline scenario. The shortest sky color bars represent the lowest environmental damage in each of the scenarios 3 will always show the lowest environmental damage.

There is a little bit of confusion in the results only in the category Eutrophication: marine (baseline score of 1.52 kg N-Eq, and Scenario 1 going up very slightly to 1.54 kg N-Eq). But this is a very insignificant gain compared to the huge gains in climate change, fossil depletion and toxicity.

Switching to 100% recycled PET and localization of transport logistics is very successful, as shown in the scenario comparison. These strategies (Scenario 3) yield the greatest environmental benefits throughout the entire life cycle of the bottled water supply chain, without negative environmental trade-offs in other environmental areas.

Sensitivity Analysis

The LCA results presented in Sections 4.1 and 4.2 are model outputs, with uncertainties due to some input parameters being derived from literature or being average Nordic parameters. According to ISO 14044, a sensitivity analysis should be conducted to determine the impact of changing the key assumptions within reasonable limits (ISO, 2006b). In this study three foreground parameters (Table 5) are tested one at a time, while all other parameters are kept at their baseline values. The approach follows the one-at-a-time (OAT) method described by Clavreul et al.

(2012).

The most important environmental parameter is (Climate Change) Global Warming Potential (kg CO_2-eq). For every variation two numbers are calculated:
Absolute change in GWP = GWP (new) – GWP (baseline)
SR = (Relative Change in GWP %) / (Relative Change in Parameter %)

The three parameters with their baseline and test values are listed in Table 5 (Section 3.7.2).

Tested Parameter	**Baseline Value**	**Low Sensitivity Variation**	**High Sensitivity Variation**
PET bottle amount	0.278 kg/bottle	0.2502 kg/bottle (–10%)	0.3058 kg/bottle (+10%)
Road transport distance	800 km	640 km (–20%)	960 km (+20%)
End-of-life recycling rate	60%	40%	90%

The baseline stage contributions (from Table 7, Section 4.1) are as follows:
Production: 2,267.99 kg CO_2-eq
Transportation: 271.34 kg CO_2-eq
Waste Management: 107.26 kg CO_2-eq
Fixed Impacts (Electricity + Packaging): 19,142.25 kg CO_2-eq
Total GWP = 21,788.843 kg CO_2-eq

Sensitivity to PET Bottle Amount

Production, Transportation and Waste Management are impacted by the weight of PET bottle. The impacts on these three stages change by the same percentage if the weight of the bottle changes.

–10% Variation (Bottle weight reduced to 0.2502 kg)

New Production: 2,267.99 × 0.90 = 2,041.19 kg CO_2-eq

New Transportation: 271.34 × 0.90 = 244.21 kg CO_2-eq

New Waste Management: 107.26 × 0.90 = 96.53 kg CO_2-eq

New Total GWP = 2,041.19 + 244.21 + 96.53 + 19,142.25 (fixed impact of electricity and packaging) = 21,524.18 kg CO_2-eq

So, Absolute Change = GWP (new) – GWP (baseline) = 21,524.18 – 21,788.84 = –264.66 kg CO_2-eq

Relative Change = (–264.66 / 21,788.84) × 100 = –1.21%

Again, Sensitivity Ratio, SR = (Relative Change in GWP %) / (Relative Change in Parameter %) = (–1.21%) / (–10%) = 0.12

+10% Variation (Bottle weight increased to 0.3058 kg)

New Production: 2,267.99 × 1.10 = 2,494.79 kg CO_2-eq

New Transportation: 271.34 × 1.10 = 298.47 kg CO_2-eq

New Waste Management: 107.26 × 1.10 = 117.99 kg CO_2-eq

New Total GWP = 2,494.79 + 298.47 + 117.99 + 19,142.25 (fixed impact of electricity and packaging) = 22,053.50 kg CO_2-eq

So, Absolute Change = 22,053.50 – 21,788.84 = +264.66 kg CO_2-eq

Relative Change = (+264.66 / 21,788.84) × 100 = +1.21%

Sensitivity Ratio (SR) = (+1.21%) / (+10.00%) = 0.12

SR of 0.12 indicates that the GWP has medium sensitivity to the weight of the bottle.

Sensitivity to Transport Distance

The transport distance only influences the Transportation stage (baseline: 271.34 kg CO_2-eq).

–20% Variation (Distance reduced to 640 km)

New Transportation: 271.34 × 0.80 = 217.07 kg CO_2-eq

Absolute Change = 217.07 – 271.34 = –54.27 kg CO_2-eq

New Total GWP = 21,788.84 – 54.27 = 21,734.57 kg CO_2-eq

Relative Change = (–54.27 / 21,788.84) × 100 = –0.25%

SR = (–0.25%) / (–20.00%) = 0.012

+20% Variation (Distance increased to 960 km)

New Transportation: 271.34 × 1.20 = 325.61 kg CO_2-eq

Absolute Change = 325.61 – 271.34 = 54.27 kg CO_2-eq

New Total GWP = 21,788.84 + 54.27 = 21,843.11 kg CO_2-eq

Relative Change = (54.27 / 21,788.84) × 100 = 0.25%

SR = (0.25%) / (20.00%) = 0.012

A value of SR = 0.012 indicates a high level of insensitivity of the total climate change result to the transport distance.

Sensitivity to End-of-Life Recycling Rate

The Waste Management stage of the baseline is 107.258 kg CO_2-eq. It equals 60 % recycling, 30 % incineration and 10 % landfill.

Recycling rate drops to 40%

When 40% is recycled, 60% becomes waste. The percent of material not recycled = 0.60.

New Waste Management = 107.26 × (60 / 40) = 160.89 kg CO_2-eq

So, Absolute Change = 160.89 – 107.26 = 53.63 kg CO_2-eq

New Total GWP = 21,788.84 + 53.63 = 21,842.47 kg CO_2-eq

Relative change in parameter (from 60% to 40%) = (40 % – 60 %) ÷ 60 % = –33.3%

Relative change in GWP = (53.63 / 21,788.84) × 100 = +0.25%

SR = (0.25%) / (–33.3%) = –0.007

Recycling rate increases to 90%

When 90% is recycled, 10% becomes waste. The percent of material not recycled = 0.10.

New Waste Management = 107.26 × (10 / 40) = 26.82 kg CO_2-eq

So, Absolute Change = 26.82 – 107.26 = –80.44 kg CO_2-eq

New Total GWP = 21,788.84 – 80.44 = 21,708.40 kg CO_2-eq

Relative change in parameter (from 60% to 90%) = (90 % – 60 %) ÷ 60 % = 50.0%

Relative change in GWP = (–80.44 / 21,788.84) × 100 = –0.37%

SR = (–0.37%) / (50.0%) = – 0.007

The total GWP is very weakly sensitive to the end-of-life recycling rate (SR = 0.007).

Table 11. The sensitivity parameters are ranked according to the Sensitivity Ratio (SR).

Rank	**Parameter**	**Sensitivity Ratio (SR)**	**Interpretation**
1	PET bottle amount	0.12	Moderately sensitive
2	Road transport distance	0.012	Weakly
3	End-of-life recycling rate	0.007	Very weakly sensitive

As seen in Table 11, the quantity of PET material is the most influential parameter in supply chain. The weight of the plastic bottle has the largest contribution to the total carbon footprint, which means that changing its weight is the most significant. On the other hand, the variations in transport distance and recycling rates have relatively small impact on the overall results. An LCA model is very stable as the overall GHG emissions remain fairly unchanged when these parameters change.

5 Discussion, Conclusions, and Recommendations

5.1 Discussion

The aim of this study was to demonstrate the value of Life Cycle Assessment (LCA) for companies to develop a green supply chain strategy in the bottled water sector. The aim was to compare a baseline supply chain with other green supply chain scenarios. The outcomes are evidence that LCA is an valuable tool as it offers clear, numerical evidence. This evidence can be used to inform the supply chain manager about environmental hotspots, to compare the various strategies, and to make decisions based on scientific evidence, not on marketing claims.

This study aimed to establish the most significant environmental impacts within a typical Nordic bottle water supply chain. The contribution analysis of the baseline scenario provided a clear answer. The electricity stage represents the largest proportion of the environmental impact in almost all impact categories as indicated in Table 7 and Figure 12. About 18879.43 kg CO_2-eq. is caused by electricity consumption for the climate change. Production stage (mostly raw material extraction and virgin PET resin production) contributes 2267.995 kg CO_2 eq, Transportation 271.342 kg CO_2 eq, and waste management 107.258 kg CO_2 eq. All the energy required to make the PET bottles from resin was provided as electricity (100 MJ per kg of PET as per Gleick & Cooley) and although the Nordic electricity mix is fairly clean, it does have a carbon footprint. As a result, the Energy-intensive bottle production was placed in the Electricity stage, which resulted in this stage being very large. The transport distance of 800 km, by contrast, is a relatively efficient road transport and the ecoinvent transport datasets already take into account average load factors. Therefore, transport is small in size.

This hotspot finding has very little significance. It explains to supply chain managers that the most effective approach to lower the carbon footprint in the Nordic context is to either use a material that contains less energy in its manufacturing process (such as recycled PET) or to use a 100% renewable electricity source. While improvements in logistics are beneficial, they will not have a significant effect on the total impact unless the packaging material is also changed.

The second goal was to compare a baseline scenario with alternative green strategies. The following four scenarios were modelled: the baseline scenario (virgin PET, 800 km); Scenario 1 (100 % recycled PET, 800 km); Scenario 2 (virgin PET, 200 km, 85 % load factor); and Scenario 3 (rPET, 200 km, 85 % load factor).

The results are clearly evident as shown in Table 8 and Figure 13. Improving logistics only (Scenario 2) leads to a reduction of almost 1.0 %, to 21565.385 kg CO_2-eq, while combining both strategies (Scenario 3) results in a reduction of nearly 8.0 %, to 20040.424 CO_2-eq.

That is why the contribution analysis across scenarios (Table 9 and Figure 14) is provided. The Production stage is significantly lower in the rPET scenarios (832.437 kg CO_2-eq) compared to the virgin-PET scenarios (2267.995 kg CO_2-eq). This is due to the fact that PET that has been recycled is available and does not need to be obtained as crude oil. The Transportation stage also decreases in improved logistics, from 271.342 kg CO_2-eq to 47.884 kg CO_2-eq, but because transportation was very small in the first place, this has a minimal impact on the total climate change. The Electricity stage is nearly equal in all scenarios, at approximately 18878.43 kg CO_2-eq, since the same electricity is consumed to process virgin PET and recycled PET.

In particular, there was no burden shifting. The other ReCiPe scenarios (Table 10) follow a similar trend as the climate change scenario: in all scenarios rPET performs at least as well. This demonstrates that recycled plastic represents an actual improvement of the environment.

A sensitivity analysis was carried out to assess the sensitivity of the results to three critical parameters, namely the quantity of PET bottles used ±10 %, the distance covered by road transport ±20 % and the end-of-life recycling rate, 40 % or 90 %. The Sensitivity Ratios (SR) derived from the one-at-a-time analysis were very clear (Table 10): the amount of PET bottles, SR = 0.12 (moderate sensitivity), the transport distance, SR = 0.012 (very low sensitivity) and the end-of-life recycling rate, SR = 0.007 (extremely low sensitivity). The most significant result of the sensitivity analysis, however, was that the order of the scenarios was always the same. In all scenarios tested that were compared, Scenario 3 (combined strategy) was the most climate-friendly scenario, followed by Scenario 1, Scenario 2, and the baseline.

The third goal was to demonstrate the use of LCA in managerial decision making. That role is illustrated by the results of this thesis. An LCA could be a tool the supply chain manager might not utilize because it is not visible and easy to understand, and so it is not the most impactful green action. Under the current Nordic conditions, the carbon footprint per transport is 1.2%, while the embedded energy in the packaging material dominates the carbon footprint, as illustrated in the LCA. This evidence helps avoid the waste of resources and help direct the business to implement first the most effective approach: material substitution. Furthermore, the cradle-to-grave boundary of the LCA avoided the burden shifting issue from being overlooked. The LCA can help determine, before a public assertion of “rPET is 100 % green”, if there are any further impacts, such as increased water usage or toxicity. No such hidden trade-offs were found in this study.

These results are broadly consistent with Horowitz et al. (2018) who found that packaging production is also a significant hotspot in life cycles of bottled water. The relative importance of transport, however, varies from one study to the other. The distances in the Horowitz study were more than 3 000 km and transport-related emissions accounted for a higher percentage of the total footprint. The Nordic situation is different today, with the 800 km road trip being significantly shorter, and average load factors being considered in the background data of ecoinvent. So transport here seems relatively insignificant.

5.2 Managerial recommendations for green supply chains

Based on the results of the LCA presented in Chapter 4 and the interpretation in Section 5.1, a set of practical recommendations are presented. These recommendations are meant to help supply chain managers and decision makers in the bottled water industry to reduce the environmental footprint of their products. The recommendations are presented in a clear and actionable manner, and are based in quantitative evidence.

Replace with 100% recycled PET the priority objective. The best thing a Nordic bottled water company can do today is to substitute virgin PET with 100 % recycled PET. As demonstrated by the results, replacing the materials alone leads to a reduction in the climate change impact of 7.0 % (Table 8). This enhancement does not require any changes to bottle design, filling operations or logistics network. Recycled PET has a significantly reduced upstream environmental footprint, which is because it does not involve the extraction and refining of crude oil.

Managers should therefore begin discussions with rPET suppliers, sign long-term contracts and make sure customers are in the know regarding the rPET content. In addition, the waste stream data presented by Horowitz et al. (2018) show that there are also significant benefits at the end-of-life of the waste stream associated with rPET bottles. Furthermore, all LCIA results (Table 10) indicate that there are no new environmental issues that arise when switching to rPET. No burden shifting is there. As a result recycled PET is a safe and authentic improvement.

Improving logistics as a means of supporting actions, but not as the primary solution. High load factors and reduction of transport distances are the most salient green measures for trucks. The results of this thesis, however, clearly indicate that, in the Nordic context, logistics improvements do not result in a significant carbon footprint reduction, with only 1.0 % being achieved (Scenario 2 in Table 8). This is because the contribution of the transportation stage in the baseline GWP is only 1.2 % (Table 7).

That is not to say logistics is something that should be overlooked. Despite the reduction in fuel consumption, there is still a benefit in logistics improvement in terms of lower operating costs and lower local air pollution. This is a good business practice. However, large carbon savings are unlikely to arise from logistics alone and managers need to take care to not expect that. The potential contribution of logistics improvements must be put in perspective within the company, to make sure that the resources are not misallocated.

Combination of material & logistics strategies for optimum result. The scenario analysis showed that recycled PET in combination with efficient logistics (Scenario 3) is the most environmentally friendly option. The decrease in climate change was 8.0 % less than the baseline and improvements were observed in all other impact categories as well (Table 10). Combined approach is the recommended best practice.

In practice, it is best for companies to find recycled PET supplies as close as possible to the site of the bottling plant and the end market. The best material and logistics benefits are realized with a regional circular economy, collecting, recycling and remanufacturing PET bottles in the same region. This finding was found to be consistent in the sensitivity analysis. Scenario 3 was always the best option.

Make use of Life Cycle Assessment as a continuous decision support tool. This study has created a functioning LCA model in openLCA with the ecoinvent database. This is not a single-shot approach. Can be reused, updated and extended. Businesses are invited to integrate LCA into the planning and improvement process. The environmental impacts may be projected before any funds are allocated if the change is planned, such as one in the electricity contract, redesigning the bottle, or switching to a new supplier.

The model can be updated with actual company data over time as well. A company that installs solar panels on its bottling plant, for instance, can measure just how much emissions the power grid has been reducing. LCA is thus not only a report but a living management tool to facilitate ongoing improvement.

Use LCA in green procurement and supplier selection. Green procurement is not only about price and quality, it is also about environmental performance. This is objective data that can be obtained from the LCA results. With the same background data, a virgin PET product can be compared with an rPET product when a company is approached by both suppliers. Results will indicate which material will present the lower carbon footprint, fossil resource usage, and toxicity impacts. This data can be included in supplier scorecards and procurement contracts.

Procurement departments can also ask their suppliers to provide LCA data themselves. This will provide a transparency from the raw material source to the finished bottle, creating a chain of transparency over time. It is an important aspect of Green Supply Chain Management: that the environmental responsibility is not borne by one company alone, but is spread throughout the entire supply chain.

Make plans for changing electricity grid. The baseline LCA model found that electricity use in the bottling plant is the single most important emitter of climate change, representing about 87% of the carbon footprint. Many managers will have to deal with the source of the energy used in the manufacturing process. Operation managers should collectively renegotiate contracts to get 100% renewables (e.g. wind, solar, hydro). Using recycled plastic in an operation but still relying on fossil-fuel energy in its factory means the total environmental impact of the company will be high. To truly make the energy supply sustainable, it is necessary to create a “green” energy supply chain.

5.3 Study limitations and future research

5.3.1 Study Limitation

This study did not gather primary data on a particular bottled water company. The sources for all foreground information were from published works such as Horowitz et al. (2018) and Gleick & Cooley (2009). This approach is transparent and reproducible but it does not reflect the actual performance of any specific brand, it is a generic Nordic supply chain. The bottle weight, energy efficiency or transport distance of a real company may vary. Thus, the numbers given here are intended as guidelines and comparisons, rather than forecasts.

One of the best sources of background LCA data is the ecoinvent database version 3.11. But numerous ecoinvent data sets are based on average European conditions. The datasets concerning waste treatment for end of life modelling, for instance, relate to European waste treatment processes, rather than specific treatment facilities in Finland. Different recycling efficiency, incineration technology or landfilling in Finland. There is some uncertainty due to this geographic mismatch. This was partially answered in the sensitivity analysis on the recycling rate but a full regionalization of all the background data was out of the scope of this thesis.

This is because the ecoinvent road freight datasets already include an average load factor of 60% which includes empty returns and partially loaded trips. A higher load factor was simulated in the improved logistics scenario by using a correction factor. Obviously a simple and clear method, but an approximation. More exact analysis could be conducted on transport datasets that are specifically developed for various load factors, which are not available in ecoinvent.

The results of the contribution analysis revealed that the baseline climate change impact is 87 % in the Electricity stage. This is partially due to modelling options that provided all bottle manufacturing energy in the form of electricity, with the Nordic energy mix. The results would change if a different energy source was used.

The sensitivity analysis was conducted on three parameters: PET bottle amount, transport distance and end-of-life recycling rate. It is important to note that these were chosen for relevance, but other factors may also affect the results including the mix of electricity generation in the power grid, the energy consumption for the energy use in bottle manufacture or the energy used in water treatment.

The mass of the PET bottle per bottle, from Horowitz et al. (2018), is 0.278 kg per bottle which is more than the mass of a typical lightweight 500 ml bottle in Europe. This was noted and cross referenced with other sources, and the Horowitz value was left as is for consistency with the source data. The total environmental impact would be less with a lighter bottle.

The results are only described in terms of a Nordic supply chain, where production takes place in Sweden while consumption takes place in Finland. Results cannot be applied to other areas that have different electricity grids, transport systems, and waste management systems. Likewise, the study makes no attempt to predict future developments, and current technology data is used.

5.3.2 Future Research

Based on the limitations of this research, some recommendations for further studies are suggested.

A future study should be able to work directly with a bottled water brand in Finland or Sweden. The generic literature values for bottle weight, electricity use and actual transport distances would be replaced with real data. This would yield outcomes which are particular and accurate and useful for that company.

Waste treatment processes and some background data are provided in average European processes in the ecoinvent database. A future study should try to replace these with Finnish-specific datasets, if they become available. This would limit uncertainty and help to render the results more representative of the true Nordic situation if based on regional data.

In this study, the load factor correction was a simple, but transparent technique. Future studies may develop a specific Nordic Road category and fill rates for various types of transport in ecoinvent. This would provide a more accurate view of the actual logistics effect.

This study found that the Electricity stage was the most prominent in the results. Future work should involve testing scenarios using other electric power sources. What would be the consequence, for instance, if the bottling plant were to purchase 100 % renewable electricity, e.g. wind or hydropower. This would change the hotspot pattern and could lead to an accentuation of transport and material decisions.

Only three parameters were varied in this thesis. Other parameters can be further tested and validated in future study which include energy consumption in the manufacturing of the bottle, energy in water treatment, type of truck used, and electricity grid mix. Additionally, a comprehensive uncertainty analysis with a multitude of random variations would also give a more complete view of the reliability of the results.

One bottle was taken from source, and gave mass of 0.278 kg. A future study could involve modelling a variety of different bottle weights which would represent bottles actually offered in the market from ultra lightweight to heavy premium bottles. This would help to appreciate the total impact of low weight plus recycled.

Disclaimer

This thesis was created with the assistance of artificial intelligence tools such as ChatGPT, Perplexity AI, Grammarly, and Napkin AI during the writing process. To brainstorm ideas, enhance academic language, and ensure clarity of text, ChatGPT and Perplexity were used. Spelling, grammar and sentence structure were checked using Grammarly. Ideas for creating the visualizations and figures were generated using NapkinAI. These technologies were used only to support. All suggestions provided by these tools were carefully reviewed, revised and verified by the author. The author's own ideas, thoughts, work and interpretation of data are presented of all intellectual content in this thesis. The author accepts responsibility for all original research, arguments and final written work of this thesis.

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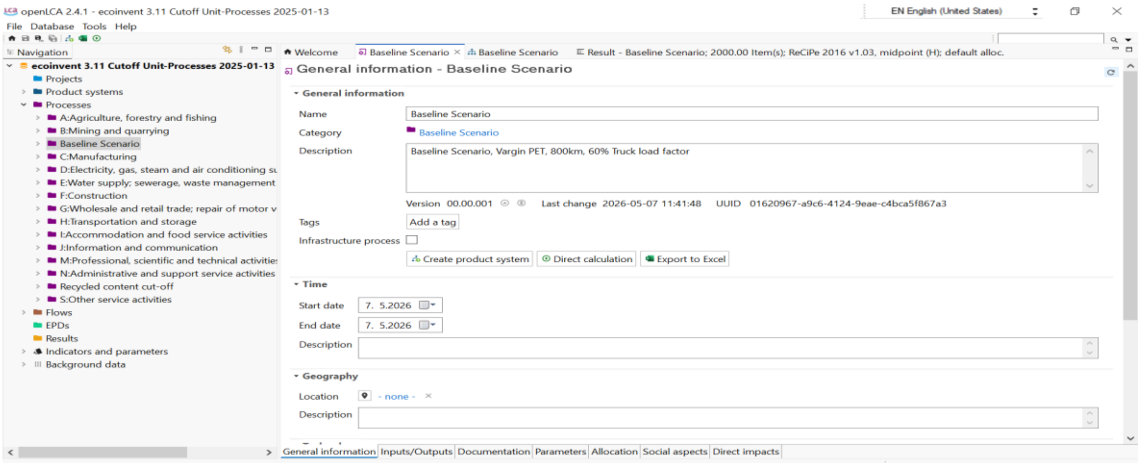
Appendix

Some screenshots of openLCA works,



General information - Baseline Scenario

General information

Name: Baseline Scenario

Category: Baseline Scenario

Description: Baseline Scenario, Vargin PET, 800km, 60% Truck load factor

Version 00.00.001 Last change 2026-05-07 11:41:48 UUID 01620967-a9c6-4124-9eae-c4bca5f867a3

Tags

Infrastructure process ☐

Time

Start date: 7. 5.2026

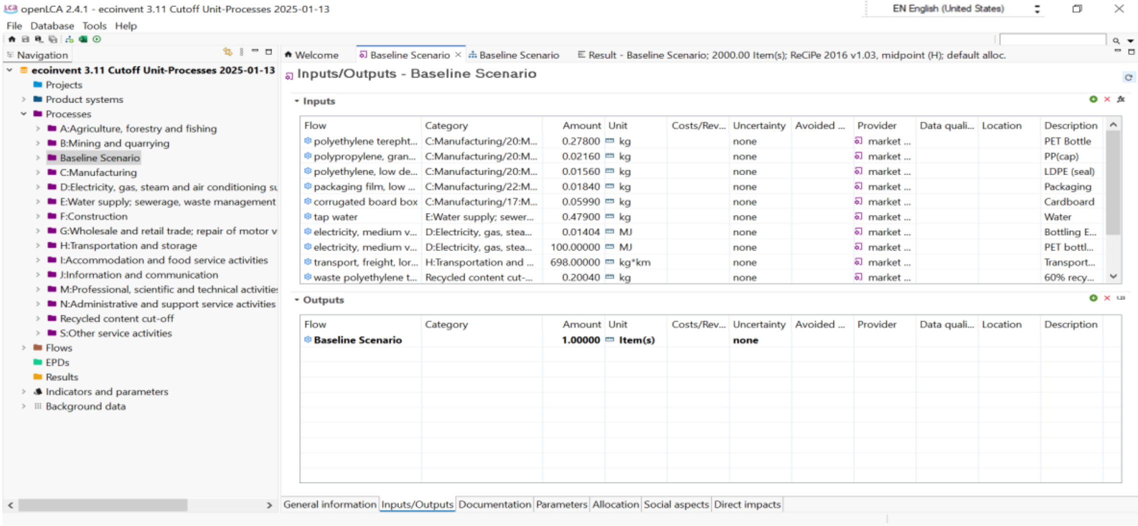
End date: 7. 5.2026

Description:

Geography

Location: - none -

Description:



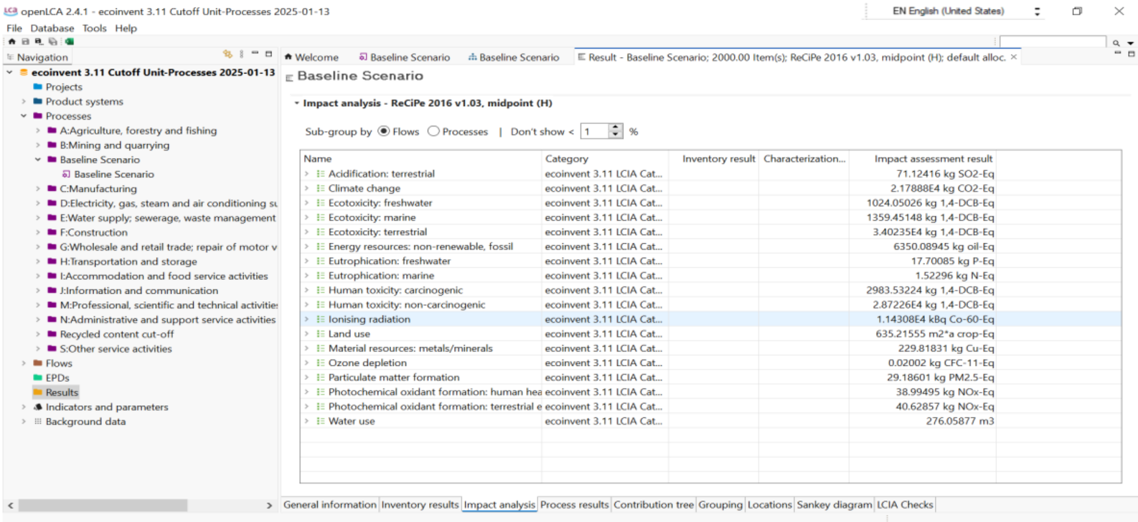
Inputs/Outputs - Baseline Scenario

Inputs

Flow	Category	Amount	Unit	Costs/Rev...	Uncertainty	Avoided ...	Provider	Data quali...	Location	Description
polyethylene terepht...	C:Manufacturing/20:M...	0.27800	kg		none		market ...			PET Bottle
polypropylene, gran...	C:Manufacturing/20:M...	0.02160	kg		none		market ...			PP(cap)
polyethylene, low de...	C:Manufacturing/20:M...	0.01560	kg		none		market ...			LDPE (seal)
packaging film, low ...	C:Manufacturing/22:M...	0.01840	kg		none		market ...			Packaging
corrugated board box	C:Manufacturing/17:M...	0.05990	kg		none		market ...			Cardboard
tap water	E:Water supply; sewer...	0.47900	kg		none		market ...			Water
electricity, medium v...	D:Electricity, gas, stea...	0.01404	MJ		none		market ...			Bottling E...
electricity, medium v...	D:Electricity, gas, stea...	100.00000	MJ		none		market ...			PET bottl...
transport, freight, lor...	H:Transportation and ...	698.00000	kg*km		none		market ...			Transport...
waste polyethylene t...	Recycled content cut-...	0.20040	kg		none		market ...			60% recy...

Outputs

Flow	Category	Amount	Unit	Costs/Rev...	Uncertainty	Avoided ...	Provider	Data quali...	Location	Description
Baseline Scenario		**1.00000**	**Item(s)**		**none**					

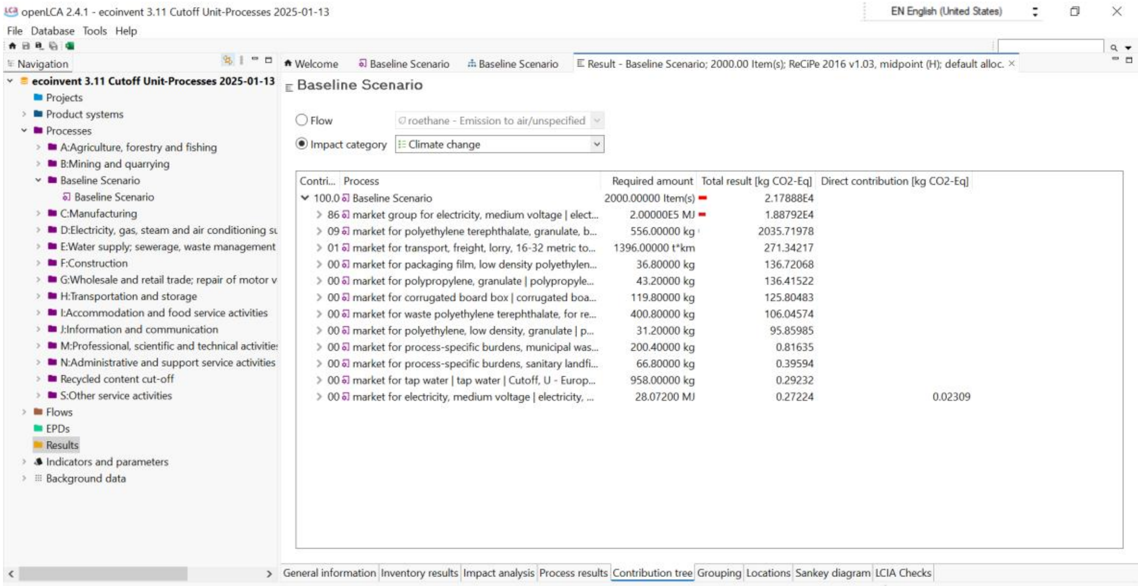


Baseline Scenario

Impact analysis - ReCiPe 2016 v1.03, midpoint (H)

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

Name	Category	Inventory result	Characterization...	Impact assessment result
Acidification: terrestrial	ecoinvent 3.11 LCIA Cat...			71.12416 kg SO2-Eq
Climate change	ecoinvent 3.11 LCIA Cat...			2.17888E4 kg CO2-Eq
Ecotoxicity: freshwater	ecoinvent 3.11 LCIA Cat...			1024.05026 kg 1,4-DCB-Eq
Ecotoxicity: marine	ecoinvent 3.11 LCIA Cat...			1359.45148 kg 1,4-DCB-Eq
Ecotoxicity: terrestrial	ecoinvent 3.11 LCIA Cat...			3.40235E4 kg 1,4-DCB-Eq
Energy resources: non-renewable, fossil	ecoinvent 3.11 LCIA Cat...			6350.08945 kg oil-Eq
Eutrophication: freshwater	ecoinvent 3.11 LCIA Cat...			17.70085 kg P-Eq
Eutrophication: marine	ecoinvent 3.11 LCIA Cat...			1.52296 kg N-Eq
Human toxicity: carcinogenic	ecoinvent 3.11 LCIA Cat...			2983.53224 kg 1,4-DCB-Eq
Human toxicity: non-carcinogenic	ecoinvent 3.11 LCIA Cat...			2.87226E4 kg 1,4-DCB-Eq
Ionising radiation	ecoinvent 3.11 LCIA Cat...			1.14308E4 kBq Co-60-Eq
Land use	ecoinvent 3.11 LCIA Cat...			635.21555 m2*a crop-Eq
Material resources: metals/minerals	ecoinvent 3.11 LCIA Cat...			229.81831 kg Cu-Eq
Ozone depletion	ecoinvent 3.11 LCIA Cat...			0.02002 kg CFC-11-Eq
Particulate matter formation	ecoinvent 3.11 LCIA Cat...			29.18601 kg PM2.5-Eq
Photochemical oxidant formation: human hea	ecoinvent 3.11 LCIA Cat...			38.99495 kg NOx-Eq
Photochemical oxidant formation: terrestrial e	ecoinvent 3.11 LCIA Cat...			40.62857 kg NOx-Eq
Water use	ecoinvent 3.11 LCIA Cat...			276.05877 m3

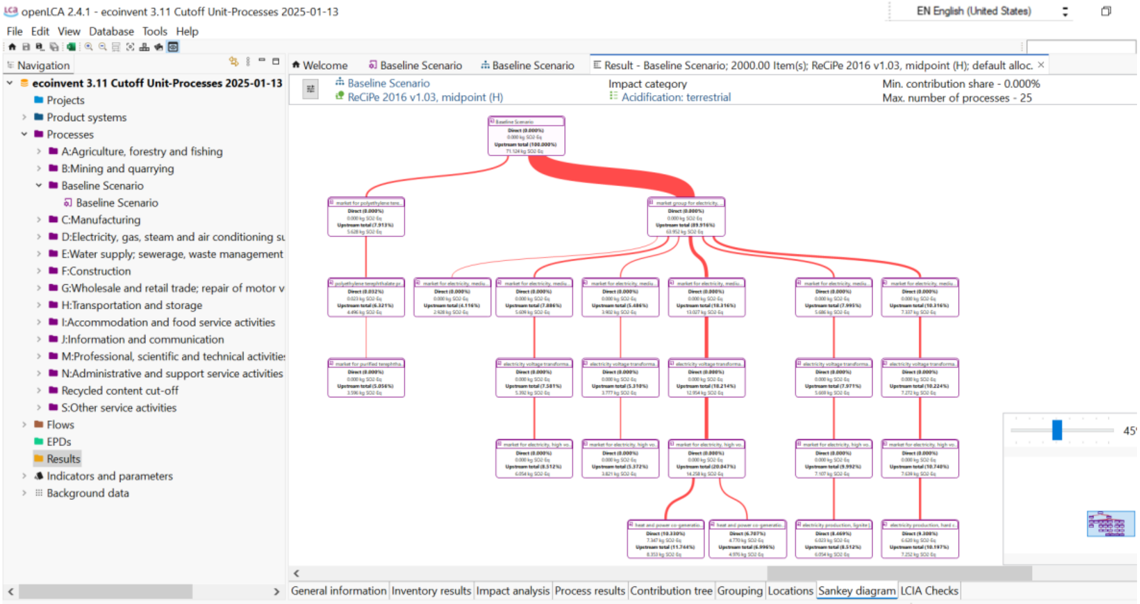


Baseline Scenario

○ Flow: roethane - Emission to air/unspecified

● Impact category: Climate change

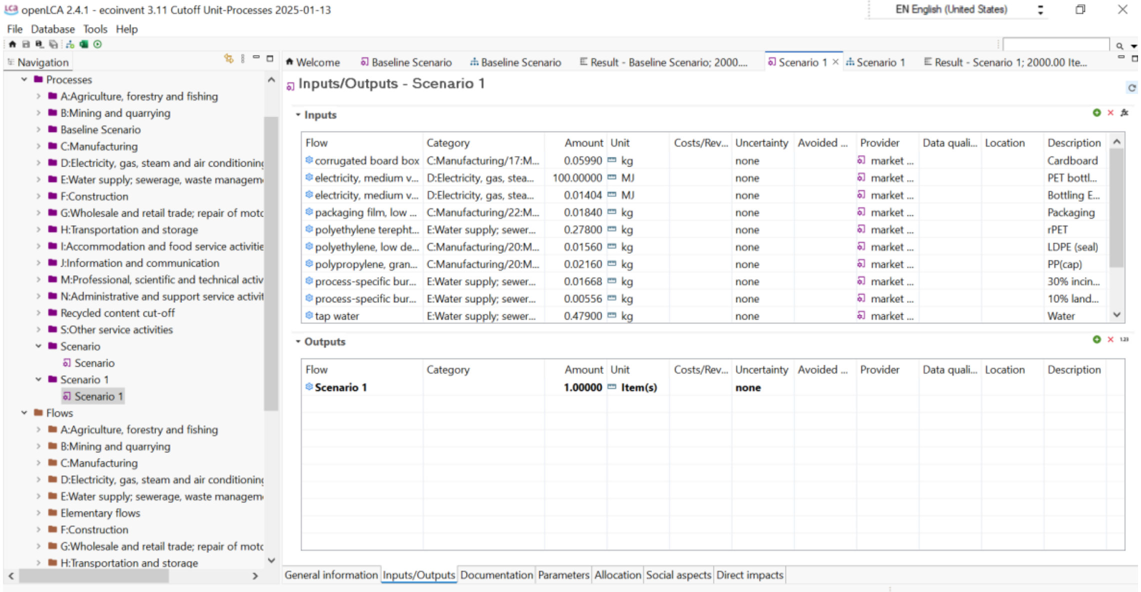
Contri...	Process	Required amount	Total result [kg CO2-Eq]	Direct contribution [kg CO2-Eq]
100.0	Baseline Scenario	2000.00000 Item(s)	2.17888E4	
86	market group for electricity, medium voltage | elect...	2.00000E5 MJ	1.88792E4	
09	market for polyethylene terephthalate, granulate, b...	556.00000 kg	2035.71978	
01	market for transport, freight, lorry, 16-32 metric to...	1396.00000 t*km	271.34217	
00	market for packaging film, low density polyethylen...	36.80000 kg	136.72068	
00	market for polypropylene, granulate | polypropyle...	43.20000 kg	136.41522	
00	market for corrugated board box | corrugated boa...	119.80000 kg	125.80483	
00	market for waste polyethylene terephthalate, for re...	400.80000 kg	106.04574	
00	market for polyethylene, low density, granulate | p...	31.20000 kg	95.85985	
00	market for process-specific burdens, municipal was...	200.40000 kg	0.81635	
00	market for process-specific burdens, sanitary landfi...	66.80000 kg	0.39594	
00	market for tap water | tap water | Cutoff, U - Europ...	958.00000 kg	0.29232	
00	market for electricity, medium voltage | electricity, ...	28.07200 MJ	0.27224	0.02309



Baseline Scenario
ReCiPe 2016 v1.03, midpoint (H)

Impact category: Acidification: terrestrial

Min. contribution share - 0.000%
Max. number of processes - 25



Inputs/Outputs - Scenario 1

Inputs

Flow	Category	Amount	Unit	Costs/Rev...	Uncertainty	Avoided ...	Provider	Data quali...	Location	Description
corrugated board box	C:Manufacturing/17:M...	0.05990	kg		none		market ...			Cardboard
electricity, medium v...	D:Electricity, gas, stea...	100.00000	MJ		none		market ...			PET bottl...
electricity, medium v...	D:Electricity, gas, stea...	0.01404	MJ		none		market ...			Bottling E...
packaging film, low ...	C:Manufacturing/22:M...	0.01840	kg		none		market ...			Packaging
polyethylene terepht...	E:Water supply; sewer...	0.27800	kg		none		market ...			rPET
polyethylene, low de...	C:Manufacturing/20:M...	0.01560	kg		none		market ...			LDPE (seal)
polypropylene, gran...	C:Manufacturing/20:M...	0.02160	kg		none		market ...			PP(cap)
process-specific bur...	E:Water supply; sewer...	0.01668	kg		none		market ...			30% incin...
process-specific bur...	E:Water supply; sewer...	0.00556	kg		none		market ...			10% land...
tap water	E:Water supply; sewer...	0.47900	kg		none		market ...			Water

Outputs

Flow	Category	Amount	Unit	Costs/Rev...	Uncertainty	Avoided ...	Provider	Data quali...	Location	Description
Scenario 1		**1.00000**	**Item(s)**		**none**					