B. Hoogerbrugge

# Measuring the environmental impact of a livestock feeding robot life cycle

*A Life Cycle Assessment case study on the Lely Vector Mixing & Feeding Robot.*

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By

B. Hoogerbrugge

in partial fulfilment of the requirements for the degree of

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# Preface and Acknowledgements

This report describes the thesis project that is conducted as the final part of the Management of Technology program to obtain the Master of Science at the Delft University of Technology. The thesis project is carried out in collaboration with Lely International N.V. which enables me to combine three areas of personal interest: agriculture, technology, and sustainability. I was working on the thesis from March 17 to July 20, 2023.

Investigating how the Life Cycle Assessment methodology can measure the environmental impact of livestock feeding robots has led me on a path with new experiences and valuable lessons. The inclusion of the Lely Vector Mixing & Feeding Robot case study provided a practical twist to the research process which contributed to an interesting and motivating project. This research is primarily written for my supervisors from the Delft University of Technology and Lely International N.V., but also to anyone else interested is welcome to read it.

I want to express my appreciation to Jelmer Ham and Maurits Huisman for helping me in my research by organizing and facilitating the internship at Lely International N.V. But also, providing me with support and acting as sparring partners during our frequent meetings. I would like to thank Dr. Ir. J. De Stefani and Dr. R.M. Verburg for supervising the thesis research as representatives from the Delft University of Technology. Also, thanks to Jacopo De Stefani for being my first supervisor and providing excellent support with a perfect mix of trust, constructive feedback, and a positive mindset during our weekly meetings. Finally, I want to say thanks to my family and friends for their help.

*B. Hoogerbrugge*
*Delft, June 20, 2023*

# Abstract

The pursuit of sustainability is at the forefront of international conversation in an era marked by urgent environmental challenges. This research aims to shed a light on tools, indicators, and methodologies used to assess sustainability, paving the way for informed decisions, actionable insights, and a brighter tomorrow.

The Paris Climate Accords urges the importance for sustainability and the reduction of environmental impact. At the same time, the demand for animal protein is growing due to an increase in world population and changing diets, resulting in growing challenges regarding the environmental impact of the agricultural and livestock sector. Firms aim to provide technological solutions that contribute to a sustainable way of farming. One of the technological solutions that lack scientific research is the livestock feeding robot. This knowledge gap offers the opportunity to investigate measuring the sustainable performance of livestock feeding robots. Additionally, scientific literature describes Life Cycle Assessment as a common and fitting methodology to measure the environmental impact of products. Furthermore, firms want to become more sustainable for competitive advantage and to be able to meet future regulations. Measuring sustainability is essential in the transition towards sustainability because the measurement can provide insights for decisions about strategic planning, product design, and supply chain design. Therefore, this research examines how the Life Cycle Assessment methodology measures the environmental impact of a livestock feeding robot life cycle by executing a case study.

A literature review was conducted to gain more detailed information on the Life Cycle Assessment methodology and environmental impact. But also, to identify multiple types of Life Cycle Assessment methodologies. The Fast Track Life Cycle Assessment methodology was selected based on data availability and compatibility with the goal of the research to measure the environmental impact of a livestock feeding robot. Carbon Footprint and Eco-costs were selected as impact indicators due to their practical characteristics for firms. The case study resulted in a Carbon Footprint of 34944 kg CO2 equivalents, equal to the offset of 1588 mature trees existing for one year. Additionally, the Eco-costs results in 9192 euro, representing the required investment to lower the environmental impact to a sustainable level by selecting the best available alternative technology which is needed to meet the required level of emission allowances.

To conclude, this study provides a case study about measuring the environmental impact of a product life cycle. Although this study focuses on the assessment of a livestock feeding robot, the same case study design can be used to measure the environmental impact of similar products. Therefore, other firms can replicate the case study design to measure environmental impact and meet future regulations, as well as maintain or improve their competitive advantage.

# Nomenclature

| | |
|---|---|
| **BOM** | Bill of Materials |
| **CED** | Cumulative Energy Demand |
| **CF** | Carbon Footprint |
| **TU Delft** | Delft University of Technology |
| **FU** | Functional Unit |
| **GHG** | Greenhouse Gas |
| **IDs** | Identifications |
| **IDEMAT** | Industrial Design & Engineering Materials |
| **ISO** | International Standardization Organization |
| **LCI** | Life Cycle Inventory |
| **LCIA** | Life Cycle Impact Assessment |
| **LCA** | Life Cycle Assessment |
| **MFR** | Mixing & Feeding Robot |
| **N/A** | Not Available |
| **PEF** | Product Environmental Footprint |
| **PRISMA** | Preferred Reporting Items for Systematic reviews and Meta-Analyses |
| **TSS** | Technical Service Support |

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# 1

# Introduction

*Chapter 1 provides background information and motivation for this research. Furthermore, the introduction defines the knowledge gap, problem statement, research questions and research objectives. This chapter additionally addresses the research approach, relevance of the research from the viewpoints of the Management of Technology (MOT) program and enterprises, as well as academic and societal relevance. The introduction ends with an outline of the rest of the report.*

## 1.1 Research Background

Planet earth is about 4.5 billion years old. The first anatomically modern human, like us, was found 300.000 years ago. Around 6000 years ago humanity evolved to establish its first civilization. But only in the past century, humanity has done a remarkable job of wasting resources on the planet, destroying vast amounts of existing forests, polluting rivers, the environment, and even changing our own climate (H.-O. Pörtner, 2022). The year 1915 counted 1.8 billion people living on earth. Fast forward to last November, the world population reached the milestone of 8 billion people according to the United Nations (UN). Projections show that there will be around 9.7 billion people on earth in 2050 (United Nations Department of Economic and Social Affairs, Population Division, 2022). Humanity demands more and more from this planet while the number of resources on earth will always stay the same. Thus, how will humanity sustain this level of production without depleting national resources, harming the environment, and compromising the ability of future generations to meet their own need? This is where the notion of sustainability comes in.

### 1.1.1 Sustainability

One of the challenges with the idea of sustainability is that it is fundamentally a social construct. Like truth, beauty, and courage, its exact meaning is somewhat influenced by the perspective of the observer. Being a site-specific and time-dynamic notion, sustainability is very challenging to measure (D. Hayati, 2010). For example, what qualifies as sustainable in India, does not necessarily do so in The Netherlands. Likewise, what was once sustainable 50 years ago, does not mean it is still considered sustainable today.

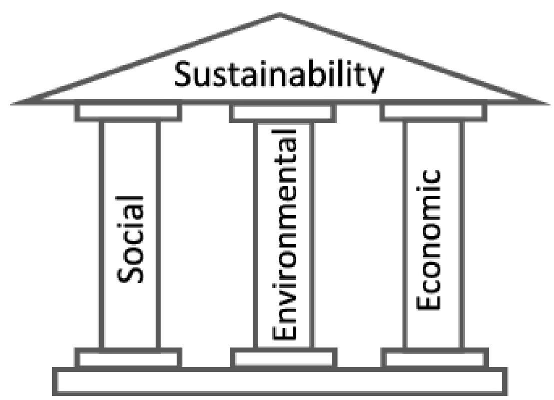


**Figure 1: The three pillars of sustainability (Ben Purvis, 2019).**

Sustainability is not only about environmental impact, but it also includes an economic and social dimension. The three dimensions, or pillars as shown on Figure 1, of sustainability are interconnected and society needs to find a balance between them (Finkbeiner, Schau, Lehmann, & Traverso, 2010). These pillars of sustainability are underpinned by the "Triple Bottom Line principle", referring to the "Triple P" of People (social), Planet (environmental) and Profit (economic). The traditional view of corporate organizations requires to take care of economic profitability. Now corporates are held continually more responsible for their social and ecological environment as well (Elkington, 1998).

#### *1.1.1.1 Social Pillar*

First, the social pillar of sustainability is concerned with the well-being of people, communities, and society. It focuses on promoting social justice, equity, and inclusion, and ensuring that everyone has access to basic human rights such as food, water, health care, education, and shelter. The social pillar also involves creating a sense of community and promoting social cohesion, as well as fostering cultural diversity and preserving traditional knowledge and practices (Ben Purvis, 2019).

#### *1.1.1.2 Economic Pillar*

Second, the economic pillar of sustainability is concerned with creating a prosperous and sustainable economy that provides for the needs of the present without compromising the ability of future generations to meet their own needs. This involves promoting economic growth and development that creates jobs and opportunities for all. The economic pillar also involves promoting innovation and entrepreneurship, as well as responsible consumption and production patterns that minimize waste and resource depletion (Ben Purvis, 2019).

#### *1.1.1.3 Environmental Pillar*

Third, the environmental pillar of sustainability is concerned with the preservation and responsible use of natural resources and ecosystems. Minimizing negative impacts on the environment by conserving natural resources, reducing pollution and waste, and promoting the sustainable use of renewable resources. This includes initiatives to reduce greenhouse gas (GHG) emissions, protect biodiversity, conserve water resources, and reduce the use of non-renewable resources such as fossil fuels (Ben Purvis, 2019). The environmental dimension receives more attention compared to the social and economic dimension. Organizations like the UN state that climate change is a global emergency. In response to climate change and accompanying negative impact world leaders signed the Paris Agreement on December 2012. Setting goals to reduce GHG emissions and starting the transition to a net-zero emissions world (United Nations, 2015). Meanwhile, the total amount of GHG emissions is still rising (IPCC, 2022). Then there are initiatives like the Sustainable Development Goals (SDGs), this is a set of 17 goals defined by the UN to create a better future for all people and the planet. The SDGs aim to end poverty, protect the planet, and ensure that all people can live healthy, prosperous lives. Furthermore, these goals promote sustainable development, which means meeting the needs of the present without compromising the ability of future generations to meet their own needs (United Nations, 2019).

### 1.1.2 Livestock Sector

To summarize, sustainability is about maintaining the status quo. However, this could be compromised by the increasing depletion of natural resources and pollution of the environment.

Lowering environmental impact become even more challenging with an increase in the world population. With the expansion of the global population, so does the demand for food. World Resources Institute states that the world needs to close a 'food gap' to meet the food demand in 2050, mainly due to diet change and population growth (Janet Ranganathan, 2016). With advances in food production across the world since the early 1960s, agricultural production has experienced tremendous expansion in recent decades. Since then, there has been a 145% increase in global food output overall. In the same time frame, the population of the world increased from three billion to more than six billion, causing the human footprint on the planet to grow as consumption habits shift (Pretty, 2007).

Figure 2 shows how the global consumption of animal-based protein is projected to increase in the coming decades. Therefore, the livestock and dairy sector, will need to upscale. At the same time the Common Agriculture Policy strategizes to reduce environmental impact. Farmers generally have two options to meet the increasing food demands. One is by upscaling, the other is to improve productivity through efficiency. Both options are heavily contested due to their ecological impact (Schierhorn & Elferink, 2016). About 22% of all greenhouse gas (GHG) worldwide come from the agriculture sector. Additionally, nearly 80% of emissions in the sector are caused by the production of livestock (Anthony J McMichael, 2007). An example of increasing pressure to reduce environmental impact can be found in the nitrogen crisis in the Netherlands. Emissions from livestock farms can potentially harm

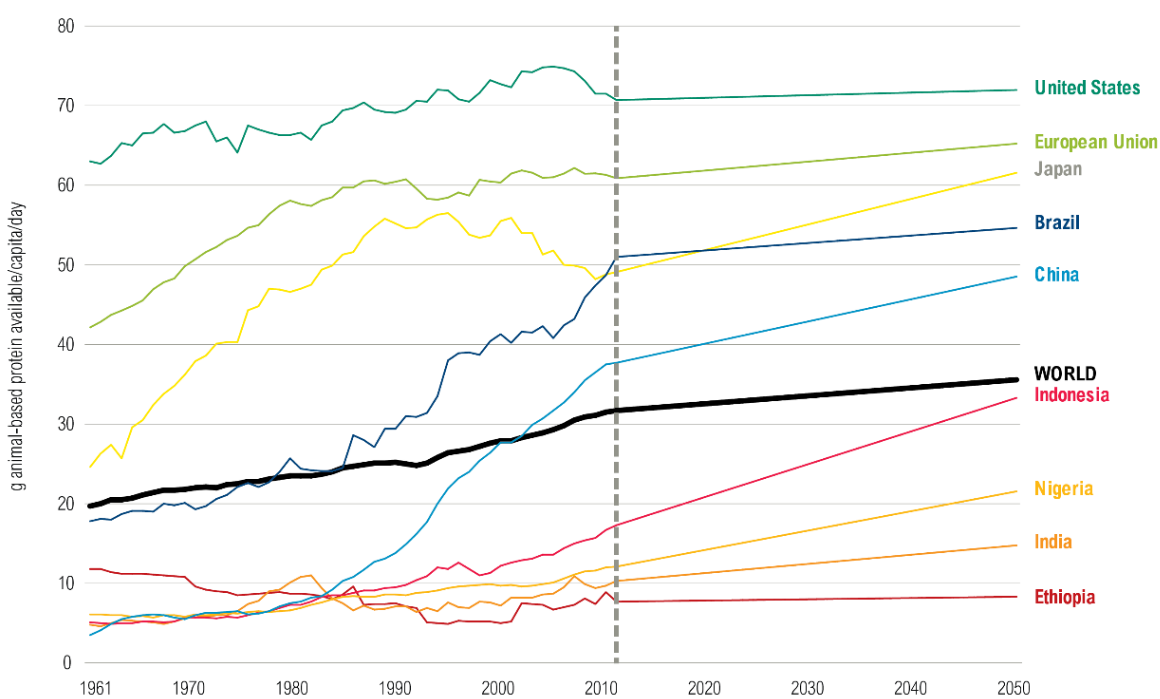



**Figure 2: Animal-based protein consumption (Janet Ranganathan, 2016).**

environmental ecosystems (Stokstad, 2019). A proposition by the Dutch government to reduce the number of livestock farms by 50% stumbled upon fierce resistance. However, a solution may be technological innovations, provided by firms, that can potentially improve efficiency while contribute to a future of sustainable farming (David Christian Rose, 2021). For example, firms promote sustainable farming solution with a livestock feeding robot. The firms that provide technological innovations are also motivated to become more sustainable themselves.

### 1.1.3 Stakeholders

One way for firms to measure their sustainability is with the use the Greenhouse Gas Protocol standard. This standard measures emissions on a firm in scope 1, 2 or 3. Scope 1 emissions refer to direct emissions from sources that are owned or controlled by the organization. Scope 2 emissions refer to indirect emissions from the consumption of purchased electricity, heat, or steam, which are generated outside of the organization. Scope 3 includes all other indirect emissions that occur in a company's value chain (Greenhouse Gas Protocol, 2013). Furthermore, firms aim to achieve sustainability is through the concept of circularity. A circular business model refers to a way of doing business that is focused on creating a closed-loop system, where products and materials are reused and recycled, rather than disposed of. The goal is to create a more sustainable and efficient business model by reducing waste and environmental impact (Guldmann & Huulgaard, 2019). However, evaluations of some current circularity practices have shown that an increase in circularity performance of a product does not always result in the reduction of environmental impact (Saidani, et al., 2022).

Besides firms there are more actors involved in the field of sustainability like governments, (international) non-government organizations (NGO), businesses, corporations, communities, academia, and individuals. All stakeholders now recognize sustainability as a core value that should inform both corporate and governmental objectives. However, the substantial and practical implementation of the sustainability idea continues to be the primary difficulty for the majority of enterprises. The issue of how sustainability performance may be measured, particularly for products and processes, lies at the heart of the implementation dilemma (Finkbeiner, Schau, Lehmann, & Traverso, 2010).

### 1.1.4 Life Cycle Assessment

Measuring sustainability is essential in the transition towards sustainability and sustainable development. The most common tool for measuring the environmental impact of products is Life Cycle Assessment (LCA) (Rauter, Zimek, Baumgartner, & Schöggl, 2019). The need for methods to better understand environmental impact has grown because of growing public awareness about the environmental impact of products, both produced and consumed. LCA can help with: (1) spotting chances to enhance the environmental performance of a product at different stages of the life cycle, (2) selecting appropriate environmental performance indicators, including measurement techniques, (3) marketing (e.g., implementing an ecolabelling, making an environmental claim) and (4) informing decision-makers in business, government, or non-government organizations. For example, providing input for decision making regarding strategic planning, product design and supply chain design (International Organization for Standardization, 2006).

## 1.2 Knowledge Gap

The need to transition to environmental sustainability is underpinned by organizations like the Intergovernmental Panel on Climate Change (IPCC), European Union, and the SDGs. This need is also present in the livestock sector which is expending due to an increase in the demand of animal-based protein. Firms aim to contribute to a future of sustainable farming with technological innovations, like livestock feeding robots. Additionally, firms want to lower environmental impact to be able to meet future regulations and for competitive advantage. However, the transition to sustainability is difficult due t0 a lack of knowledge about the measurement of environmental impact on products throughout their lifecycle. The LCA methodology is established in scientific literature as a tool to measure the environmental impact of products over their lifecycle. This measurement provides information on the status quo and input for sustainable oriented decision making. Additionally, the measurement identifies potential improvements and marketing material. Lastly, using the LCA provides insight in the methodology and environmental impact indicators. In conclusion, this research aims to create knowledge about the measurement of environmental impact of a livestock feeding robot life cycle.

## 1.3 Problem Statement

Currently, the environmental impact of the livestock feeding robot is unidentified. Also, it is unclear how the LCA methodology measures the environmental impact of livestock feeding robots because it is simply never done before. The unidentified sustainability performance of products potentially compromises the competitive advantage and ability to meet future regulations of firms. Furthermore, society might experience negative consequences in the form of climate change and resource depletion which can potentially be improved.

Measuring environmental impact provides input for informed decisions and actionable insights to achieve sustainability. First, measuring sustainability results in the identification of hotspots for improvements. Second, specific action can be taken like product design changes, modification of the supply chain or redefining company strategies. Additionally, the measurement of sustainability enables to feeding robot to be compared to conventional feeding methods and new feeding robots. Thereby, verifying progress as well as providing potential marketing material to promote the green image of a company. Also, not knowing the environmental impact is irresponsible for the producing company as their product might contribute significantly to the pollution of land, water, and air on earth.

## 1.4 Research Questions

In this research the LCA methodology is used to measure the environmental impact of a livestock feeding robot. Apart from the main research question there are also sub questions being put forward. The sub questions are derived from the main research question or from other sub questions.

**Main research question:** How does life cycle assessment measure the environmental impact of a livestock feeding robot life cycle?

**Sub questions:**

1. What is the definition of environmental impact according to scientific literature?

2. What are the existing LCA methodologies for measuring environmental impact according to scientific literature?

3. What is the available data to measure the environmental impact of a livestock feeding robot life cycle?

4. Which LCA methodology is most suitable for measuring the environmental impact a livestock feeding robot life cycle?

5. What is the required product data based on the selected LCA methodology for measuring the environmental impact a livestock feeding robot life cycle?

### 1.4.1 Research Objectives

The objective of this research is to investigate how to measure the environmental impact of a livestock feeding robot life cycle with the use of an LCA methodology. Thereby, providing input for informed decisions and actionable insights to achieve sustainability.

## 1.5 Research Approach

This section describes the research approach including the applied research methods. Each part of the research builds upon the previous part in a systematic process. The research approach is generally divided in 3 parts: Literature review in Chapter 2, Methodology in Chapter 3, and the case study in Chapter 4. Figure 3 provides a flow diagram of the research. Preliminary research resulted in the identification of a knowledge gap and research questions. To answer the research question, the first step was to gather knowledge on environmental impact, LCA methodologies as well as the available data with the use of a literature review. Subsequently, a certain methodology was defined based on the results of the literature review to measure the environmental impact of the product life cycle. The next step is the actual execution of the case study. Followed by the results, conclusion, and recommendations of the research.

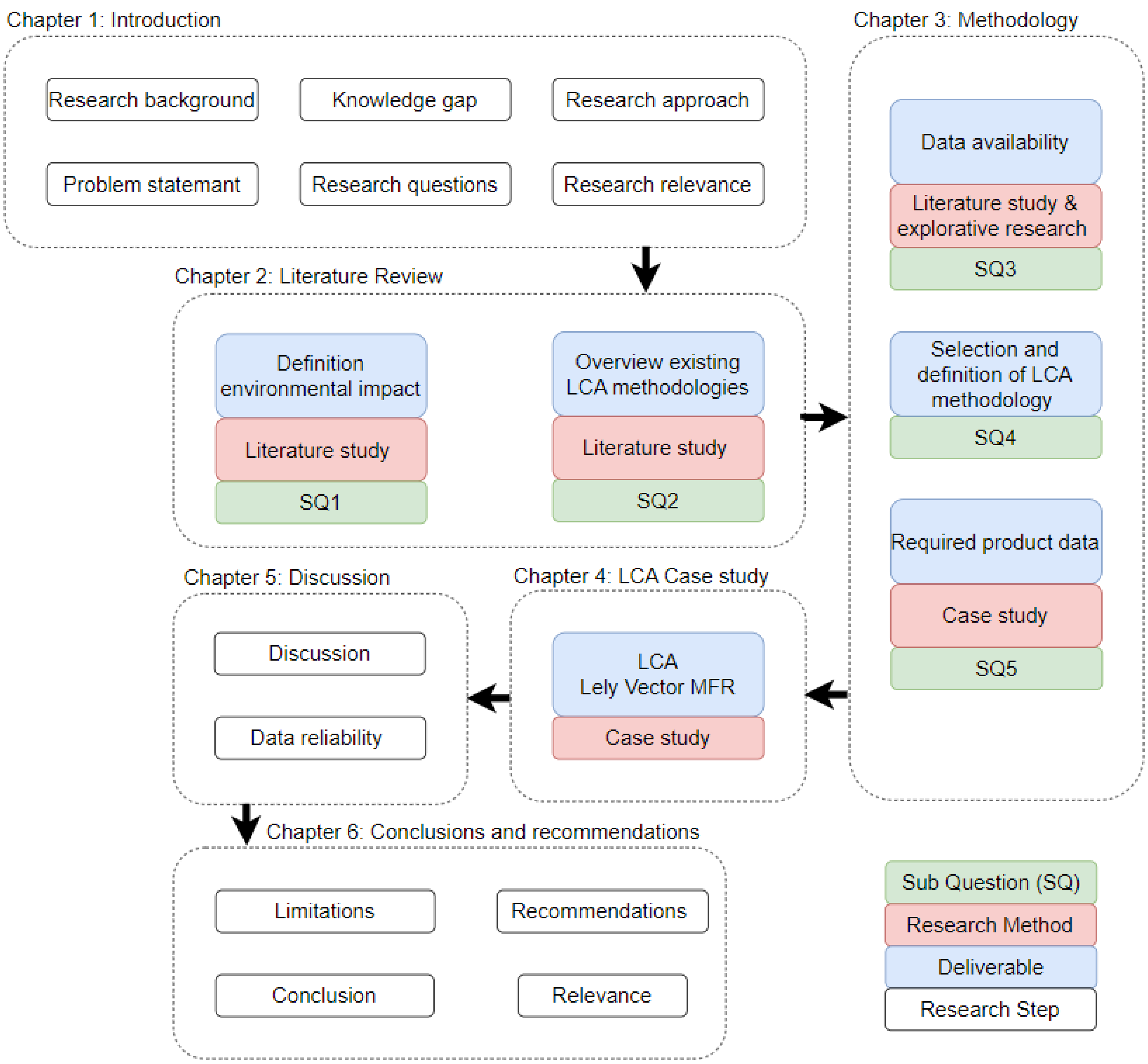



**Figure 3: Research flow diagram.**

### 1.5.1 Literature Review

The first part of the research is the literature review that investigates existing literature on LCA methodologies and aims to further specify the definition of environmental impact. This section focusses on sub questions 1 and 2. The aim of the literature is to identify existing knowledge and gaps in existing knowledge (Jill Jesson, 2011). Section 2.1 provides a description of the design of the literature review including search and evaluation criteria. The approach of the literature review includes the selection of data sources, search criteria, evaluation of literature and documentation (Uma Sekaran, 2016). The documentation of findings makes use of Mendeley software and a diagram from the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) (Page, 2021). An overview of the results is provided in Section 2.2 which serves as input for the rest of the research.

### 1.5.2 Methodology

This part of the research explains which methodology that is used to assess the environmental impact of the livestock feeding robot. It builds upon the results of the literature review to select a specific LCA methodology based on availability of product data, availability of environmental impact databases, availability of LCA software and available time. This section aims to answer sub question 3, 4 and 5.

### 1.5.3 Case Study

The case study aims to measure the environmental impact of a livestock feeding robot. This part of the research consists of a single case study design based on quantitative data in the form of product data and an environmental impact database. A single case study design means that the study will only focus on a single unit of analysis, which means the case study will include one product provided by a certain firm. The required product data will be gathered from the archives of the firm. This data collection method is observational, so there are no measurements made (Uma Sekaran, 2016). Baxter (2008) states that a case study design should be taken into consideration when the goal of the study is to provide 'how' and 'why' answers. Therefore, the case study research design is selected because this study investigates how the LCA measures the environmental impact of the MFR. The type of case study is explorative as it is used to investigate circumstances where the intervention being assessed does not have a clear of results (P. Baxter, 2008).

# 1.6 Research Relevance

This section describes the potential relevance of this research to scientific and societal knowledge. Additionally, explaining how various stakeholders of this project, including Delft University of Technology (TU Delft) and firms can potentially benefit from the results.

## 1.6.1 Scientific Relevance

Research about how LCA measures the environmental impact of livestock feeding robots holds scientific relevance. Consider that agriculture contributes to environmental impact, investigating this impact can fuel the transition towards sustainable agriculture. Additionally, this research can allow for comparison of environmental impact between conventional livestock feeding or new models of feeding robots. Furthermore, measuring environmental impact using LCA can identify potential improvements in the life cycle of the robot, eventually contributing to more sustainable driven decision making and advancements to minimize the environmental footprint.

## 1.6.2 Relevance for Delft University of Technology

One of the stakeholders of this research project is the TU Delft. More specifically the Management of Technology (MOT) program of the Technology, Policy, and Management faculty. The research project is relevant for the academic stakeholder because it contributes to scientific knowledge by identifying and filling a knowledge gap. As stated, the knowledge gap regards an environmental sustainability measurement of livestock feeding robot life cycle. Tackling this knowledge gap is relevant because the transition to sustainability is difficult due to a lack of knowledge about the measurement of environmental impact on products throughout their lifecycle. Additionally, the work aims to understand how firms can contribute to improve their sustainability performance with the use of a scientific study, including a LCA case study. The measurement of environmental impact of a product life cycle with the use of a LCA methodology provides input for actionable insights, such as changes to the product design. Furthermore, the research is executed in a technological context due to the inclusion of advanced technological product in the form of a livestock feeding robot. In conclusion, this research contributes to enriching the research field regarding the measurement of environmental sustainability of products life cycle. Furthermore, advancing the LCA methodology by applying to a livestock feeding robot. A product that has not been assessed by an LCA methodology before.

### 1.6.3 Relevance for Firms

The relevance of the research for firms is provided by gaining insight to the process of measuring the environmental impact of a product life cycle. This research is in line with the ambition of firms for sustainability and can provide relevant knowledge on how meet tightening regulations regarding environmental impact as well as maintaining their competitive advantage. Firms can maintain their license to operate by investing in sustainability. Subsequently, firms can offer more sustainable product to clients.

## 1.7 Thesis Outline

After the introduction, the rest of this document describes the other chapters regarding the thesis research. Chapter 2 presents a literature review on the variety of LCA methodologies that can be found in scientific literature. Additionally, explaining key concepts linking to LCA, such as impact categories and the International Standardization Organization (ISO) standard. The following Chapter 3 describes which LCA methodology is used for the case study about a livestock feeding robot and why. Chapter 4 contains the case study, including the goal, scope, functional unit, system, system boundaries, input quantification, excel calculations, results, and interpretation. A discussion of the results if provided in Chapter 5. Lastly, Chapter 6 presents the conclusion which answers the research questions and provides recommendations for future research.

# 2

# Literature Review

*An exploratory literature review that was previously conducted during the development of this research, showed that Life Cycle Assessment (LCA) is a widely described subject in scientific literature. Furthermore, revealing that there are a variety of different LCA methodologies. Therefore, this literature review aims to identify the existing literature regarding LCA methodologies and gain insight in the difference between them. But also, to gain more in-depth information on how LCA is used to assess environmental impact. The results of this literature review must provide sufficient information to select an LCA method for the case study.*

## 2.1 Methodology

The literature review consists of 3 steps. First, the design of the literature review, including the selection of search engines and relevant key words. Second, the evaluation of findings. This step investigates which source is considered relevant for the research and which source is discarded. The last step is to document the findings and describe the relevant content of these findings in more detail (Snyder, 2019). Additionally, the methodology and documentation of the literature review is partly based on the PRISMA model for reporting systematic review (Page, 2021). Furthermore, documenting and managing findings are done with the use of a reference management software called Mendeley. All three steps of the literature review are described below.

### 2.1.1 Search

The review started with the selection of search engines. SpringerLink, Google Scholar, and Scopus are academic search engines that have been selected for this literature review. First, SpringerLink is a database of scientific literature published by Springer Nature. It provides access to journals, books, reference works, and articles of high-quality and peer-reviewed research. Second, Google Scholar is a search engine that provides academic content from various sources, including journal articles, conference papers and theses. It provides a wide range and variety of scientific literature. Consider that Google Scholar can also return results from SpringerLink and Scopus. Third, Scopus is also a database that provides peer-reviewed literature, including journal articles, conference papers, books, and book chapters. Scopus is selected for this literature review because it covers a wide range of academic content from various disciplines and provides advanced search options that allows for classification by keywords and topic areas.

Other search engines like Journal Storage (JSTOR), ScienceDirect, Web of Science and Clarivate Journal Citation Reports are excluded from this literature review, because the findings from the other search engines already provided sufficient knowledge. Additional search engines would lead to more results without an increase in new knowledge. After selecting the search engines, the literature review continuous with selecting multiple sets of keywords. The first set aimed to investigate LCA methodologies as a tool to measure environmental impact and is displayed in Table 1.

| Set 1 | | |
|---|---|---|
| **Goal** | **Keywords** | **Search Engine (+hits)** |
| **Identify variants of LCA methodologies.** | (LCA OR Life Cycle Assessment) AND Measuring Sustainability | SpringerLink (63.427)<br>Google Scholar (1.470.000)<br>Scopus (220) |
| **Set 1 Follow up #1** | ISO AND LCA | SpringerLink (9.817)<br>Google Scholar (132.00)<br>Scopus (1440) |

**Table 1: Keywords for literature review set 1.**

A second set of keywords strives to investigate more information on environmental impact and the link between LCA and circularity. Set 2 is presented in Table 2.

| Set 2 | | |
|---|---|---|
| **Goal** | **Keywords** | **Search Engine (+hits)** |
| **Identify environmental impact.** | LCA AND (Environmental Impact Assessment OR Environmental Impact) | SpringerLink (17.771)<br>Google Scholar (362.000)<br>Scopus (19245) |
| **Set 2 Follow up #1** | “GHG protocol” AND LCA | SpringerLink (1799)<br>Google Scholar (4390)<br>Scopus (66) |
| **Set 2 Follow up #2** | (Circular Measurement OR Measuring circularity) AND LCA | SpringerLink (787)<br>Google Scholar (4860)<br>Scopus (21) |

**Table 2: Keywords for literature review set 2.**

A third and last set of keywords used in the literature review focusses on case study specific aspects. The main goal is to identify if there are existing studies about using LCA to measure the environmental impact of livestock feeding robotics. Set 3 is displayed in Table 3.

| **Set 3** | | |
|---|---|---|
| **Goal** | Keywords | Search Engine (+hits) |
| **Identify case specific literature.** | LCA AND (Robots OR Robotics) | SpringerLink (2322)<br>Google Scholar (12500)<br>Scopus (328) |
| **Set 3 Follow up #1** | LCA AND (Robots OR Robotics) AND (Agriculture OR Livestock) | SpringerLink (919)<br>Google Scholar (2780)<br>Scopus (132) |
| **Set 3 Follow up #2** | LCA AND Livestock AND (“Automated Feeding Robot” OR “Automated Feeding Robotics”) | SpringerLink (252)<br>Google Scholar (0)<br>Scopus (0) |

**Table 3: Keywords for literature review set 3.**

The process of executing the literature review also involved snowballing. This term is used to describe the technique of expending the search by examining citations in the findings. There are two types of snowballing: forward and backward snowballing. Backward snowballing involves looking at the reference list of the finding to identify other relevant findings, whereas forward snowballing involves looking at the findings that have cited the original finding. The use of snowballing is displayed; however, some relevant findings are included in this research.

### 2.1.2 Evaluation

The findings of the literature review have been evaluated to determine whether they must be included in the research. This is done based on the evaluation criteria of: publication date, type of source, language, and relevance of the content, as presented in Table 4. The relevance of the content was based on personal evaluation of the title, abstract and conclusion. If the title of a findings seemed relevant, then I would decide to read the abstract and conclusion. Based on the relevance of the findings to the research questions they were included or excluded from the research.

The number of findings in the order of millions in some cases. For example, the first set of keywords in combination with the search engine Google Scholar resulted in 1.4 million hits. It was not doable to evaluate all the findings. I alternatively started selecting and evaluating findings until I noticed a repetitive pattern in themes, concepts, definitions, and methodologies. This pattern started to emerge in the range between evaluating 10 to 40 findings. For example, the concept of Life Cycle Inventory (LCI) was common on the findings, each time providing the same definition and description. Another example was the definition of the life cycle definition. Multiple sources provided the same information regarding the life cycle of products.

| **Evaluation criteria** | |
|---|---|
| **Date** | 2000-2023 |
| **Type of source** | Books, scientific articles, journals, scientific magazines, case studies and reference work. |
| **Language** | English |
| **Relevance of the content** | Personal evaluation based on the title, abstract and conclusion. |

**Table 4: Evaluation criteria for literature review results.**

## 2.2 Results

To summarize the findings of the literature review, there are several different LCA methodologies described in existing literature. The variation between the methodologies mainly comes from differences in the definition of goal and scope, including the selection of impact categories and single indicators. In other words, what is the unit of analysis and what is the scope of the entity being analyzed. For example, a LCA methodology is defined by measuring the $CO_2$ emissions of the production activities of an organization. Additionally, the findings of the literature review shows that environmental impact is expressed in sets of impact categories. Furthermore, impact categories are often reduced to single indicators for usability. Carbon Footprint (CF) is a single indicator based the combination of many greenhouse gas (GHG) emissions. The most common GHG emissions are Methane ($CH_4$), Nitrous oxide ($N_2O$) and Fluorinated gases. Besides CF another relevant single indicator is Eco-costs, this indicator represents the cost of an environmental burden based on the required mitigation of that burden in order to reduce the environmental impact to a sustainable level. CF is useful for this study because it quantifies environmental impact. Additionally, CF is useful due to the compatibility with scientific research, policy regulations, and marketing content. Also, the measurement of CF can enable firms to gain a position in the voluntary market for carbon credits. The Eco-costs indicator is selected for this study because it provides understanding of the monetary value of investments to achieve sustainability. Expressing environmental impact in Eco-costs contributes to understandable input for decisions and actions for sustainability.

Findings show that all the different LCA methodologies deviate from the International Standardization Organization (ISO) 14040 standard. This standard defines the LCA structure follows the steps of: Goals and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation. The LCI consists of the sum of all inputs (materials or energy) and outputs (environmental impact). The LCIA combines the LCI database with data regarding the studied entity to calculate the environmental impact that is expressed in one or multiple indicators.

The findings of the literature review are illustrated in Appendix A, B and C with the use of a flowchart based on the PRISMA model. Furthermore, a description of the relevant findings is provided in Section 2.2.4. Starting with an explanation of the general LCA standard as described in the literature. But also including more in-depth information on the LCA methodology like scope definition, LCI, impact categories and single point indicators. Following up on the general LCA description is the result of the literature study that shows the different LCA methodologies as described in existing literature. A finding that cannot go unnoticed is that which results from search criteria set 3 because the result shows no research was found on environmental impact assessment of livestock feeding robots. Hereby identifying a knowledge gap.

### 2.2.1 General LCA Standard

This section describes the relevant findings from the literature review. The findings provide an explanation of the LCA methodology as defined by the International Standardization Organization (ISO) standard. Furthermore, this section describes each step of the ISO defined LCA methodology and elaborates on each step. A typical Life Cycle Assessment regards the assessment of products from their raw materials source up to the moment of disposal, as presented in Figure 4.

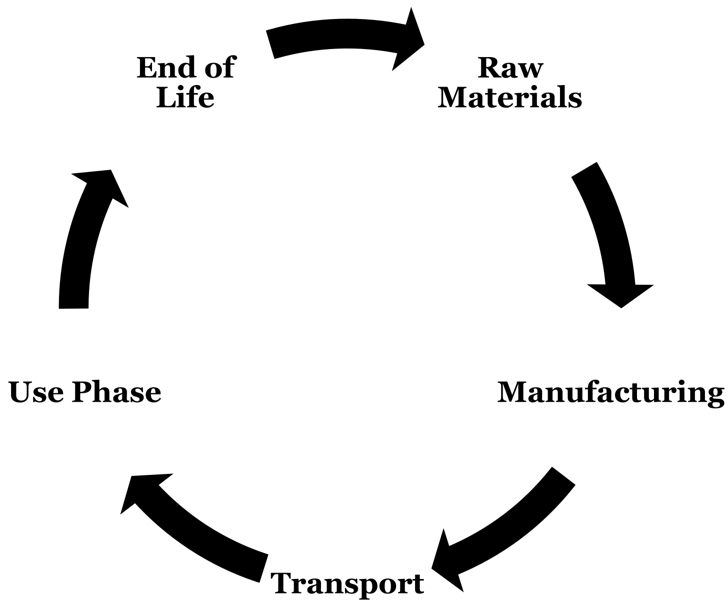



**Figure 4: Typical life cycle of a product.**

The results of the literature review show that all the different LCA methodologies deviate from the general and holistic ISO standard. LCA, as governed by the ISO standards 14040 and 14044. Since 2006 LCA has become a recognized instrument to measure the environmental impact of the life cycle of products, processes, and services. The measurement of environmental impact increasingly being used since the year 2000 in the application and implementation of decision making (Klöpffer, 2014). A significant amount of LCA variants is derived from the ISO standard in the last decade. In more recent times, various advancements and trends drove the development of unique types of LCA. One trend is toward simplification, to improve applicability of the results. The other is toward sophistication, to improve the accuracy of the results. On the side of simplification, the term "Footprint" began to surface (Finkbeiner, Special Types of Life Cycle Assessment, 2016). The market spread of the LCA methodology was significantly assisted by the consideration of Carbon Footprints. Discussions surrounding the Carbon Footprint (CF) has resulted in the increasement of different standards and guidelines, such as ISO 14067 on the CF of products (International Organization for Standardization, 2018), the GHG Protocol Product Life Cycle Accounting and Reporting Standard made by the World Business Council for Sustainable Development (WBCSD) and the World Resources Institute (WRI) (Bhatia, et al., 2011).

The structure of LCA, as defined by the International Standardization Organization (ISO) 14040 series, consists of the four phases: Goals and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation (International Organization for Standardization, 2006). The next paragraphs describe the phases of LCA and relevant additional findings.

### *2.2.2.1 Goals and Scope Definition*

The first step in LCA, as defined by ISO 14040, is to determine the goal and scope of the analysis. A goal definition states the motive, intended application, and intended audience. Subsequently, defining the scope of the analysis includes a description of the product, functions of the product, functional unit (FU), system boundary, impact categories, data requirements, assumptions, and limitations (International Organization for Standardization, 2006). The system boundary, FU, and impact categories require an additional explanation which is provided below.

Starting with the system boundary. At its essence, how the study boundary is drawn defines where the analysis of a certain life cycle begins and where it ends. The difference in defining the life cycle boundaries is directly linked to the variety of different LCA methodologies (Curran, 2017). Some well-known terms associated with the boundaries in life cycle related studies are Cradle-to-cradle, Cradle-to-Grave, Gate-to-Gate, Cradle-to-Gate and Cradle-to-Site as displayed in Figure 5. But also, the delineation of upstream and downstream emissions related to the greenhouse gas (GHG) scope 1, scope 2 and scope 3 emissions are based on the variable definition of life cycle boundaries (Bhatia, et al., 2011).

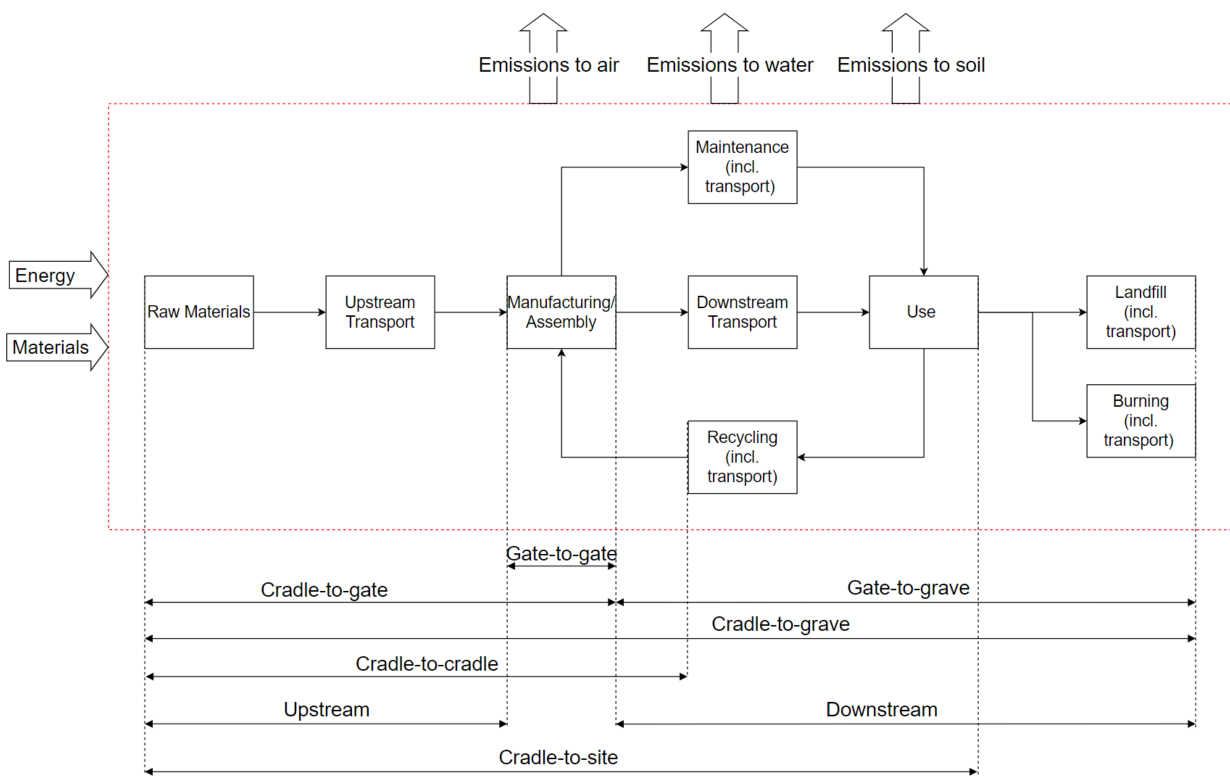



**Figure 5: Different life cycle scopes**

Second important part of LCA that need clarification is the functional unit (FU). It serves as the basis for LCA studies. A FU is a quantified description of a product, process, or service. The FU also referred to as the unit of measurement. With a FU it is possible to compare different products, processes or services that have the same functionality (Curran, 2017). An example of a FU for a garbage truck: collected garbage in kg per year.

### *2.2.2.2 Life Cycle Inventory*

The second step and core of every LCA study is the LCI. It is also regarded as the component that is the most scientific and quantitative. The inventory consists of the sum of all inputs (materials or energy) and outputs (environmental impact). LCI is a database with primary or secondary data that provides an average on the environmental impact of materials and processes (Andreas Ciroth & Rickard Arvidsson, 2021). For example, 1 piece of A4 paper costs 5.1 liters of water to produce (F. Schyns, J. Booij, & Y. Hoekstra, 2022). Water usage is only 1 environmental impact category but there are many more which are defined in Section 2.2.2.3.

Primary data is directly measured data while secondary data is already collected and indirectly measured. The primary data often comes in the form of datasets as a result of a specific study on a product or process focusing on a set of impact categories. LCI databases provide an average environmental impact based on a big collection of datasets. These datasets are generated with extensive research by universities, research institutes, commercial firms, and governmental institutions. There are commercial and academic LCI databases. Some examples of commercial LCIs are Ecoinvent, Industrial Design & Engineering Materials (IDEMAT), GaBi and Nationale Milieu Database (NL) (Jolliet, Saade-Sbeih, Shaked, Jolliet, & Crettaz, 2016) ; (Andreas Ciroth & Rickard Arvidsson, 2021). The academic LCI databases are often free, like IDEMAT provided by the Sustainable Impact Metrics Foundation (SIMF), a non-profit spin-off of the TU Delft (Vogtländer J. , 2017) (Stichting Sustainability Impact Metrics, 2023).

### *2.2.2.3 Life Cycle Impact Assessment*

ISO 14040 states the third phase of an LCA consists of the LCIA. This phase aims to combine the LCI with the product data to determine the environmental impact. However, the LCIA phase also provides the calculation of impact indicators.

The LCI provides environmental impact indicators, also known as elementary flows or pollutants, for materials or processes. For example, 1 kg of steel produced in Europe comes with an x amount of kg CO2 emission. A complete list of all the different impact indicators is shown in Appendix D from the Ecoinvent v3.6 Cut-Off (Ecoinvent, 2023). But, the list of environmental impact indicators can be lengthy, and all the different indicators result in a complex decision-making process. This list of different indicators can be reduced to a single indicator so that the results are simpler to interpretate (Hauschild & Huijbregts, Life Cycle Impact Assessment, 2015). Furthermore, multiple impact indicators can be assigned to impact categories. For example, $CO_2$ and Nitrogen emissions both fall in the impact category of climate change. Additionally, there are several impact assessment methods such as IPCC 2021, EF v3.1 or ReCiPe. However, the road to a single indicator generally follows the following steps (Vogtländer J. , 2017).

1. Select impact categories (climate change), single indicators (Carbon Footprint) and characterization models. Selecting impact categories must be in line with the goal that is formulated in the goal and scope definition of the LCA.
2. Classification = Assigning pollutants (impact indicators) to an impact category, also known as midpoint indicators. ($CO_2$ assigned to Climate change)
3. Characterization = Calculating equivalent emissions per type of impact category by calculating the relative impact of each emission. (Climate change impact in $CO_2$ eq equivalents)
4. Normalization = Calculating the magnitude of a category indicator relative to a reference. (Climate change in Europe)
5. Weighting = Adding weight to category indicators based on a panel of experts.

Essentially, the single indicators can be divided into three groups: (1) single issue; (2) damage based; (3) prevention based (Vogtländer J. , 2017). First, the best-known single-issue indicator is CF (unit=kg $CO_2$ equivalent). CF serves as an umbrella term for different kind of GHG emissions, including carbon dioxide ($CO_2$), Methane ($CH_4$), Nitrous oxide ($N_2O$), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), Sulfur hexafluoride ($SF_6$), Nitrogen trifluoride ($NF_3$) (Jha, Soren, & Mehta, 2021). All the different GHG emissions are calculated to $CO_2$ equivalents to the CF indicator.

Second, the damage based single indicator is expressed in points, for example ReCiPe (unit=points). The ReCiPe 2016 indicator and underlaying impact categories is provided in Appendix E. Damage based single indicators are designed to show the environmental impact of production and consumption. However, the calculations are based on complex assumptions, not transparent, and do not have a subjective weighting procedure at the end (Vogtländer J. , 2017).

Third, prevention-based indicators are relatively new compared to other single indicators. The results of prevention-based indicators can be monetized. A good example is the is Eco-costs which is expressed in euros. This single indicator is designed to be used in the decision-making processes as it is relatively easy to calculate and understand. The Eco-costs single indicator method for monetarization of environmental impact follows the framework as defined by the standard ISO14008 (International Organisation for Standardizaton, 2019). This ISO standard is specifically designed for the monetary valuation of environmental impacts. Eco-costs, represent the cost of an environmental burden based on the required mitigation of that burden in order to reduce the environmental impact to a sustainable level (Vogtländer & Bijma, 2000). Vogtländer provides the following example to explain the concept of Eco-costs. The Eco-costs of 1000kg CO2 are 123 euro. Therefore, for each 1000kg CO2 emission one must invest 123 euro in clean energy production, like offshore windmill parks. A more detailed illustration on the concept Eco-costs is provided in Appendix F.

#### *2.2.2.4 Interpretation*

The interpretation phase is the last in the LCA standard as defined by ISO 14044. This phase presents results and identifies issues during the execution of the LCA. Additionally, making use of completeness, sensitivity, and consistency of the analysis (International Organization for Standardization, 2006).

### 2.2.2 LCA Methodologies

The second part of the literature review focusses on existing LCA methodologies in the literature. These existing LCA methodologies are all based on the same ISO standard, but certain definitions deviations from the standard became so common that separate naming was applied over time. Appendix G provides an overview of the different LCA methodologies as described in existing literature.

# 3

# Methodology

*Chapter 3 describes the process of selecting the Life Cycle Assessment (LCA) methodology for the case study. The selection of this LCA methodology was based on existing LCA methodologies, availability of product data, availability of environmental impact databases, compatibility with the case study, and project duration. Eventually settling upon the Fast Track LCA methodology by J. Vogtländer. This LCA uses a database called Industrial Design & Engineering Materials (IDEMAT) that is provided by Sustainable Impact Metrics Foundation (SIMF), a non-profit spin-off of the TU Delft.*

As stated earlier, data availability is an important indicator for selecting an LCA methodology for the case study. Data that is required for the LCA can be divided in product data and environmental impact data. First, the product that is being analyzed for this research is a livestock feeding robot. Relevant data regarding the product will be gathered from company archives. More detailed information regarding the product and company are provided in Chapter 4. Second, data regarding environmental impact can be found in databases. The Ecoinvent and Simapro databases required licensing, meanwhile IDEMAT is accessible without licensing. Additionally, Dr. Ir. J.G. Vogtländer explains that the IDEMAT database is calculated based on the Simapro database and therefore of the same level of quality. Furthermore, IDEMAT is more adept in product design and engineering, while Ecoinvent has more data on chemicals and chemical processes. Also, the environmental impact inventory of electricity by IDEMAT is more up to date than Ecoinvent (Stichting Sustainability Impact Metrics, 2023).

Besides the data availability there are also case study specific factors that weigh in on the LCA selection process. The first case study specific factor is the project duration of the case study, which influences the level of detail that can be achieved with the LCA. Second, the goal and scope of the case study. Differences between LCA methodologies, as described in literature, are mainly based on a variation of goal and scope definition. For instance, the goal of O-LCA is to assess the environmental impact of an organization while the goal of Product Environmental Footprint (PEF) is to assess the environmental impact of a product. Furthermore, Carbon Footprint (CF) is a type of LCA that limits the goal to one environmental impact category, namely $CO_2$ emissions. Meanwhile, the goal of LCSA includes multiple impact categories, even including the economic and social dimension. Additionally, the scope is used to define the life cycle for the study. Some LCA studies look at the full Cradle-to-Cradle life cycle while others define a shorter Cradle-to-Grave life cycle for example. These examples show that the goal and scope are important for choosing an LCA methodology.

Thus, the LCA methodology selection is based on project duration, goal, and scope of the case study. Looking at the case study, it is characterized by the following criteria. First, the study focusses on a product, not an organization or service. Second, the scope of the study is Cradle-to-Grave. This scope includes the life cycle phases of Manufacturing-Materials, Upstream Transport, Manufacturing, Downstream Transport, Use-phase, and End-of-life. This scope definition was selected to ensure a comprehensive view on the complete life cycle. Additionally, if the case study shows that data is unavailable then this would also be regarded as a value finding because it identifies possible improvements. Third, the execution time of the project is 3 months because it is part of a master thesis. Lastly, the study aims to measure environmental impact and not the social or economic dimension of sustainability.

In conclusion, the Fast Track LCA is selected for the case study because of the following reasons. First, the Fast Track LCA is designed to assess products. Second, the Fast Track LCA is compatible with the defined product life cycle scope, namely Cradle-to-Grave. Third, a standard LCA takes a lot of effort and money, at least months but sometimes up to years. But when the necessary input data are present, the Fast Track LCA only needs a couple of hours or a few days. Therefore, the Fast Track LCA fits the project duration of 3 months. Additionally, the accuracy of a Fast Track LCA is equal to or greater than that of a standard LCA. Fourth, the Fast Track LCA is used to measure the environmental impact which is in line with the goal of this research. Lastly, the Fast track LCA is compatible with the free IDEMAT database. Section 3.1 describes the Fast Track LCA in more detail.

The selection of the Fast Track LCA accompanies the exclusion of several other LCA methodologies. Appendix H provides an overview of the different LCA methodologies and if they are compatible with the selection criteria. Assessment based on the first criteria resulted in the exclusion of the Organizational LCA (OLCA), Organizational Environmental Footprint (OEF), Input Output-LCA (IO-LCA), Hybrid LCA, Life Cycle Management (LCM) and Resource Efficiency Assessment (REA) because they are not compatible with the assessment of a product life cycle assessment. Second, LCA methodologies are compatible with the Cradle-to-Grave scope except for the Life Cycle Impact Assessment (LCIA). Third, assessing if an LCA methodology is executable within a period of 3 months is difficult to determine, it depends on the goal and scope of the study. But the duration of an LCA study is mostly influenced by the inclusion of life cycle inventories. Fourth, the Consequential LCA (CLCA), LCM, Life Cycle Costing (LCC), Social LCA (SLCA), Eco-efficiency Assessment (EEA) and REA are excluded because they are not compatible with the assessment of environmental impact. Last, CLCA, IO-LCA, Hybrid LCA, MFA, Attributional LCA (ALCA), LCM, LCC, SLCA, LCIA, LCI, EEA and REA are not compatible with the IDEMAT database and therefore excluded. Only the Fast Track LCA, Product Environmental Footprint (PEF) and Environmental Footprint (EF) are compatible with all the different selection criteria. These 3 methodologies for assessing environmental impact are closely linked to each other. The Fast Track LCA falls under the PEF methodology, in turn the PEF falls under the EF methodology. Fast Track LCA is ultimately chosen for this study since it is the most specific.

## 3.1 Fast Track Life Cycle Assessment

The Fast Track LCA has been introduced by the TU Delft. However, Philips Electronics was the first to execute an LCA study in this way in 1998. Therefore, Fast Track LCA is also referred to as the "Philips Method". Fast Track is a practical and time saving approach compared to more classic and formal LCA methodologies, due to the fact that the Fast Track LCA excludes the process of making a Life Cycle Inventory (LCI) database and excludes the calculation process of single indicators. Instead, Fast Track builds on an existing LCI database, namely Industrial Design & Engineering Materials (IDEMAT), and uses predefined single indicator factors. These single indicators are Carbon Footprint (CF) (kg $CO_2$ equivalent), Eco-costs (euro), ReCiPe (points), Cumulative Energy Demand (CED) in Mega Joule (MJ) and EF (points). The Fast Track LCA uses excel lookup tables to multiply the input (materials or energy) and outputs (environmental impact) with factors to calculate single indicators. These factors are calculated with the use of Simapro LCA software and based on data from the Ecoinvent database (Vogtländer J. , 2017). The Fast Track LCA hereby excludes the need for the researcher to execute the single indicator calculation the steps, consisting of classification, characterization, normalization, and weighting. Vogtländer explains that the Fast Track LCA uses a single indicator as a starting point. Thus, before starting the Fast Track LCA study, a selection of single indicator must be made.

Considering the goal of the research is to measure environmental impact the CF single indicator is selected as a starting point for the case study. Furthermore, CF is the most common indicator in scientific research, policy, and marketing content. Also, the measurement of CF can enable firms to gain a position in the voluntary market for carbon credits. A carbon credit or offset is a transferable instrument to represent a reduction in emissions, expressed in $CO_2$ equivalents. Trading carbon credits can assist firms to achieve goals regarding greenhouse gas (GHG) emissions (Christopher Blaufelder, 2021).

The CF contains multiple emission categories expressed in kg $CO_2$ equivalent. However, the disadvantage of CF is that it excludes material depletion and therefore not suitable for Cradle-to-Cradle product life cycle. The CF single indicator in IDEMAT is calculated with Simapro software. Due to licensing of Simapro the calculations are not accessible.

The Eco-costs single indicator was also chosen for the case study in addition to CF because the prevention-based indicator provides understanding of the monetary value of sustainable alternatives which is interesting to firms. Considering the goal of firms is to become more sustainable while maintaining or improving competitive advantage is essential to also investigate the potential investments. Furthermore, the Eco-costs single indicator is easy to understand and provides valuable input for sustainable related decision making in firms which main goal is to make a profit. Eco-costs can be seen as hidden obligations to our society. The pollution issue is expected to be resolved when all businesses adopt preventive measures up to the level of the Eco-costs (Vogtlander, Eco-efficient Value Creation, 2023). Figure 6 provided by Vogtländer explains the trend towards sustainability will result in additional costs for the manufacturer. Costs that firms do not take responsibility for yet, but this is likely to change due to regulations. LCA studies can identify and measure these hidden costs so that firms can strategize accordingly. The challenge is to market a ‘green image’ to increase the willingness to pay among customers. Thereby, being able to cover investments for sustainability or Eco-costs (Vogtlander, 2010).

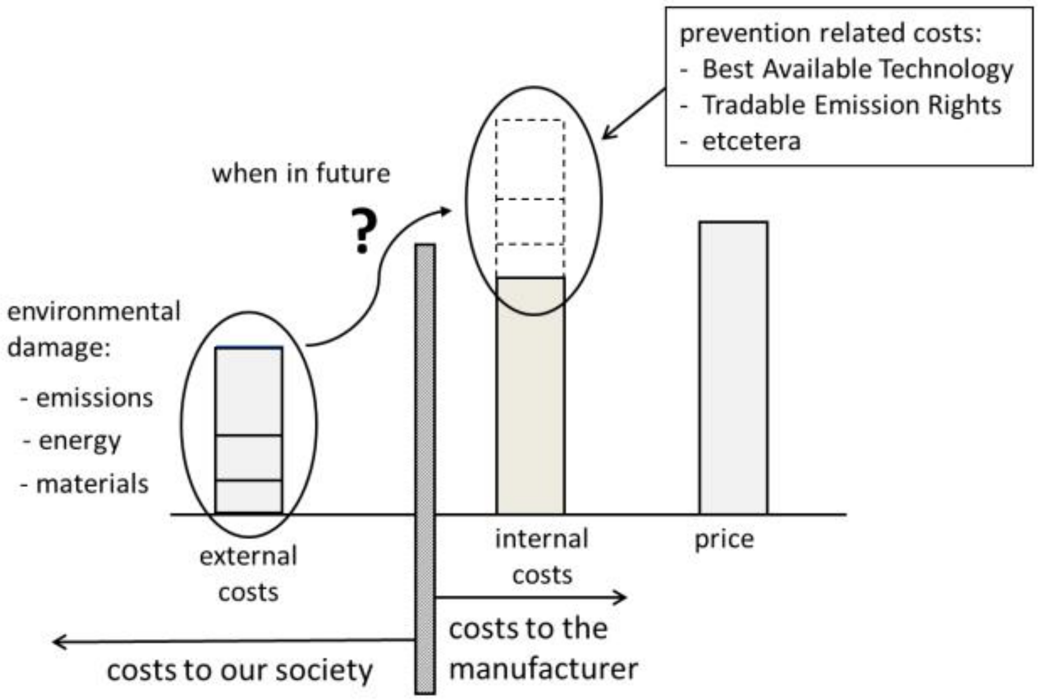



**Figure 6: Concept of Eco-costs (Vogtlander, 2010).**

Besides CF and Eco-costs there are other single indicators provided by Idemat. These other indicators, ReCiPe (points), CED (MJ) and EF (points), are excluded from the case study. First, the ReCiPe provides information on damage-based impact with the use of points. The purpose of damage-based single indicators is to display how production and consumption affect the environment. However, the calculations lack transparency, are based on complex assumptions, and do not include a subjective weighting process. Therefore, the ReCipe single indicator is excluded from the case study. Second, the CED provides information about the required energy demand. This indicator is excluded because it does not provide information on the environmental impact. For example, a high energy demand can be met with sustainable energy production which would limit environmental impact. Third, the EF provides information on environmental footprint in points. This indicator is excluded because points do not provide insight how potential improvement influence certain impact categories. For example, changing the design from steel to plastic would result in a lower number of EF points. However, the indicator does not show is this reduction in due to lower $CO_2$ emissions or lower resource depletion.

In summary, Fast Track LCA is the most suitable LCA methodology for measuring the environmental impact of a livestock feeding robot. The goal of the case study is to measure the CF of a livestock feeding robot with the scope of a Gradle-to-Grave life cycle. In addition, Eco-costs are calculated to enhance the ability to improve on the status quo. The required data is provided by the IDEMAT database and company archives. Chapter 4 describes the case study while following the Fast Track methodology.

The Fast Track LCA defines a step-by-step plan which overlaps with the International Standardization Organization (ISO) 14040 standard. Consisting of:

- Step 1: Goal and Scope Definition.
- Step 2: Functional unit, System and System Boundaries.
- Step 3: Quantify materials, use of energy, etc.
- Step 4: Enter data and calculate.
- Step 5: Interpretation of results.

# 4

# Life Cycle Assessment Case Study: Lely Vector Mixing and Feeding Robot

*This chapter describes a case study about a livestock feeding robot by Lely International N.V. called: Lely Vector Mixing & Feeding Robot (Lely Vector MFR). Before the case study, this chapter first provides detailed information regarding the Lely and the Lely Vector MFR. The case study makes use of the Fast Track Life Cycle Assessment methodology in combination with the Industrial Design & Engineering Materials (IDEMAT) database. Furthermore, this chapter describes the process of collecting product data and the development of assumptions to partly account for incomplete, inaccurate, and non-compatible data. At last, the results of the case study are presented.*

## 4.1 Lely International N.V.

Lely is an organization that believes in a future of sustainable farming with the use of innovative robots and smart data systems. Like many other organizations, Lely is aiming to be more sustainable by lowering environmental impact of their business activities and products. Lely strives for sustainability to meet future regulations and maintain their competitive advantage, as well as maintain their license to operate in the market. This ambition for sustainability is underpinned by their vision: "A sustainable, profitable, and enjoyable future in farming". Lely has put more emphasis on sustainability since 2020 with the launch of their sustainability program that focusses on scope 1 and scope 2 emissions. Scope 1 emissions refer to direct emissions from sources that are owned or controlled by the organization. Scope 2 emissions refer to indirect emissions from the consumption of purchased electricity, heat, or steam, which are generated outside of the organization (Greenhouse Gas Protocol, 2013). Furthermore, Lely is one of the leadings manufacturers of autonomous feeding robots for the livestock sector with their robot named: Lely Vector Mixing & Feeding Robot (MFR). Structured research regarding the environmental impact of this robot is insufficiently present within Lely. Also, research on the sustainability of livestock feeding robots is missing in scientific literature.

## 4.2 Product Description

The Lely Vector MFR, also referred to as MFR, provides food for livestock cattle. A complete overview of the Lely Vector MFR system also includes the feed grabber. This grabber is displayed on Figure 7, it grabs food from the feed kitchen and loads it into the MFR. The feed kitchen is the location where feed is stored, chosen, picked up, and loaded into the robot for mixing. A crane structure with a feed grabber is put in the kitchen and moves above the workspace to the right block of feed. It is simple to store enough food for three days in the kitchen, depending on its width and depth.

The MFR is a self-contained battery-powered machine that can automatically feed a self-mixed diet. Research by Lely shows that compared to feeding with a tractor, the Lely Vector MFR saves around 4000 euros worth of gasoline on yearly basis and contributes to an increase of 1.8 kg milk production per cow per day (Lely, 2023). Additionally, the robot is designed for a lifetime of at least 10 years working 24/7. Altogether, the Lely Vector MFR is proposed as the sustainable alternative, but research is lacking to underpin this. A picture of the Lely Vector MFR (or MFR) in action is shown on Figure 7 and 8.


Figure 8: Lely Vector grabber and Mixing and Feeding Robot.


Figure 7: Lely Vector MFR feeding at the fence.

# 4.3 Step 1: Goal & Scope Definition

Goal and scope definition are customary parts according to the Fast Track LCA and the ISO14040 standard for LCA. The goal of the Fast Track LCA is to measure the environmental impact of the Lely Vector MFR. This LCA case study is targeted at Lely and the academic world in general. The single indicators that are selected for this case study are Carbon Footprint (CF) (kg $CO_2$ equivalent) and Eco-costs (euros).

# 4.4 Step 2: Functional Unit, System & System Boundaries

## 4.4.1 Functional Unit

The definition of the functional unit (FU) is based on the designed lifetime and function of the Lely Vector MFR. A FU unit is a quantified performance of a project, to be used as a reference unit. The FU should include a description of what (the function(s)/service(s) provided), how much (the extent of the function or service), how well (the expected level of quality) and how long (the duration/lifetime of the product). Therefore, the FU of the Lely Vector MFR is defined as follows:

FU = Feeding in reach of the cows for 10 years working 24/7.

## 4.4.2 System and System Boundaries

The scope, or system boundaries, defines the product life cycle of the case study. This case study includes all the life cycle phases of the Lely Vector MFR as shown in Figure 9, consisting of raw materials, transportation, manufacturing, use-phase, and end-of-life phase. This life cycle scope is also referred to as Cradle-to-Grave. However, some parts of the life cycle are excluded. The recycling part was initially part of the analysis but had to be discarded due to the lack of available data about it. Additionally, note that the upstream transport only consists of the data between the supplier and the manufacturing/assembly hall in Maassluis. However, there can be multiple processing plants between the mine and the supplier inventory. Gathering this data is excluded from the research because it is extremely difficult and time consuming due to number of actors in the supply chain.

In addition to the system boundaries, or scope, there is also the need for a geographical delineation because the origin of materials used for the robot and the final location of the robot influence the environmental impact. This impact mainly comes from transportation distance and location specific energy production. For example, the IDEMAT database defines that the production of 1 Mega Joule (MJ) electricity in China has a Carbon Footprint (CF) of 0.19 kg $CO_2$ equivalent while in France it is 0.02 kg $CO_2$ equivalent. The geographical delineation for this study is Europe. This delineation is made because the use-phase required a location specific energy production. By selecting the average energy production in Europe from the IDEMAT database the downstream transport had to be adjusted accordingly. Meaning, only including orders of clients located in Europe for the downstream transport dataset.

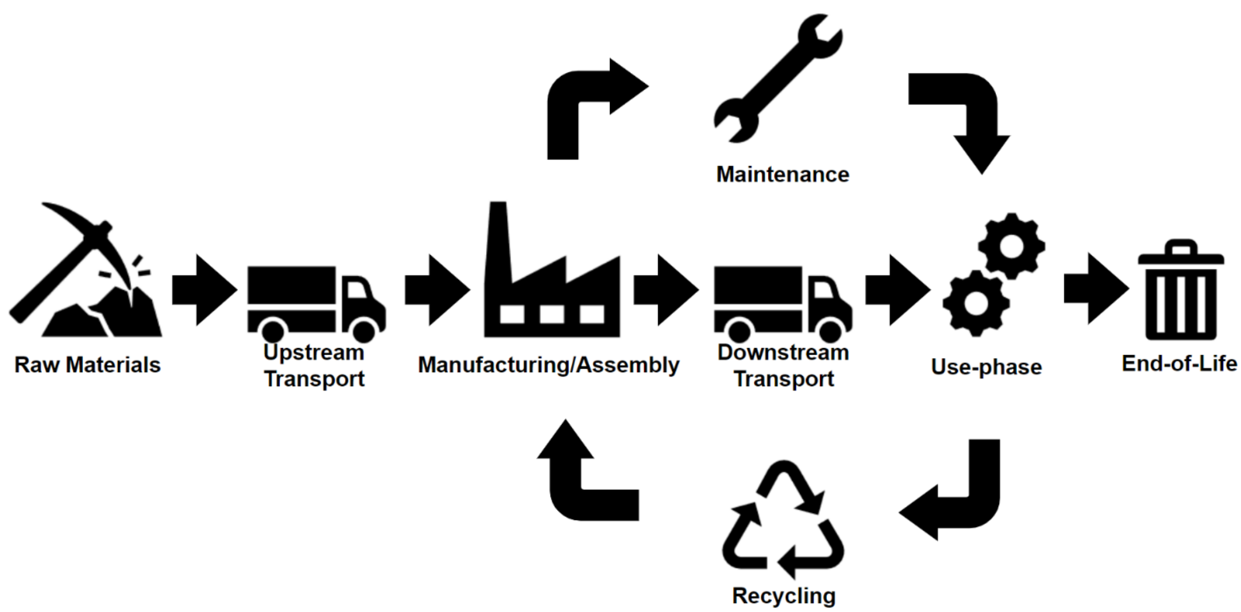



**Figure 9: The complete life cycle of the Lely Vector Mixing and Feeding Robot.**

## 4.5 Step 3: Input Quantification of Product Data

After the goal and scope definition the next step is to gather product life cycle data. Table 5 provides an overview of the different datasets, including the sources, that were used for each phase of the product life cycle. First, the bill of materials dataset is used for the materials life cycle phase and is provided by the product development department. Second, the Country of Origin dataset is used for the upstream transport life cycle phase and is provided by the purchasing department. Third, the energy consumption dataset is used for the manufacturing life cycle phase and is provided by the property management department. Fourth, the item & customer dataset is used for the downstream transport life cycle phase and is provided by the product management department. Fifth, the energy consumption dataset is used for the use-phase and is provided by the product management department. Sixth, the maintenance dataset is also used for the use-phase but provided by the technical service support department. Last, for the end-of-life phase of the life cycle there is no dataset available. All the datasets allow for a numerical significance of two numbers after the comma mark. Results from the dataset allow for a higher precision but this does not add value.

| Life cycle phase | Datasets | Sources |
|---|---|---|
| **Materials** | Bill of Materials (BOM) | Product Development Department |
| **Upstream transport** | Country of Origin | Purchasing Department |
| **Manufacturing** | Energy consumption hall 5 | Property Management Department |
| **Downstream transport** | Item & Customer Data | Product Management Department |
| **Use phase** | Energy consumption MFR | Product Management |
| | Maintenance | Technical Service Support (TSS) Department |
| **End of life** | N/A | N/A |

**Table 5: Overview of the collected datasets.**

Section 4.5.1 to Section 4.5.6 describes the process of data collection and developing assumptions. During the data collection process there were several issues identified in the form of missing, incorrect, and non-compatible data. An iteration on the gathered data partly solved the identified issues by developing assumptions. Thus, the LCA is executed twice. Once with data excluding assumptions and a second time with data including assumptions, meanwhile keeping the calculation methods consistent. The results from first LCA served as input for the second, as shown in Figure 9. Section 4.7.3 discusses both results and conclusions, as well as make comparisons between the two results.

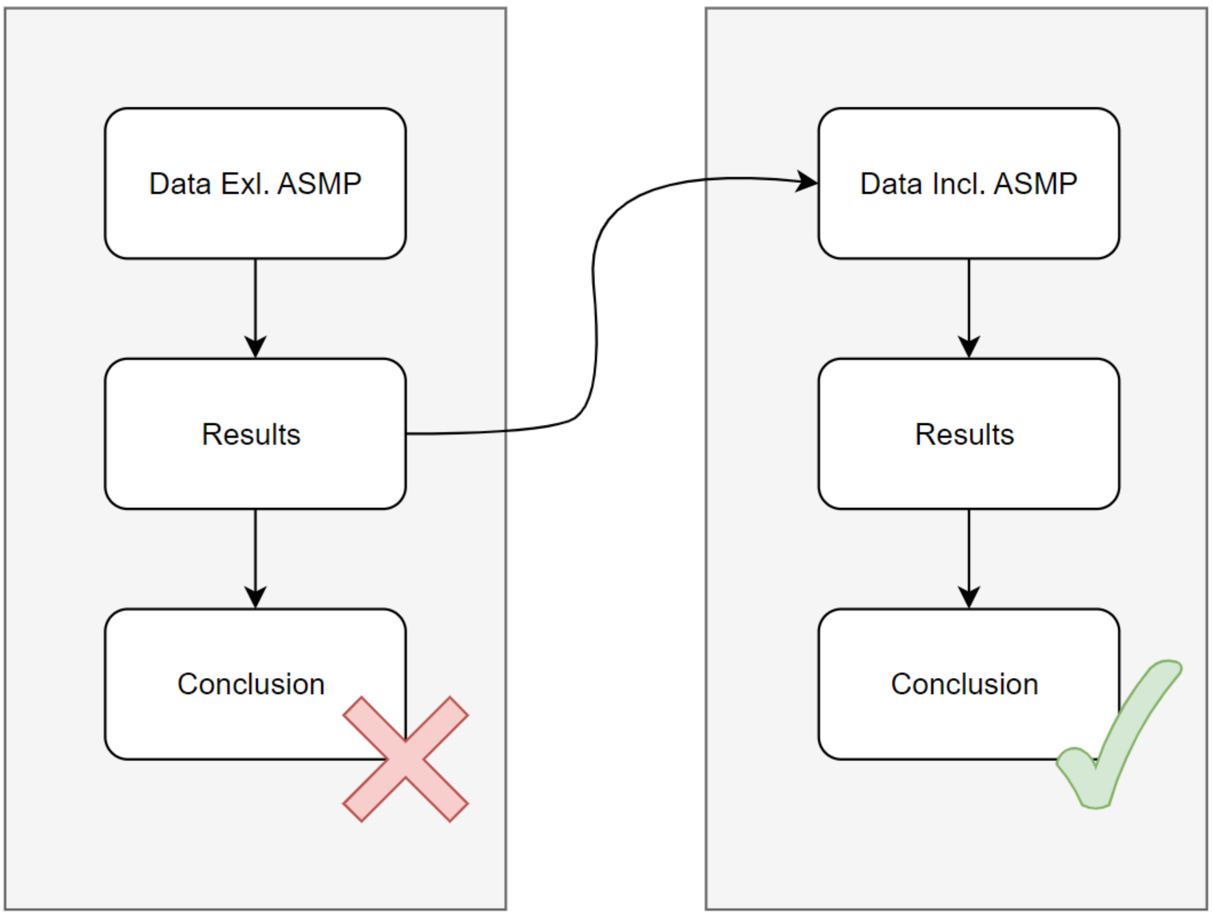



**Figure 9: Product data including and excluding assumptions.**

Table 6 presents an overview of the gathered data. Including a description and data quality evaluation it the Bill of Materials, Country of Origin, Energy consumption hall 5, Item & Customer, Energy consumption MFR and maintenance dataset. The data in Table 6 is named as "data excluding assumptions", which means that the data is unmodified.

| **Product data completeness** | | | |
|---|---|---|---|
| **Base line – excluding assumptions** | | | |
| **Life cycle phase** | **Dataset** | **Description** | **Data quality** |
| **Materials** | Bill of Materials (BOM) | The BOM dataset contains information about the parts, including part IDs, material, weight, quantity of parts. | The total defined weight in the BOM is 1413.96 kg. 74.8% of the total weight is assigned to a specific material. |
| **Upstream transport** | Country of Origin | The Country of Origin dataset contains information about the assembly IDs, part IDs, name of supplier and country code. | 44 of 445 datapoint were unidentifiable. 101 of 445 datapoints do not match with the BOM dataset, therefore a cumulative transport distance of 1060357.96 km for 196 kg is defined. |
| **Manufacturing** | Energy consumption hall 5 | The Energy consumption of hall 5 dataset contains information about the electricity consumption of hall 5 over the last 9 months. | The energy consumption of hall 5 is complete. However, the data does not represent the energy consumption that is required to build the Lely Vector MFR. |
| **Downstream transport** | Item & Customer | The Item & Customer dataset contains the sold Lely Vectors in Europe in the last 10 years and the address of the client farm | 760 datapoints about client locations in Europe contribute to an average downstream transport distance of 707 km. |
| **Use phase** | Energy consumption MFR | The Energy consumption MFR data contains an average energy consumption of a Lely Vector MFR in kWh per cow per day. | The energy consumption is 0.07-0.012 kWh per cow per day based on measurement from a case study farm. |
| | Maintenance | The maintenance dataset contains part IDs, Assembly IDs, and the average failure interval. | The maintenance dataset contains 61 parts. 16 of these 61 parts matched with the BOM dataset. 2 of these 16 parts is assigned to a specific material. |
| **End of life** | N/A | N/A | N/A |

**Table 6: Product data excluding assumptions.**

Table 7 presents an overview of the assumptions that were made to correct for missing, incorrect, and non-compatible data. The first assumption aims to identify the material for all the parts that are heavier than 10 kg. Assumption II investigates the material and weight of the most important parts according to a product specialist. Furthermore, assumption III calculates the average transport distance based un the available datapoints and uses that average for the unknown datapoints. At last, assumption IV investigates the top 10 most replaced parts to identify their material and weight. A more detailed description of the assumptions is provided in Section 4.5.1.1, 4.5.2.1 and 4.5.5.1.

| Life cycle phase | Data(set) | Nb. | Assumptions |
| --- | --- | --- | --- |
| **Materials** | Bill of Materials (BOM) | I | Unidentified part with a weight higher than 10 kg were investigated. Resulting in the identification of material for 8 parts. |
| | | II | Investigated the most significant parts based on consultation with an MFR product specialist. Resulting in the identification of material and weight for 78.9 kg. |
| **Upstream transport** | Country of Origin | III | Calculating the average transport distance. The result is multiplied by the amount of weight for which transport distance is unidentified. |
| **Use phase** | Maintenance | IV | Investigated the top 10 most replaced parts in consultation with an MFR product specialist. |

**Table 7: Product data assumptions.**

The assumptions were used to improve the quality of the data. Table 8 combines contains the data quality excluding assumptions, the assumptions and the data including assumptions. The datasets that were used for the Manufacturing, Downstream transport and Use-phase life cycle phase remain unchanged. However, the assumptions for the BOM, Country of Origin and maintenance dataset result in a change of data quality. First, the Bill of Materials went from 74.8% to 88.1% of the weight for which the material is identified. Although, the total weight also increased from 1413.96 kg to 1492.88 kg. Second, the Country of Origin dataset went from cumulative transport distance of 1060357.96 km for 196 kg to a cumulative transport distance of 1060454.58 km for 1487.39 kg. Third, the maintenance dataset went from the 2 to 7 parts for which the quantity of replacements is known.

**First iteration – including assumptions**

| Life cycle phase | Data(set) | Data quality excluding assumptions | Assumptions | Data quality including assumptions |
|---|---|---|---|---|
| **Materials** | Bill of Materials (BOM) | The total defined weight in the BOM is 1413.96 kg. 74.8% of the total weight is assigned to a specific material. | Unidentified part with a weight higher than 10 kg were investigated. Resulting in the identification of material for 8 parts. | The total defined weight by the BOM is 1492.88 kg. 88.1% of the total weight is assigned to a specific material. |
| | | | Investigated the most significant parts based on consultation with a product specialist. | |
| **Upstream transport** | Country of Origin | The cumulative transport distance of 1060357.96 km for 196 kg is defined. | Calculating the average transport distance. The result is multiplied by the amount of weight for which transport distance is unidentified. | The cumulative transport distance of 1060454.58 km for 1487.39 kg is defined. |
| **Manufacturing** | Energy consumption hall 5 | The energy consumption of hall 5 is complete. However, the data does not represent the energy consumption that is required to build the Lely Vector MFR. | | |
| **Downstream transport** | Item & Customer Data | 760 datapoints about client locations in Europe contribute to an average downstream transport distance of 707 km. | | |
| **Use phase** | Energy consumption MFR | The energy consumption is 0.07-0.012 kWh per cow per day based on measurement from a case study farm. | | |
| | Maintenance | The quantity of replacements of 2 parts is defined. | Investigated the top 10 most replaced parts in consultation with a product specialist. | The quantity of replacements of 7 parts is identified. |
| **End of life** | N/A | | | |

**Table 8: Product data including assumptions.**

### 4.5.1 Materials

Product data regarding the manufacturing stage of the Vector is first in the life cycle. The product development department provided a Bill of Materials (BOM), which is an export file from Windchill 3D modeling software, that contains parts ID numbers, material category, material type, quantity of parts, and mass per part. The BOM dataset was rearranged to define total mass per material category, as shown in Table 9. There is only 74.8% of weight for which a material is defined, the remaining 35.2% being undefined (N/A). Besides unidentified material there is also an issue with incorrect weight in the BOM. Note that in Table 9 the total weight of copper is zero. The BOM contains copper parts with a weight of absolute zero which is impossible and therefore considered an incorrect datapoint.

| Material | Total Weight (kg) |
|---|---|
| Aluminum | 6.72 |
| Stainless-steel | 688.40 |
| Steel | 323.21 |
| Rubber | 12.82 |
| Copper | 0 |
| Plastic | 26.51 |
| #N/A | 356.26 |
| **Total Weight (kg)** | 1413.96 |
| **% Material defined** | 74.80 |

**Table 9: Material data excluding assumptions.**

#### *4.5.1.1 Assumptions I & II*

Based on an assessment of the BOM is turned out there were a substantial amount of part for which there was data missing. The missing data in the BOM was divided in 3 categories, as shown in Figure 10. The first category consists of parts for which there was neither a material nor a weight defined. The second category consists of parts for which there was a material identified but not a weight. And the third category consists of parts for which there was a weight identified but not a material. Multiple assumptions are described below in order to make the input data more complete.

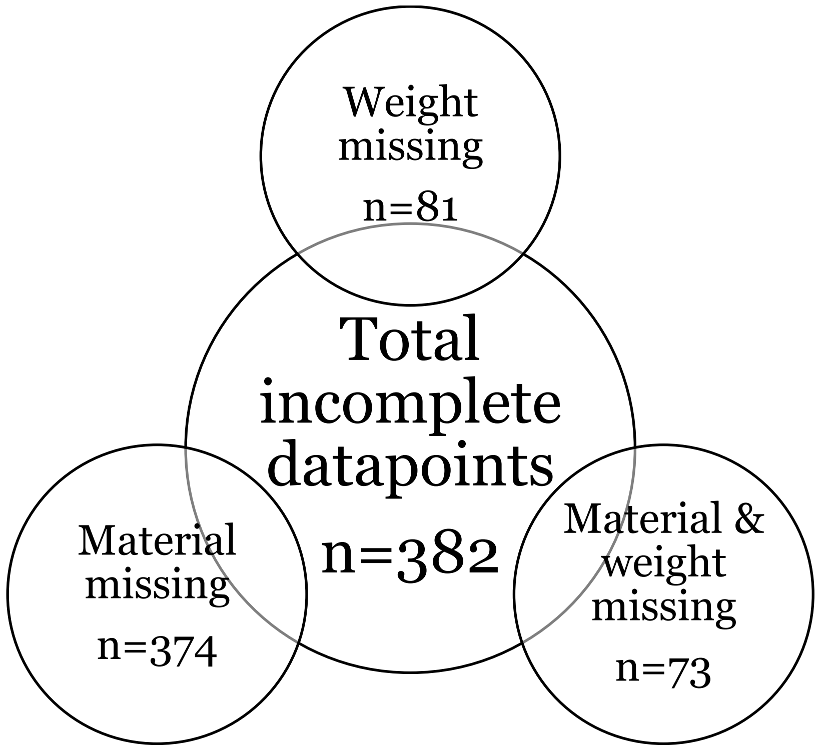



**Figure 10: Overview of incomplete data in the Bill of Materials.**

The first assumption uses a cut-off criterion of 10 kg. There are 374 parts of which the material is not defined in the BOM. An investigation to identify the material of each unknown part would take a considerable amount of time and is not feasible within the timeframe of this research. Therefore, only the parts with a weight more than 10 kg were selected for further investigation to identify the material. Resulting in 9 parts from which 8 investigations were successful in identifying the material.

The second assumption aims to identify the weight (and material) of significant parts. There are 208 parts in the BOM that weigh less than 0.0100 kg, from which 81 parts have a weight of 0.000 kg. Investigating 80 parts is not feasible within the timeframe of this research. Therefore, the most significant parts in terms of weight and potential environmental impact were checked in consultation with a product specialist of the Lely Vector MFR. These parts were: electromotors, batteries, steel frame, steel knifes, steel barrel and wheels. Resulting in the weight and material identification of the batteries, good for 78.9 kg and significant potential environmental impact. The overview of material data including assumption is provided in Table 10.

| Material | Total Weight (kg) |
|---|---|
| Aluminum | 6.72 |
| Stainless-steel | 688.40 |
| #N/A | 177.46 |
| Steel | 323.21 |
| Rubber | 12.82 |
| Copper | 0 |
| Plastic | 26.51 |
| **Assumption** | 257.72 |
| **Total Weight (kg)** | 1492.88 |
| **% Material defined** | 88.11 |

**Table 10: Material data including assumptions.**

## 4.5.2 Upstream Transport

The purchasing department in Lely provided a dataset with part IDs, assembly IDs, name of the suppling organization and country code. I identified the location of the supplier based on their company name with the use of Google Maps. Then calculated the distance in km between the location of the supplier and the assembly location of Lely in Maassluis. Resulting in 196 kg transported over 1.060.358 km, as shown in Table 11. Furthermore, 5 kg of transported parts over 1.987 km had a country code that was either “Blanks”, “#N/A”, “ZZ” or “QV” in the dataset.

Note the total weight of the Vector is at least 1492 kg, so a substantial amount of weight is not defined. The weight is unidentified because of the BOM dataset from the engineering department only partly matched with the Country of Origin dataset from the purchasing department. The reason these datasets do not match is because the BOM dataset contains part IDs, but the Country of Origin dataset contains mostly assembly IDs. Therefore, it is not possible to match the weight of the part to the assembly IDs.

Windchill provides insight to which assembly IDs contains which part IDs. However, from the total of 859 parts there are 513 parts that fall under an assembly IDs. Considering 10 minutes per part it would take almost 90 hours of work to create a dataset that matches the part IDs to the Assembly IDs. This is not feasible within the timeframe of this research.

| *Excl assumptions* | Distance (km) | Weight (kg) |
|---|---|---|
| **Within Europe (truck):** | 56611.58 | 160.92 |
| **Outside Europe (boat):** | 1003746.36 | 35.15 |
| **Total:** | 1060357.96 | 196.07 |

**Table 11: Upstream transport data excluding assumptions.**

### *4.5.2.1 Assumptions III*

The assembly IDs cannot be linked the weight of combined parts. However, the location of the suppliers is known and the amount of weight that is missing. Therefore, it was possible to calculate the average distance from suppliers to Maassluis and multiple that by the remaining amount of weight. The result of upstream transport data is presented in Table 12.

| *Incl assumptions* | Distance (km) | Weight (kg) |
|---|---|---|
| **Within Europe (truck):** | 56708.25 | 1452.24 |
| **Outside Europe (boat):** | 1003746.33 | 35.15 |
| **Total:** | 1060454.58 | 1487.39 |

**Table 12: Upstream transport data including assumptions.**

## 4.5.3 Manufacturing

The data to assess the electricity consumption of the assembly process in Maassluis is provided by the facility management department of Lely. The provided dataset contains information regarding the electricity consumption in Hall 5 over the last 9 months, including heating. All Vector related production is located in hall 5 but there are also other activities. To assess the energy consumption, I calculated the electricity consumption per square meter and multiplied that number by the amount of square meters that of hall 5 that is used for the assembly of the Vector. This data imputation method is a novel approach inspired by mean imputation. Mean imputation replaces missing data with the mean value of the sample (Donders, 2006). Furthermore, I calculated the electricity consumption per hour and multiplied that by the average production time of the Vector (13.8 hours). Resulting in 4191.78 MJ to produce 1 Lely Vector MFR, see Table 13.

| | kW | MJ |
|---|---|---|
| **Energy consumption for producing one Lely Vector MFR** | 1165.21824 | 4191.78 |

**Table 13: Energy consumption during manufacturing.**

## 4.5.4 Downstream Transport

The downstream transport is the transportation of the Vector from the assembly location in Maassluis to the farm. Since Lely sells the majority of its products abroad the distance to the location of the farms can differ significantly. The product management department of Lely provided a dataset with the sold Vectors in Europe in the last 10 years and the address of the client farm. Note that this dataset, consisting of 1285 datapoints, also contains the previous model version of the Vector. Selecting only the Vector M2 (5.2011.0055.1) leaves 760 datapoints.

For each farm address I look up the latitude and longitude and calculated the straight-line distance in km between Maassluis and each of the farms (clients). Then I calculated the average distance between Maassluis and the farms in Europe. Resulting in the average downstream transport distance of 707.48 km, see Table 14. Note that the straight-line distance is not representative for the exact distance that the transport trucks drive to the client farms. Although, it does provide an estimated transport distance.

| | **Distance (km)** |
|---|---|
| **Average transport distance of product** | 707.48 |

**Table 14: Downstream transport distance.**

## 4.5.5 Use-Phase

The use phase of the Vector looks at the electricity consumption. A Vector robot uses 0.07-0.12 kWh per cow per day. This number is variable because of the distance between the feeding fences and the food kitchen can differ between farms. One Lely Vector MFR can provide food for around 200 animals, this results in an electricity consumption of 18 kW per day. The Vector provides food at the feed fence for 24 hours a day throughout the whole year. Resulting in an electricity consumption of 6570 kW or 236520 MJ per year as shown in Table 15. There are times that the robot is not working because of defects or maintenance. However, considering downtime it is still reasonable to assume that the Lely Vector can make sure there is food available in reach of cows all day, for 10 years.

| | **kW** | **MJ** |
|---|---|---|
| **Energy consumption of one Lely Vector MFR over a period of 10 years, working 24/7** | 65700 | 236520 |

**Table 15: Energy consumption during use-phase.**

#### *4.5.5.1 Maintenance*

Data regarding the maintenance of the Lely Vector MFR can provide a valuable contribution to the measurement of environmental impact. However, this data is always available. Lely works with a franchise organizational structure; this means that Lely Head Quarters (HQ) (Maassluis) sells its products to local Lely Centers which on their turn sell the products to the farms. The Lely Centers are responsible for what happens to the defect parts. They can either sell the material from defect parts to waste processing organizations, repair the part, or send the part back to Lely HQ for possible declaration. Unfortunately, there is no information available on the number of repairs per Vector. There are a couple of reasons for that. First, the service technician neglects to report the replacement of a part. Second, the service technician incorrectly reports a replacement of a part because of entering a wrong part ID. It is also possible that the service technician replaces a complete assembly which is not linked to part IDs.

The software that is used to track repairs is called Summit. This software provides input for Tableau, which is a data visualization software. The data regarding the maintenance of the Lely Vector MFR in Tableau is not reliable because the parts IDs do not match the BOM, and some parts originate from other Lely products. Besides the unreliable data from Summit in Tableau there was also independent research on Lely Vector MFR maintenance provided by the technical service support (TSS) department. The maintenance dataset contains 61 parts and the average failure interval in years per part. Out of the 61 parts IDs only 16 matched with the BOM part IDs. From the 16 parts IDs only 2 parts have their material identified in the BOM dataset. It is possible to track back the material of the maintenance parts in Windchill, but this would take a considerable amount of time which does not fit the project timeframe.

##### 4.5.5.1.1 Assumption IV

In consultation with a product specialist of the Lely Vector MFR the top 10 most replaced parts are investigated. Resulting in 7 parts for which the number of items per functional unit (FU) was adjusted in the Fast Track LCA. The maintenance data of these parts is presented in Table 16. For example, the batteries are replaced 5 times during the FU of 10 years. Resulting in an environmental impact that is 5 times greater than without taking maintenance into consideration.

| Item | Average failure interval in years | Number of parts in the MFR | Item nr | Average amount of replacements in 10 years |
|---|---|---|---|---|
| **Knife mixing screw (big)** | 1 | 3 | 9.1127.0027.0 | 10 |
| **Battery** | 2 | 4 | 9.1188.0001.2 | 5 |
| **New drive wheel MFR** | 2 | 2 | 5.2011.1069.0 | 5 |
| **Bumper spring assembly** | 2 | 4 | 5.2011.0310.0 | 5 |
| **Wheel of Swivel Castor (separate) incl. bearings** | 2 | 1 | 9.1175.0082.0 | 5 |
| **Swivel wheel (incl. steel parts and bearing)** | 3 | 1 | 9.1175.0081.0 | 3.3 |
| **skirt rubber** | 3 | 4 | 5.2011.0191.0 | 3.3 |

**Table 16: Maintenance data.**

### 4.5.6 End of Life

Data regarding the end-of-life stage in the life cycle of the Lely Vector MFR there is not available. When parts of the Vector or a complete Vector are defect, and not repairable, the material in the robot is sold to waste processing organizations. The Lely Centers are free to determine to which waste processing plant the defect parts are sold to and no data regarding this process is being documented.

## 4.6 Step 4: Excel Calculations

The results from step 3 are entered into an Excel calculation sheet, provided by Jeremy Faludi of the TU Delft, which combines the product data with an environmental impact indicator. Matching the material or process data of the product with material or process data in the Industrial Design & Engineering Materials (IDEMAT) database is done by hand. The quality of the match is required to be defined according to the Fast Track LCA methodology. There are 3 categories of uncertainty coefficients. A perfect match is 10%, a plausible substitution is 30% and significant differences is defined with 100% uncertainty. For example: the calculated impact for 2.157 kg of the material AlMg3 (5754a) is 25.56 kg CO2 equivalent Because the material match between the MFR and IDEMAT is categorized as perfect, 10% of the impact is deducted from the environmental impact. Resulting in 23.01 kg CO2 equivalent, taking uncertainty into consideration.

Manufacturing and use phase of the MFR life cycle investigate electricity consumption. The impact of the use phase is calculated based on the average impact of electricity consumption in Europe. Meanwhile the impact of the manufacturing phase is based on the average impact of electricity consumption in The Netherlands. Also, for truck transport a 24-ton truck & trailer combination was selected. Regarding shipment, calculations include the environmental impact of a Handysize 1577 twenty-foot equivalent container vessel.

CF (kg CO2 equivalent) and Eco-costs (euros) are used to express the environmental impact of the Lely Vector MFR. A link to the Excel file containing the calculations is provided in Appendix I. Furthermore, the Excel calculation sheet excluding assumptions is presented in Appendix J and the Excel calculation sheet including assumptions is presented in Appendix K.

## 4.7 Step 5: Interpretation

The last step of the Fast Track LCA is the interpretation. According to the International Standardization Organization (ISO) 14040 standard, and the Fast Track methodology this section presents the results of the LCA and discusses reliability of the study. However, in the report the results and discussion chapter are separated to improve readability. The results are presented in Sections 4.7.1 and 4.7.2 and the discussion on the reliability of the results can be found in Chapter 5.

The results are presented in 2 sections. One section describes the results from the product data excluding assumptions. The other section describes the results from the product data including assumptions. Subsequently, both results are compared to each other in Section 4.7.3.

## 4.7.1 Results Excluding Assumptions

Table 17 presents the results of Carbon Footprint (CF) and Eco-costs calculations per product life cycle phase. A bar chart of the results in CF and Eco-costs excluding assumptions is provided in Appendix L. As stated in Section 4.5.1, 25.2% of the total weight is not taken into considerations in the Materials phase. Additionally, the upstream transport data only defines 196 kg of the 1413.96 kg in total. Lastly, the data regarding the maintenance only provides 2 complete datapoints. In conclusion, part of the data is either missing, incorrect or not compatible. Therefore, several assumptions were made to improve reliability of the results.

| Life Cycle Phases | CO2 equivalents [kg] | Eco-costs [euros] |
|---|---|---|
| Materials | 3192 | 1086 |
| Upstream transport | 1221 | 352 |
| Manufacturing | 394 | 85 |
| Downstream transport | 87 | 25 |
| Use phase | 22207 | 4801 |
| End-of-life | N/A | N/A |
| **Total:** | 27101 | 6349 |

**Table 17: Results in carbon footprint excluding assumptions.**

## 4.7.2 Results Including Assumptions

The identification of missing, incorrect, and non-compatible data served as input for the assumptions to make the results more reliable. Table 18 presents the results of Carbon Footprint (CF) and Eco-costs calculations per product life cycle phase. A bar chart of the results in CF and Eco-costs excluding assumptions is provided in Appendix M. As stated, the number of identified materials in the BOM is 88.1%. Furthermore, the upstream transport data accounts for 1487.39 kg. Lastly, the maintenance includes 7 complete data points for the most critical parts of the Lely Vector MFR. In conclusion, the developed assumptions partly accounted for missing, incorrect, and non-compatible data. However, the results would be more reliable is they were based on complete, correct, and compatible data, instead of assumptions. Thus, even though the assumptions contributed to more reliable result, the data issues regarding reliability, completeness and compatibility persists.

| Life Cycle Phases | CO2 equivalents [kg] | Eco-costs [euros] |
|---|---|---|
| Materials | 4398 | 2024 |
| Upstream transport | 7850 | 2257 |
| Manufacturing | 394 | 85 |
| Downstream transport | 95 | 25 |
| Use phase | 22207 | 4801 |
| End-of-life | N/A | N/A |
| **Total:** | 34944 | 9192 |

**Table 18: Results in carbon footprint including assumptions.**

### 4.7.3 Comparison

This section compares the two results, one based on data excluding assumptions and one based on data including assumptions. The two results have different outcomes, however there are also similarities. The first finding that stands out is the results for the End-of-life phase of the Lely Vector MFR Life cycle. This due to the complete absent of data regarding this part of the life cycle. Another interpretation that can be made from the results of the LCA is that the environmental impact of the Use-phase is significantly larger than the other parts of the life cycle. The second highest environmental impact comes from the upstream transport followed by the manufacturing stage. The lowest environmental impact comes from the downstream transport stage of the Lely Vector MFR life cycle. However, the Eco-costs scores are closer to each other than the carbon footprint impact scores. This is because each part of the life cycle has a different environmental impact. Some are less expensive to prevent than others. For example, the Eco-costs of 1 MJ (0.27 kWh) electricity in Netherlands is 0.0187 euros while the Eco-costs of kg of Stainless steel (X5CrNiMo18 (316) 70% inox scrap) from Europe is 1.72, according to the IDEMAT database.

To quantify the comparison between the two results a sensitivity analysis, defined by ISO14040, is made which assesses the impact of input data on the outcomes (International Organization for Standardization, 2006). Meanwhile the calculation method stays unchanged. Furthermore, the sensitivity, displayed in Table 19 and Table 20 is expressed as a percentage of increased output. The variable factor between the two results are the assumptions I, II, III and IV for input data. Resulting in an 28.9% increase in Carbon Footprint with absolute deviation of 7843 kg. The Eco-costs increase by 44.8% with an absolute deviation of 2843 euros.

| | Carbon Footprint - CO2 equivalents [kg] | | | |
|---|---|---|---|---|
| | **Base – exl. assumptions** | **First iteration – incl. assumptions** | **Deviation** | **Assumptions** |
| **Materials** | 3192 | 4398 | 1206 | I & II |
| **Upstream transport** | 1221 | 7850 | 6629 | III |
| **Manufacturing** | 394 | 394 | 0 | N/A |
| **Downstream transport** | 87 | 95 | 8 | N/A |
| **Use phase** | 22207 | 22207 | 0 | IV |
| **End-of-life** | N/A | N/A | N/A | N/A |
| **Total:** | 27101 | 34944 | 7843 | |
| | | | | |
| **Sensitivity %** | 28.9 | | | |

**Table 19: Carbon footprint comparison.**

| Eco-costs [euro] | | | | |
|---|---|---|---|---|
| | **Base – exl. assumptions** | **First iteration – incl. assumptions** | **Deviation** | **Assumptions** |
| **Materials** | 1086 | 2024 | 938 | I & II |
| **Upstream transport** | 352 | 2257 | 1905 | III |
| **Manufacturing** | 85 | 85 | 0 | N/A |
| **Downstream transport** | 25 | 25 | 0 | N/A |
| **Use phase** | 4801 | 4801 | 0 | IV |
| **End-of-life** | N/A | N/A | N/A | N/A |
| **Total** | 6349 | 9192 | 2843 | |
| | | | | |
| **Sensitivity %** | 44.8 | | | |

**Table 20: Eco-costs comparison.**

# 5

# Discussion

*This chapter evaluates the results of the case study by discussing the reliability of the input data for the Fast Track Life Cycle Assessment, consisting of product related data, data from the Industrial Design & Engineering Materials (IDEMAT) database and the compatibility between them.*

The output of the LCA is a direct consequence of the combined data from the IDEMAT database and data regarding the Lely Vector Mixing & Feeding Robot (MFR). Therefore, both components are discussed in the paragraphs below. Section 5.1 zooms in on the reliability of the product related data that were used in the LCA.

The Life Cycle Inventory (LCI) provides information regarding the environmental impact (output) and materials or processes (input). It is possible to conduct research to gather data for the LCI, this is why LCA research can take a long time. An example, of this would be to trace back the origin of the steel in a product and calculate its environmental impact. Over the years many of these LCA studies are done and the results are gathered in LCI databases. Nowadays it is possible to use these collections of LCI databases, like IDEMAT, saving a significant amount of time. Regarding the reliability of the IDEMAT database there is no scientific literature that can be found. However, since the IDEMAT database is based on previously conducted scientific research it is plausible to assume that the reliability is sufficient but always limited to some extent. Additionally, the compatibility between the IDEMAT database and product related data does not always provide a perfect match. For example, the steel production listed in the IDEMAT database might not be the same steel that is used in the Lely Vector MFR. Therefore, the matches are divided into categories of 'perfect match', 'plausible substitution' and 'significant difference'.

During the process of collection data about the Lely Vector MFR from Lely archives there were several issues identified. The issues can be divided into the categories of incomplete data, incorrect data, and non-compatible data from different life cycle stages. Incorrect data is identified in the Bill of Materials (BOM), Country of Origin and maintenance dataset. Additionally, incomplete data is identified in the BOM, Country of Origin and maintenance dataset. Data regarding the End-of-life phase of the Lely Vector MFR is completely missing. Lastly, the BOM dataset is not compatible with the Country of Origin dataset and not with the maintenance dataset. This is because BOM is specified in part IDs while the Country of Origin and maintenance dataset are specified in part IDs and Assembly IDs.

Table 21 presents each life cycle phase in relation to a dataset and the identified data issue. The issues in the product data were partly corrected by making assumptions. However, the identification of these issues has the potential for significant improvements. Clearly, the required data for this research was never demanded from the organization of Lely. Specially, the compatibility between data from different life cycle phases ask for an alternative, more sustainable oriented, data governance mindset.

| Life cycle phase | Dataset | Complete? | Correct? | Compatible? |
|---|---|---|---|---|
| Materials | Bill of Materials (BOM) | No | No | The BOM dataset is not compatible with the Country of Origin and maintenance dataset. |
| Upstream transport | Country of Origin | No | No | The Country of Origin dataset is not compatible with the BOM dataset. |
| Manufacturing | Energy consumption hall 5 | Yes | Yes | Yes |
| Downstream transport | Item & Customer | Yes | Yes | Yes |
| Use phase | Maintenance | Yes | Yes | The maintenance dataset is not compatible with the BOM dataset. |
| | Lely Vector MFR energy consumption | Yes | Yes | Yes |
| End of life | N/A | N/A | N/A | N/A |

**Table 21: Completeness, correctness, and compatibility of the datasets.**

## 5.1 Data Reliability

The data reliability is described per dataset, which are the BOM, Country of Origin, Energy, Consumption, Item & Customer, and maintenance dataset. This section describes the reliability of the datasets regardless of the assumptions that were made to correct for missing, incorrect, and non-compatible data. The Lely Vector MFR energy consumption is not described in this section because it is not a dataset but a calculated number.

### 5.1.1 Bill of Materials (BOM)

The BOM dataset is provided by the purchasing department. This dataset is a direct export file from the 3D model in Windchill, which is created by the mechanical engineering department.  The dataset, partly presented on Figure 11, contains all the Lely Vector MFR parts specified in Part ID, Title, Image, Material Category, Material Category specified, Material type, Quantity, Mass per part (kg) and Total Weight (kg).

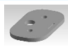
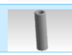
| PRODUCT PARTS: | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| BOM level | Part ID | Title | Image | Material Category | Material Category Specified | Material type | Quantity | Mass per part (kg) | Processing | Total Weight (kg) |
| | 1.1606.0305.0 | PLATE |  | Aluminium | Aluminium | ANODIZED ALUMINUM | 1 | 0.0036 | | 0.0036 |
| | 5.1004.2595.0 | PLATE |  | Stainless Steel | Stainless Steel | AISI 304 | 8 | 0.0345 | | 0.2759 |
| | 5.1004.2620.0 | PIN |  | Stainless Steel | Stainless Steel | AISI 304 | 4 | 0.0198 | | 0.0793 |
| | 5.2011.0109.0 | PLATE |  | Stainless Steel | Stainless Steel | AISI 304L EN10088 | 1 | 0.4894 | | 0.4894 |
| | 5.2011.0116.0 | TUBE |  | #N/A | | | 1 | 0.0579 | | 0.0579 |
| | 5.2011.0123.0 | BRACKET |  | #N/A | | | 2 | 1.1951 | | 2.3902 |

**Figure 11: Snapshot of the Bill of Materials dataset.**

The reliability of the BOM dataset is questionable due to the following reasons. First, 80 parts out of the total of 859 parts have a weight of 0.000 kg, therefore this data is incorrect. Second, the total weight of all the parts in the BOM is 1413.96 kg excluding assumptions and 1492.88 kg including assumptions. Meanwhile, the robot is weighted at 1360 kg with the use of a scale just before transport. So even with 80 parts having an incorrect weight of 0.000 kg the BOM calculates a weight of 53 kg more than the weighted weight, indicating that the information in the dataset is not correct. Third, there are 377 parts that have an unidentified material in the BOM dataset. Making the dataset incomplete. Lastly, the BOM dataset is not compatible with the Country of Origin and maintenance dataset because the BOM contains part IDs while the Country of Origin and maintenance dataset contains part IDs as well as assembly IDs.

## 5.1.2 Country of Origin

Data regarding upstream transport was provided by purchasing department. The dataset is incorrect and incomplete because out of the 445 datapoint there are 44 who have an unidentifiable country code. As mentioned before, 101 datapoints do not match with the BOM dataset, consequently there is only 196 kg of parts for which the transport distance defined. The reason that the IDs in the Country of Origin dataset do not match with the IDs numbers in the BOM dataset is due to a difference in documentation by part and by assembly. Therefore, the Country of Origin dataset is not compatible with the BOM dataset.

## 5.1.3 Energy Consumption Hall 5

The energy consumption dataset provided by facility management department can be considered reliable because of the certified electricity measurement system. However, the data was not suitable for the research because it also contains energy consumption used for non-Vector related activities. It is not possible to determine what percentage of the energy consumption can be related to Vector production activities and what percentage cannot. But an estimation was made based on the surface area of the hall and area used for Vector production.

## 5.1.4 Item & Customer

For the calculation of the environmental impact in the downstream transport phase of the life cycle the product management department provided a dataset. This dataset was stripped of non-relevant data, leaving a dataset with ItemNumber, CustomerAdress1, CustomerAdress4 and CustomerCountry. Out of the 747 datapoints there were 25 datapoints which address was not identifiable. Also, there are 10 datapoints with the address of Cornelis van der Lelylaan 1. This is because the robots for testing clients and demo installations are documented with the same address as the Lely headquarters address.

## 5.1.5 Maintenance

The maintenance dataset was provided by the technical service support (TSS) department after the data from Summit in Tableau was evaluated as not sufficient. This evaluation was made due to the identification of parts from other robots in the maintenance dataset. Furthermore, the amount of maintenance defined in Tableau was deemed not accurate in consultation with a product specialist of the Lely Vector MFR. However, another source for the maintenance dataset was provided by TSS. The maintenance dataset from TSS included Part ID, Item Description, Average failure interval in years and # items in the machine. The dataset serves as an advice and is based on maintenance data from 2012-2019. After 2019 the collection of data was stopped due to unknown reasons. The maintenance dataset contains 61 parts, out of the 61 parts IDs only 16 matched with the BOM part IDs. From the 16 parts IDs only 2 parts have their material identified in the BOM dataset. To conclude, the maintenance dataset is not compatible with the BOM because the part IDs and assembly IDs do not match with the part IDs in the BOM.

# 6

# Conclusion

*This chapter describes the conclusions of the research. It answers the main research question and other sub questions. Furthermore, this chapter describes the limitations, recommendations, scientific relevance, and societal relevance of the research.*

This study investigates how Life Cycle Assessment (LCA) measures the environmental impact of a livestock feeding robot life cycle. Therefore, the research started with a literature review focusing on the definition of environmental impact and the identification of LCA methodologies. The environmental impact is expressed in sets of impact categories. However, there are various other sets of environmental impact categories defined in existing literature. Among others, in the EN15804 standard for LCA and the Product Environmental Footprint (PEF) defined by European commission. Furthermore, impact categories are often reduced to single indicators to enhance the practicability of LCA results for informed decision making and actionable insights.

Another conclusion that can be drawn from the literature review is the identification of multiple different LCA methodologies from existing literature. The variation between the methodologies mainly comes from differences in the definition of goal and scope, including the selection of impact categories and single indicators. Furthermore, the availability of an environmental impact database, also referred to as Life Cycle Inventory (LCI), is an indispensable component of any LCA. Data regarding the environmental impact for this study is provided by the Industrial Design & Engineering Materials (IDEMAT) database from the TU Delft since other databases like Simapro and Ecoinvent were not available due to licensing issues. However, IDEMAT only provides environmental impact in the form of single indicators, like Eco-costs and Carbon Footprint. The single indicators in IDEMAT are calculated on the impact categories from the Ecoinvent V3 dataset.

Subsequently, the research investigates which LCA methodology is most suitable for measuring the environmental impact a livestock feeding robot. LCA requires two forms of data, product related data and environmental impact related data. The availability and reliability of product data would be identified during the execution of the LCA case study. Any potential issues with product data will also be identified so that improvements can be made in the future. As stated, the available environmental impact database is IDEMAT. Thus, the LCA methodology selection is based on the compatibility with IDEMAT. However, the LCA methodology must also be compatible with the goal of the study which results in several selection criteria. Therefore, the LCA methodology must be compatible with a product assessment, a Cradle-to-Grave life cycle scope, a project timeframe of 3 months, an environmental impact assessment and the available environmental impact database.

The Fast Track LCA is selected for the case study because of the following reasons. First, the Fast Track LCA is designed to assess products. Second, the Fast Track LCA is compatible with the defined product life cycle scope, namely Cradle-to-Grave. Third, a standard LCA takes a lot of effort and money, at least months but sometimes up to years. But when the necessary input data are present, the Fast Track LCA only needs a couple of hours or a few days. Therefore, the Fast Track LCA fits the project duration of 3 months. Additionally, the accuracy of a Fast Track LCA is equal to or greater than that of a standard

LCA. Fourth, the Fast Track LCA is used to measure the environmental impact which is in line with the goal of this research. Lastly, the Fast track LCA is compatible with the free IDEMAT database.

Output of the Fast Track LCA is provided in Carbon Footprint (CF) and Eco-costs indicators. The single indicators of CF and Eco-costs are selected based on their practical characteristics for firms. CF has become a focus point for regulations and a well-known term among society. Thus, CF is relevant for firms because it enables them to meet future regulations and improve their image regarding sustainability. However, firms must maintain their competitive advantage. Therefore, it is important to identify the financial investments that are required to improve the sustainable performance of the firm. Eco-costs is a relevant and practical single indicator for firms because it provides a monetary valuation of environmental impact.

After selecting the Fast Track methodology, IDEMAT database, CF, and Eco-costs indicators the next step was executing the case study. The firm Lely accommodated the case study about their livestock feeding robot called the Lely Vector Mixing & Feeding Robot (Lely Vector MFR). The data collection process was separated for each life cycle phases of the product, consisting of: Raw Materials, Upstream Transport, Manufacturing, Downstream Transport, Use-phase, and End-of-Life. Resulting in several datasets including Bill of Materials (BOM), Country of Origin, Energy Consumption Hall 5, Item & Customer and maintenance. The gathered data was processed, and several assumptions were made to account for missing, incorrect, and non-compatible data. All assumptions combined result in a CF increase of 28.9% and an Eco-cost increase of 44.8%.

In conclusion, this research shows how to measure the environmental impact of a livestock feeding robot life cycle using the Fast Track LCA methodology in a case study about the Lely Vector MFR. The environmental impact measurement of the Lely Vector MFR results in a CF of 34944 kg CO2 equivalents. According to the European Environment Agency this CF is equal to the offset of 1588 mature trees existing for one year (European Environment Agency, 2012). Additionally, the Eco-costs results in 9192 euro, representing the required investment to lower the environmental impact to a sustainable level by selecting the most expensive and best available technology which is needed to meet the required level of emission allowances.

Firms aim to lower the environmental impact to be able to meet future regulations and gain or maintain competitive advantage. However, defining or improving the sustainable performance of firms is hindered by a lack of knowledge about the measurement of environmental impact. This study provides a case study about measuring the environmental impact of a product life cycle. The case study focusses the assessment of a Lely Vector Mixing & Feeding Robot with the use of a Fast Track LCA methodology and IDEMAT database. However, the same research method can be used for products in other firms to measure environmental impact.

## 6.1 Limitations

The limitations of the research are divided into three parts, the first parts consist of limitations regarding the case study. Which, for a large part, is already discussed in chapter 5, Data Reliability. The second part of the limitations reflects on the methodology, and the third part of this section focusses on more general limitations of the research.

Starting with case study specific limitations. First, the research selected the Carbon Footprint (CF) and Eco-costs as single indicators and excluding ReCiPe2016 and CED due to time related project limitations and their lower practical value for firms. Second, this research assesses the Lely Vector MFR with a Cradle-to-Grave scope. The cradle-to-cradle life cycle was not selected due to a lack of recycling data. However, as the case study progressed it turned out that there was no data regarding the end-of-life stage. If this was known beforehand a consideration for a Cradle-to-Site scope could have been made. Third, another component of the goal and scope definition of the case study was to set geographical boundaries for Europe. This delineation affects the downstream transport, use-phase, and end-of-life phase of the Lely Vector MFR life cycle. Lastly, the IDEMAT is not completely accurate. The data is based on 472 peer-reviewed scientific papers, plus 472 LCIs from the TU Delft, 40 from Plastics Europe, 25 from Probas, 20 from United States LCI, 16 from European Life Cycle Database, 7 from CESedupack, 4 from University of Chalmers and 2 from Ecoinvent. There is no scientific literature assessing the reliability of the IDEMAT database. In conclusion, the availability and reliability of product data forms a limitation of the research. As well as the ability to match the product data with the IDEMAT database and IDEMAT itself.

The methodology that was selected for this study is the Fast Track LCA with the use of the IDEMAT database. When reflecting on the execution of the Fast Track LCA there are limitations based on which the methodology can be improved. First, the output of the Fast Track LCA is limited to single indicators only. Additionally, the computation of the single indicators is not completely transparent. Thus, the specific impact categories on elemental level are unknown. Although the simplification through single indicators improves practicability, it also excludes valuable information. Second, matching the product specific data with the IDEMAT database was problematic in some cases. Simply because some materials are not included in the IDEMAT database.

Looking at the research in general there are limitations as well. Starting with the literature research. The search criteria resulted in a significant number of results, in the order of millions, for which it was unable to read and evaluated all of them within the determined timeframe for research. It is possible that some relevant findings are therefore unidentified.

Furthermore, by selecting the Fast Track LCA other LCA methodologies are excluded. This represents a tradeoff between scope and precision. If the research would focus on only one phase of the life cycle the results would be more precise and detailed. However, the research contains a complete life cycle resulting in less detailed and less precise results compared to the alternative of focusing on one part of the life cycle. The advantage of focusing on one life cycle is the increased reliability of the result, the disadvantage is that only a one phase of the complete life cycle is defined, and no comparison can be made between the different life cycle phases. However, the advantage of focusing on the complete life cycle is that it enables to compare the result of different life cycle phases, the disadvantage is that the reliability is lower due to the limited amount of time of the research project.

## 6.2 Recommendations

The results of this study show various opportunities for improvement to be taken into consideration for future research. Recommended improvements are provided in this section. Additionally, this section describes how the results of this research can serve as a starting point for new research. As mentioned before, there are several issues with the collected product data, including incomplete, incorrect, and non-compatible data. The data issues are partly accounted for with a set of assumptions. However, these assumptions improve reliability of the study they do not tackle the origin of the product data issues. The paragraphs below describe the datasets which are problematic and how these datasets can be improved. Data quality of the datasets is evaluated based on the correctness, completeness and compatibility.

First, issues regarding the Bill of Materials (BOM) dataset. The dataset contains 81 parts with a weight of absolute zero and 374 parts with an unidentified material. A part with an absolute weight of zero is impossible and therefore incorrect data. The unidentified material is an issue of incomplete data. Both weight and material specification of each part is essential for the LCA study. Since the BOM dataset is a direct print out of the 3D Model in Windchill it can be concluded that the data issues originate from insufficient documentation during the design process. It is recommended to identify the missing material and weight to increase the reliability of the LCA. To improve the quality of the data there are two approaches needed. One approach to correct for the current data issues by going through each part in collaboration with the product development department. The other approach is to make sure that new parts are documented in a sufficient way from now on.

Second, from 445 datapoints in the Country of Origin dataset there are 44 datapoint for which the country code is incorrect. Additionally, there are a 101 datapoints that do not match the BOM dataset. As a result, there is only 196 kg of parts for which the transport distance defined. The reason that the datasets are not compatible is because the ID numbers in the Country of Origin dataset do not match with the ID numbers in the BOM dataset. The difference in ID numbers is because the Country of

Origin contains assembly IDs and the BOM only part IDs. To improve the quality of the Country of Origin dataset there are three approaches. The first approach must focus on the identification of the incorrect datapoints in collaboration with the purchasing department and suppliers of Lely. A second approach must focus on making the Country of Origin compatible with the BOM dataset by matching assembly IDs to part IDs. The third approach must focus on preventing incorrect data by documenting transport distance of parts in consultation with suppliers.

Third, the maintenance dataset is partly not compatible with the BOM. The maintenance dataset contains 61 parts, out of the 61 parts IDs only 16 matched with the BOM part IDs. Only 2 of the 16 part IDs have a material and weight listed in the BOM dataset. Similar to the compatibility issues between the Country of Origin and BOM dataset the reason that the maintenance and BOM dataset are not compatible is due to mismatches in part IDs and assembly IDs. It is recommended to solve this issue by matching the part IDs and assembly IDs in collaboration with the product development and technical service support (TSS) department.

Last, data about the End-of-life and potential recycling is not existing. This would require lengthy research in collaboration with the Lely centers. The ideal results of this research would include information about which parts are recycled by Lely and what happens to the parts that go to waste processing plants.

Regarding the Industrial Design & Engineering Materials (IDEMAT) database was the only available Life Cycle Inventory (LCI) for this research. Other databases like Simapro and Ecoinvent required the purchase of licenses. According to Vogtländer there is no difference in quality. However, the IDEMAT database is not fully transparent as it provides single indicators and not a complete set of impact categories. Therefore, Simapro or Ecoinvent license would be recommended for more transparency.

The results of the research serve as input for informed decisions and actionable insights to achieve sustainability. It is recommended to use to results of the LCA to lower environmental impact. This can be done by changing the product design or make changes in the life cycle of the Lely Vector MFR. For example, results show that the use-phase provides the largest contribution thereby identifying a hotspot for potential improvements. If the electricity consumption in the use-phase is produced with green alternatives, then this would significantly lower the Carbon Footprint (CF) of the Lely Vector MFR. Also, it is recommended to execute more LCA studies. The research is limited to the assessment of one livestock feeding robot, namely the Lely Vector MFR. However, there are several other livestock feeding robots in the market. The reason for selecting the Lely Vector MFR is simply because Lely offered an internship and cooperation for the research. A comparative LCA study between two livestock feeding robots would enable to compare different livestock feeding robots. However, this does require access to the product data from one of the competitors of Lely. After a design change a new iteration of the LCA can verify a reduction in CF. Additionally, comparing the current MFR to conventional feeding techniques can identify a competitive advantage for one of the two feeding techniques. Finally, it is recommended to integrate the measurement of environmental impact in the already existing data systems instead of doing it by hand every time. Considering the data is there, the only requirement would be the rearrange datasets and make them compatible with each other to monitor the environmental impact of a product over its life cycle. This improvement in data governance would allow for an instant and up-to-date measurement of environmental impact per product.

## 6.3 Relevance

This section reflects on the research process from a personal perspective and explains the relevance of the work from an academic, societal, practical, and managerial point of view. Additionally, looking at the relevance of the work from the perspective of Lely and the Management of Technology (MOT) program.

### 6.3.1 Scientific Relevance

This study describes how Fast Track LCA can measure the environmental impact of livestock feeding robots. Thereby, contributing to the research field of LCA and enabling future research in the transition towards sustainability. For instance, research about the comparison of new robots and conventional feeding techniques with. Furthermore, the literature research shows a lack of existing research on the measurement of livestock feeding robots with the use of the LCA methodology. This research can therefore be considered as a novel approach as it is the first time the environmental impact of a livestock feeding robot is measured using the LCA methodology.

### 6.3.2 Relevance for Delft University of Technology

The MOT program of the TU Delft demands a contribution to scientific knowledge by identifying and filling the knowledge gap. Furthermore, the work must be conducted in a technological context with the use of scientific methods. Also, the research aims to understand how firms can contribute to improve outcomes with the use of a scientific study. The identified knowledge gap is about the lack of research on measure environmental impact of livestock feeding robots by applying the LCA methodology. This gap is bridged by measuring the environmental impact of the Lely Vector MFR by applying the Fast Track LCA methodology. The scientific contribution can be derived from the results of Carbon Footprint (CF) and Eco-costs. As well as the process of executing the LCA case study resulting in the identification of issues regarding product data governance.

### 6.3.3 Societal Relevance

The societal relevance of this research comes from the potential of sustainable development. Because the results of this research are not relevant for society directly. However, this study identifies opportunities for improvement and provides input to move towards a more sustainable product. Potentially resulting in a lower environmental impact by reducing the pollution of air, water, and land on earth. Society directly benefits from climate change mitigation because of more sustainable robots in the agricultural sector.

### 6.3.4 Relevance for Firms

This research includes a case study about the Lely Vector MFR, a livestock feeding robot from Lely. However, the research is also generalizable to other firms that aim to improve on their sustainable performance. Measuring the environmental impact of a product life cycle provides firms with valuable insights into their environmental performance, enabling them to make informed decisions, reduce risks, meet regulatory requirements, and enhance their competitive advantage. This research measures the environmental impact of the Lely Vector MFR with the use of the Fast Track LCA. A similar case study can be executed for other firms to measure the environmental impact of their products life cycle. One of the main conclusions from this research is that it can be challenging to collect the required product data as input for the LCA. This challenge can inform other firms about the required product data before starting sustainability assessment research on a product life cycle. Additionally, besides the product data an environmental impact database, like IDEMAT, is essential as well.

#### 6.3.4.1 Managerial Relevance

Management of Lely and other firms can use this research to take action in the pursuit of making products and organizations more sustainable. The following actions can be taken based on the results of the research. First, the sustainability measurement enables the identification for improvements in product design and life cycle arrangement. Second, the measurement of sustainability can be used to compare the Lely Vector MFR to other robots, conventional feeding techniques or new iterations of the product. Third, the measurement can potentially be used as marketing content to promote a sustainable image of the product and organization. Lastly, this research provides insight for firms on the required measurement to verify compliance with future regulations regarding Carbon Footprint.

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# Appendix

# A PRISMA Diagram Set 1

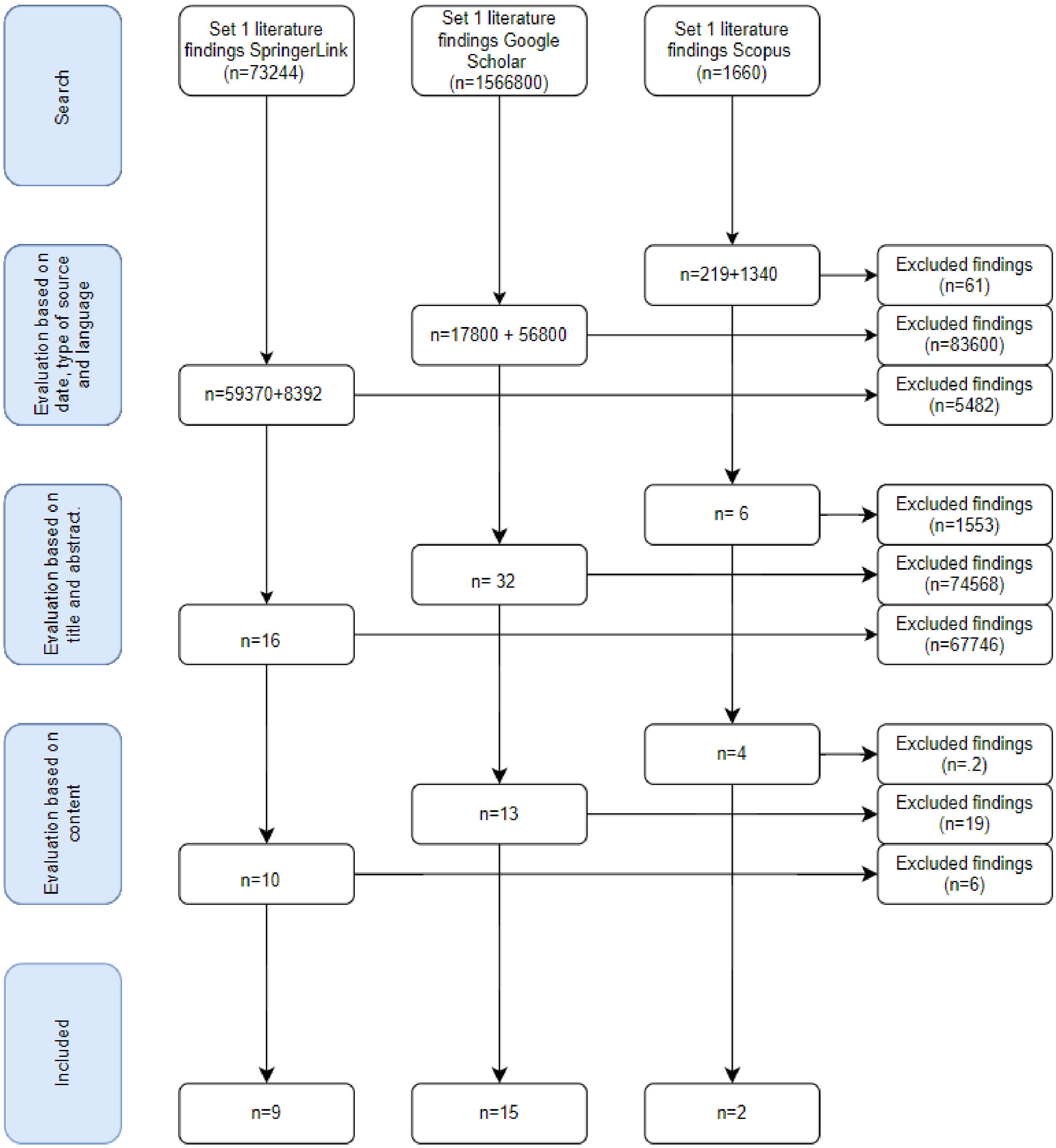


**Figure 12: PRISMA diagram Set 1.**

# B PRISMA Diagram Set 2

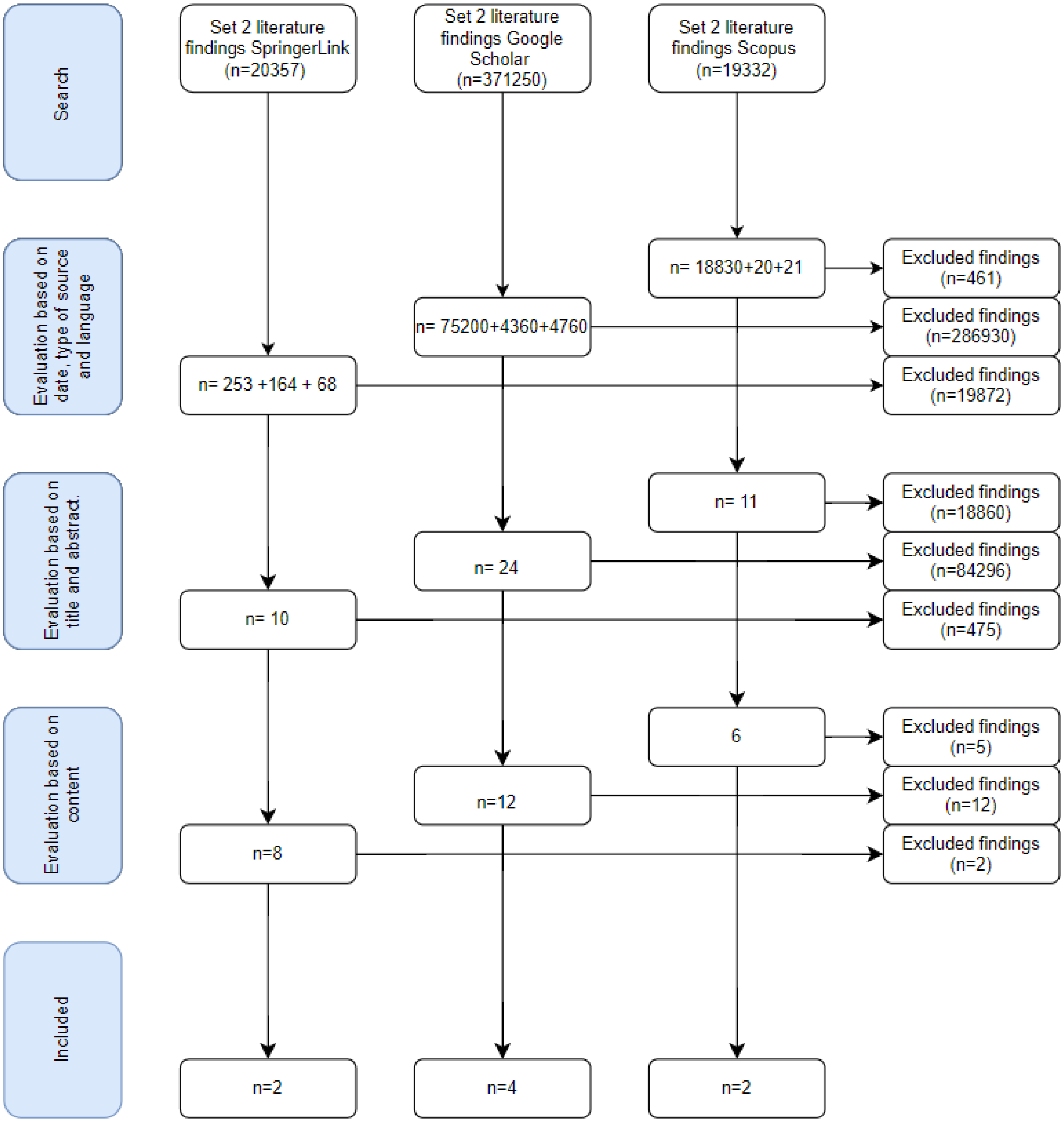


**Figure 13: PRISMA diagram Set 2.**

# C PRISMA Diagram Set 3

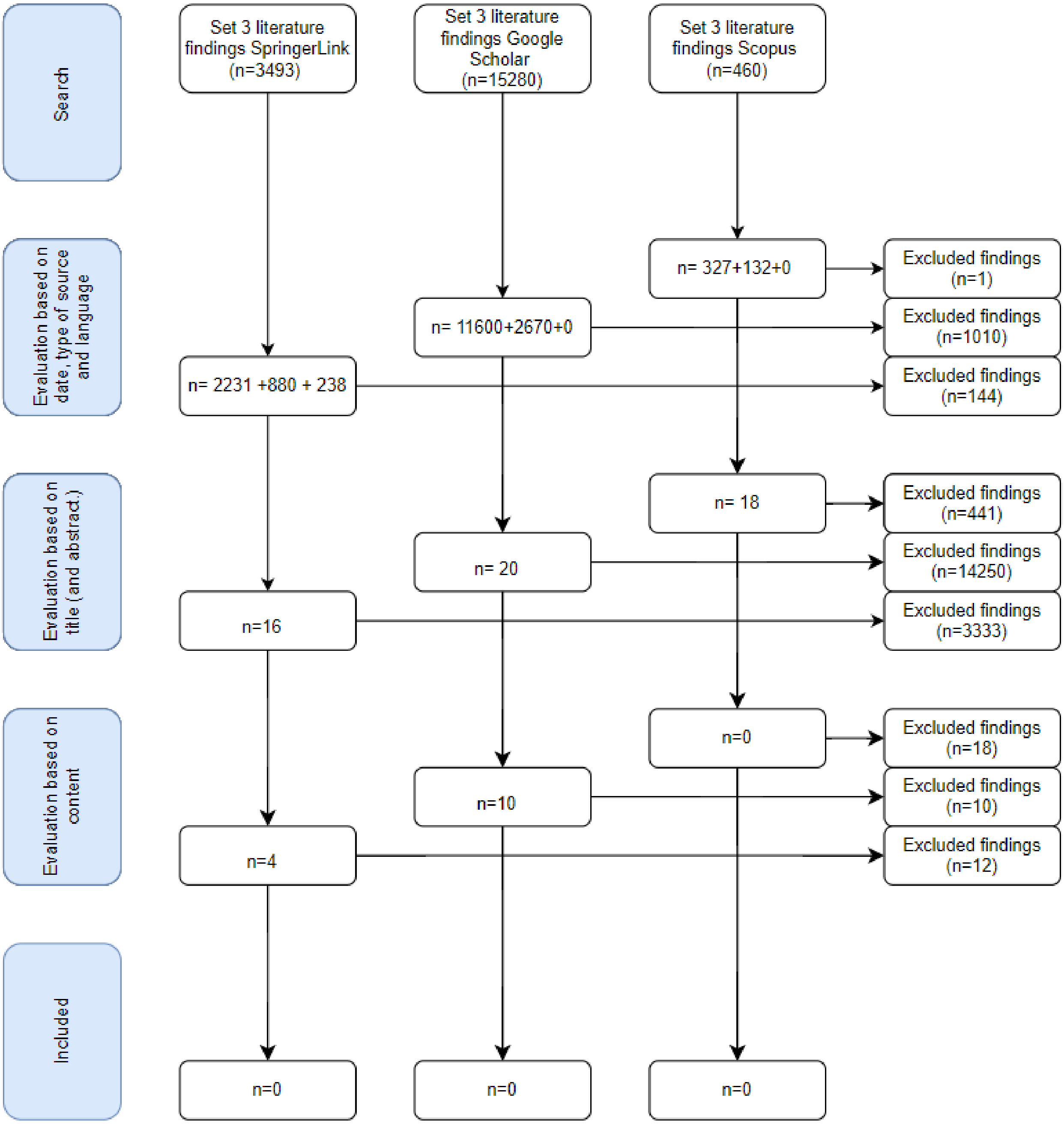


**Figure 14: PRISMA diagram Set 3.**

# D Impact Categories

Table 22 presents the impact categories as defined by Ecoinvent (Ecoinvent, 2023).

| **Impact category name** | **Reference unit** |
|---|---|
| Ozone depletion | kg CFC11 eq |
| Resource use, minerals and metals | kg Sb eq |
| Ecotoxicity, freshwater - organics | CTUe |
| Land use | Pt |
| Climate change - Biogenic | kg CO2 eq |
| Human toxicity, cancer - organics | CTUh |
| Human toxicity, non-cancer | CTUh |
| Climate change - Land use and LU change | kg CO2 eq |
| Acidification | mol H+ eq |
| Water use | m3 depriv. |
| Ecotoxicity, freshwater | CTUe |
| Photochemical ozone formation | kg NMVOC eq |
| Ecotoxicity, freshwater - inorganics | CTUe |
| Ionising radiation | kBq U-235 eq |
| Resource use, fossils | MJ |
| Climate change - Fossil | kg CO2 eq |
| Human toxicity, cancer - inorganics | CTUh |
| Particulate matter | disease inc. |
| Human toxicity, non-cancer - metals | CTUh |
| Human toxicity, cancer - metals | CTUh |
| Eutrophication, marine | kg N eq |
| Human toxicity, cancer | CTUh |
| Ecotoxicity, freshwater - metals | CTUe |
| Eutrophication, terrestrial | mol N eq |
| Human toxicity, non-cancer - organics | CTUh |
| Human toxicity, non-cancer - inorganics | CTUh |
| Eutrophication, freshwater | kg P eq |
| Climate change | kg CO2 eq |

**Table 22: Impact categories defined by Ecoinvent.**

# E ReCiPe

Figure 15 displays an overview of the ReCiPe strcuture (RIVM, 2011).

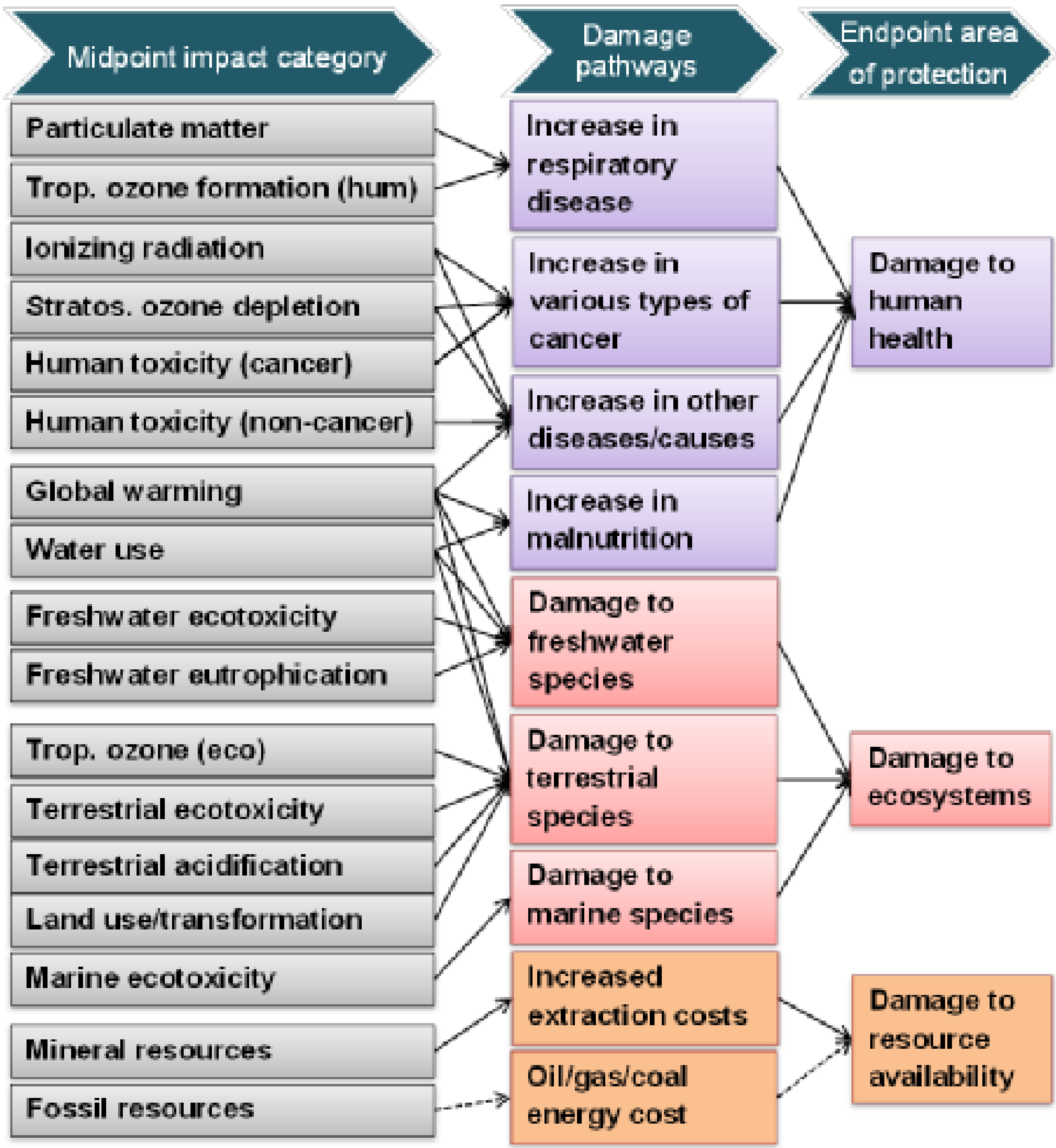


**Figure 15: Concept of ReCipe 2016.**

# F Eco-costs

Figure 16 presents the concept of Eco-costs and the impact categories underlaying the single indicator.

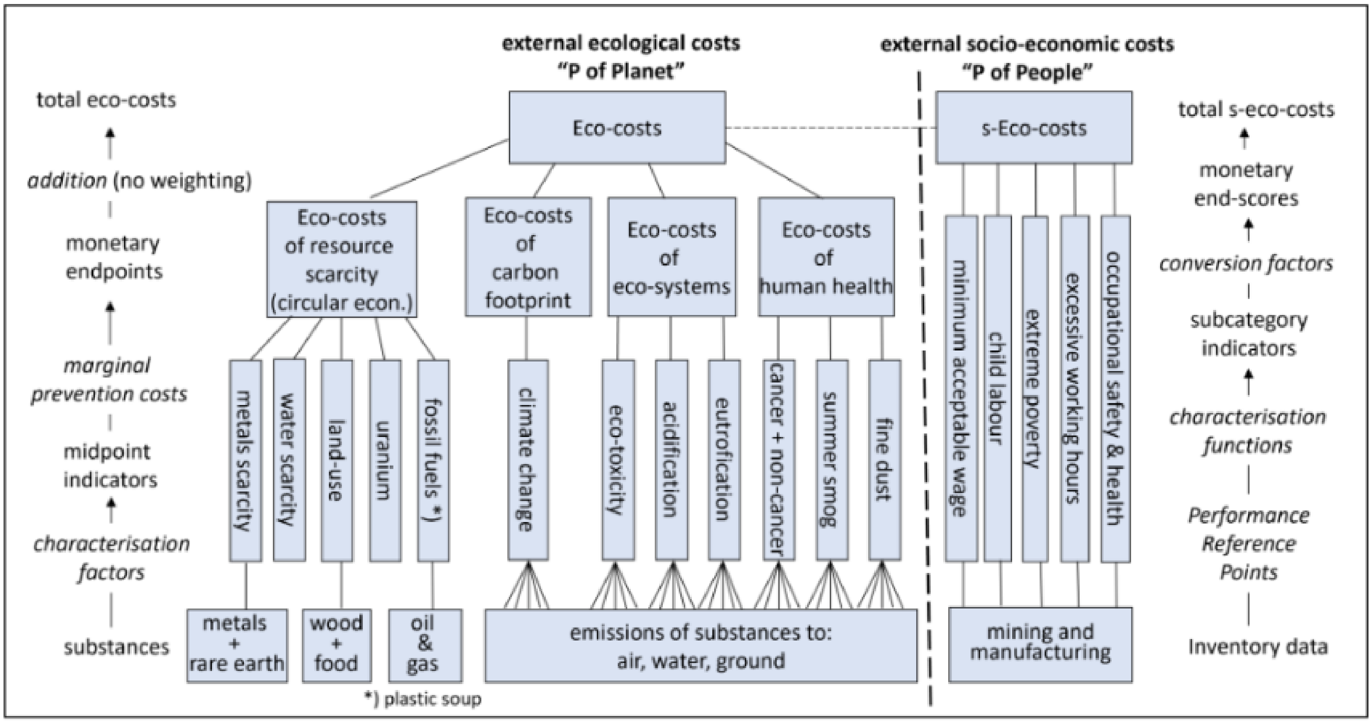


**Figure 16: Concept of eco-costs.**

# G Life Cycle Assessment Methodologies

Table 23 provides an overview of the different LCA methodologies found in scientific literature.

| Methodology | Description | Source |
|---|---|---|
| **O-LCA** | Organizational Life Cycle Assessment (O-LCA) focuses on an organizational portfolio and value chain. O-LCA was introduced by ISO/TS 14072. In addition, the European Commission has released a guide for the Organization Environmental Footprint (OEF). | (Klöpffer, 2014), (Finkbeiner, Special Types of Life Cycle Assessment, 2016), (Atsushi Inaba, et al., 2016), (Hauschild & Huijbregts, Life Cycle Impact Assessment, 2015) |
| **CLCA** | Consequential LCA (CLCA) focusses on the indirect consequences of a product or service by including economic concepts and market mechanisms. | (Klöpffer, 2014), (Finkbeiner, Special Types of Life Cycle Assessment, 2016) (Curran, 2017) |
| **Fast Track LCA** | Fast Track LCA is developed by the TU Delft as a simplification and time-efficient approach compared to standard LCA. It is used to analysis products or processes. | (Vogtländer J. , 2017) |
| **PEF** | Product Environmental Footprint (PEF) focusses on a single impact or multiple impact categories of a product. | (Finkbeiner, Special Types of Life Cycle Assessment, 2016), (Andreas Ciroth & Rickard Arvidsson, 2021) |
| **OEF** | Organizational Environmental Footprint (OEF) is a form of O-LCA that focuses on the environmental impact of an organization. | (Finkbeiner, Special Types of Life Cycle Assessment, 2016) |

| | | |
|---|---|---|
| **EF** | Environmental Footprint (EF) can focus on a single or multiple impact categories of a product or organization. Carbon Footprint (CF) and Water Footprint (WF) are examples of a single impact category LCAs. | (Klöpffer, 2014), (Finkbeiner, Special Types of Life Cycle Assessment, 2016), (Berger, Pfister, & Motoshita, 2016), (Atsushi Inaba, et al., 2016) |
| **IO-LCA** | Input-Output LCA (IO-LCA) is based on the flows of goods and services between different sectors in the economy. It provides a macro-level analysis of environmental impacts. | (Finkbeiner, Special Types of Life Cycle Assessment, 2016), (Nakamura & Nansai, 2016), (Hauschild & Huijbregts, Life Cycle Impact Assessment, 2015) |
| **Hybrid LCA** | Hybrid Input-Output LCA is a combination of process-based LCA (PLCA) and IO-LCA. This method is often used to develop LCI. | (Finkbeiner, Special Types of Life Cycle Assessment, 2016) |
| **MFA (or SFA)** | Mass Flow Analysis (MSA) or Substance Flow Analysis (SFA) is a tool to quantify the flows of materials within a specified system boundary. MFA and LCA have some overlapping characteristics. Therefore, MFA can be used as a basis for impact assessment methods such as LCA. | (Finkbeiner, Special Types of Life Cycle Assessment, 2016), (Laner & Rechberger, 2016) |
| **ALCA** | Attributional LCA (ALCA) is a confined approach based on material flow to assess impact or a product or service. | (Curran, 2017) |
| **LCM** | Life Cycle Management (LCM)is a framework for organizations to improve on | (Klöpffer, 2014), (Sonnemann & Margni, 2015) |

| | | |
|---|---|---|
| | technological, economic, environmental, and social impact of its products and services. LCM can be divided into Product Life Cycle Management (PLCM) and Information Life Cycle management (ILCM). | (Hauschild & Huijbregts, Life Cycle Impact Assessment, 2015) (Hunkeler, et al., 2003) |
| **LCC (or WLC)** | Life Cycle Costing (LCC) or Whole Life Costing (WLC) is applied to evaluate the costs of a product or service during its lifecycle. | (Klöpffer, 2014), (Sonnemann & Margni, 2015), (Finkbeiner, Special Types of Life Cycle Assessment, 2016), (Hauschild & Huijbregts, Life Cycle Impact Assessment, 2015), (Nakamura & Nansai, 2016), (Saling, 2016), (Vogtländer J. , 2017) |
| **SLCA** | Social Life Cycle Assessment (SLCA) focusses on the social impacts on people generated by products, processes or services. | (Klöpffer, 2014), (Hauschild & Huijbregts, Life Cycle Impact Assessment, 2015) (Sonnemann & Margni, 2015), (Finkbeiner, 2016) |

| | | |
|---|---|---|
| **LCIA** | Life Cycle Impact Assessment (LCIA) is used to evaluate the environmental impact of a product or service. The LCIA is usually part of a LCA but can also be executed separately. | (Hauschild & Huijbregts, Life Cycle Impact Assessment, 2015), (Finkbeiner, Special Types of Life Cycle Assessment, 2016), (Andreas Ciroth & Rickard Arvidsson, 2021), (Laner & Rechberger, 2016), (Schneider, et al., 2016), (Berger, Pfister, & Motoshita, 2016) (Hauschild & Huijbregts, Life Cycle Impact Assessment, 2015), (Vogtländer J. , 2017) |
| **LCI** | Life Cycle Inventory (LCI) is a database with quantitative data regarding materials and environmental impact. The LCI is usually part of a LCA but can also be executed separately. | (Klöpffer, 2014), (Andreas Ciroth & Rickard Arvidsson, 2021), (Vogtländer J. , 2017) |
| **LCSA** | Life Cycle Sustainability Assessment (LCSA) focusses on the sustainability (environmental, social, and economic) of products, processes, and services. | (Sonnemann & Margni, 2015), (Finkbeiner, Special Types of Life Cycle Assessment, 2016), (Schneider, et al., 2016) |
| **Streamlined LCA** | Streamlined LCA is an umbrella term for simplified LCA. (e.g., Carbon Footprint, Water Footprint) | (Klöpffer, 2014) |

| | | |
|---|---|---|
| **EEA** | Eco-efficiency Assessment/Analysis (EEA) is a quantitative management tool that focusses on the environmental impact of products or processes in combination with its monetary value to a stakeholder. | (Sonnemann & Margni, 2015),<br>(Saling, 2016) |
| **REA** | Resource Efficiency Assessment (REA) uses the LCA methodology to determine the ratio between added value and resource input. | (Finkbeiner, Special Types of Life Cycle Assessment, 2016) |

**Table 23: Overview of Life Cycle Assessment methodologies.**

# H LCA Methodology Selection

Table 24 provides an overview of the different LCA methodologies and their compatibility with the selection criteria.

| LCA Methodologies | Compatible with product assessment. | Compatible with Cradle-to-grave scope. | Compatible with 3 months' timeframe. | Compatible with environmental impact. | Compatible with the IDEMAT database. |
|---|---|---|---|---|---|
| **O-LCA** | ✗ | ✓ | ✗ | ✓ | ✓ |
| **CLCA** | ✓ | ✓ | ✗ | ✗ | ✗ |
| **Fast Track LCA** | ✓ | ✓ | ✓ | ✓ | ✓ |
| **PEF** | ✓ | ✓ | ✓ | ✓ | ✓ |
| **OEF** | ✗ | ✓ | ✓ | ✓ | ✓ |
| **EF** | ✓ | ✓ | ✓ | ✓ | ✓ |
| **IO-LCA** | ✗ | ✓ | ✗ | ✓ | ✗ |
| **Hybrid LCA** | ✗ | ✓ | ✗ | ✓ | ✗ |
| **MFA (or SFA)** | ✓ | ✓ | ✓ | ✓ | ✗ |
| **ALCA** | ✓ | ✓ | ✓ | ✓ | ✗ |

| | | | | | |
|---|---|---|---|---|---|
| **LCM** | ✗ | ✓ | ✓ | ✗ | ✗ |
| **LCC (or WLC)** | ✓ | ✓ | ✓ | ✗ | ✗ |
| **SLCA** | ✓ | ✓ | ✓ | ✗ | ✗ |
| **LCIA** | ✓ | ✗ | ✗ | ✓ | ✗ |
| **LCI** | ✓ | ✓ | ✗ | ✓ | ✗ |
| **LCSA** | ✓ | ✓ | ✗ | ✓ | ✓ |
| **Streamlined LCA** | ✓ | ✓ | ✗ | ✓ | ✓ |
| **EEA** | ✓ | ✓ | ✓ | ✗ | ✗ |
| **REA** | ✗ | ✓ | ✓ | ✗ | ✗ |

**Table 24: Selection LCA Methodology**

# I Excel Calculations

Fast Track LCA Calculations (Public)

# J Calculations Excluding Assumptions

Figure 17 displays the Excel calculation sheet for the Carbon Footprint, excluding assumptions.

| **Manufacturing** | **item** | **database name** | **Eco-intensity (impacts per kg)** | **Mass per item (kg)** | **Items per func.unit (#)** | **Uncertainty %** | **Notes** | **Calculated Impact** |
|---|---|---|---|---|---|---|---|---|
| | Aluminium (5754) | Idemat2023 AlMg3 (5754a) | 11.851 | 2.157 | 1 | 10% | | 25.565645 |
| | Aluminium (Anodized) | Idemat2023 AlMg3 (5754a) | 11.851 | 0.004 | 1 | 30% | | 0.0426647 |
| | Aluminium (6082) | Idemat2023 AlMgSi0.5 (6060) | 12.945 | 2.565 | 1 | 30% | | 33.20164 |
| | Aluminium (5083) | Idemat2023 AlMg1 (5005) | 11.735 | 0.211 | 1 | 30% | | 2.4737944 |
| | Aluminium (ALSi9 EN AB-44400) | Idemat2023 Aluminium trade mix (80% prim 20% sec) | 7.631 | 1.759 | 1 | 30% | | 13.426069 |
| | Aluminium (7075) | Idemat2023 AlZnCuMg (7075) | 11.584 | 0.026 | 1 | 10% | | 0.2965502 |
| | Plastic (PA6) | Idemat2023 PA 6 (Nylon 6, Polyamide 6) | 6.700 | 2.091 | 1 | 10% | | 14.00836 |
| | Plastic (PVC) | Idemat2023 PVC (Polyvinylchloride, trade mix) | 2.104 | 0.830 | 1 | 10% | | 1.7454784 |
| | Plastic (HMPE) | Idemat2023 PE (Polyethylene) expanded | 2.397 | 7.246 | 1 | 30% | | 17.366531 |
| | Plastic (HDPE) | Idemat2023 PE (HDPE, High density Polyethylene) | 1.800 | 0.916 | 1 | 10% | | 1.64916 |
| | Plastic (ABS) | Idemat2023 ABS (Acrylonitrile butadiene styrene) | 3.100 | 10.027 | 1 | 10% | | 31.08246 |
| | Plastic (PA66) | Idemat2023 PA 66 (Nylon 66, Polyamide 6-6) | 6.400 | 0.218 | 1 | 10% | | 1.3952 |
| | Plastic (3M3690 laminate 3M8993) | Idemat2023 Hylite (1 m2, 1.2 mm thickness, 1.8 ton/m3) | 12.759 | 0.123 | 1 | 30% | | 1.5731915 |
| | Plastic (PC) | Idemat2023 PC (Polycarbonate) | 3.400 | 0.702 | 1 | 10% | | 2.38612 |
| | Plastic (PE) | Idemat2023 PE (Polyethylene) expanded | 2.397 | 2.152 | 1 | 10% | | 5.1566101 |
| | Plastic (PET) | Idemat2023 PET 30% glass fibre | 1.905 | 0.992 | 1 | 10% | | 1.8891885 |
| | Plastic (POM) | Idemat2023 POM (Polyoxymethyleen, polyacetaal) | 3.200 | 0.335 | 1 | 10% | | 1.07232 |
| | Plastic (PP) | Idemat2023 PP (Polypropylene) | 1.630 | 0.005 | 1 | 10% | | 0.007335 |
| | Plastic (PS) | Idemat2023 PS (GPPS, general purpose polystyrene) | 2.250 | 0.190 | 1 | 10% | | 0.426825 |
| | Plastic (PU) | Idemat2023 PU (polyurethane) rubber for shoe soles | 4.359 | 0.688 | 1 | 10% | | 2.9975148 |
| | Stainless-steel (304) | Idemat2023 X5CrNi18 (304) 70% inox scrap (EU, USA) | 3.939 | 71.741 | 1 | 10% | | 282.58833 |
| | Stainless-steel (301) | Idemat2023 X12CrNi17 7 (301) 70% inox scrap (EU, USA) | 3.244 | 0.029 | 1 | 10% | | 0.0934196 |
| | Stainless-steel (303) | Idemat2023 X10CrNiS (303) 70% inox scrap (EU, USA) | 3.838 | 0.920 | 1 | 10% | | 3.5298733 |
| | Stainless-steel (304L) | Idemat2023 X5CrNi18 (304) 70% inox scrap (EU, USA) | 3.939 | 607.332 | 1 | 10% | | 2392.2956 |
| | Stainless-steel (316) | Idemat2023 X5CrNiMo18 (316) 70% inox scrap (EU, USA) | 4.021 | 0.393 | 1 | 30% | | 1.5786593 |
| | Stainless-steel (Unspecified) | Idemat2023 Stainless Steel (secondary), average | 1.965 | 7.986 | 1 | 30% | | 15.693356 |
| | Steel (S235JR) | Idemat2023 Steel (21% sec = trade mix average) EU | 0.958 | 221.386 | 1 | 30% | | 211.99206 |
| | Steel (S235JR Galvanized) | Idemat2023 Steel (21% sec = trade mix average) EU | 0.958 | 4.468 | 1 | 30% | | 4.2787031 |
| | Steel (S235JR Zinc plated) | Idemat2023 Steel (21% sec = trade mix average) EU | 0.958 | 0.253 | 1 | 30% | | 0.2425521 |
| | Steel (S275J2) | Idemat2023 Steel (21% sec = trade mix average) EU | 0.958 | 1.176 | 1 | 30% | | 1.1260047 |
| | Steel (42CrMoS4) | Idemat2023 42CrMo4 | 1.245 | 6.326 | 1 | 10% | | 7.8758757 |
| | Steel (C45) | Idemat2023 C45 | 1.120 | 0.313 | 1 | 10% | | 0.3503538 |
| | Steel (S355J2) | Idemat2023 Steel (21% sec = trade mix average) EU | 0.958 | 59.625 | 1 | 30% | | 57.095306 |
| | Steel (GGG40) | Idemat2023 GGG40 | 1.464 | 13.544 | 1 | 10% | | 19.831964 |
| | Steel (Springs Class B) | Idemat2023 67SiCr5 | 1.144 | 0.001 | 1 | 30% | | 0.0012579 |
| | Steel (Springs Class C) | Idemat2023 67SiCr5 | 1.144 | 0.463 | 1 | 30% | | 0.5293304 |
| | Steel (40MnB4) | Idemat2023 37MnSi5 | 1.037 | 12.347 | 1 | 30% | | 12.808288 |
| | Steel (11SMn30) | Idemat2023 9SMnPb (1.0718) | 0.980 | 3.304 | 1 | 30% | | 3.2378272 |
| | Rubber (NBR) | Idemat2023 NBR (nitrile rubber) | 3.688 | 0.057 | 1 | 10% | | 0.211322 |
| | Rubber (RB10) | Idemat2023 BR (butadiene rubber) | 4.083 | 0.165 | 1 | 10% | | 0.6723977 |
| | Rubber (EPDM) | Idemat2023 EPDM (ethylene propylene diene monomer rubber) | 2.458 | 0.196 | 1 | 10% | | 0.4807958 |
| | Rubber (Unspecified) | Idemat2023 Natural rubber | 1.412 | 12.400 | 1 | 30% | | 17.50323 |
| | **subtotal Bill of Materials (BOM)** | | weight check: | 1057.6577 | | | **3192** | 0 |
| **Manufacturing** | | | **Eco-intensity (impacts per MJ)** | **Energy per activity (MJ)** | **Items per func.unit (#)** | **Uncertainty %** | **Notes** | |
| | Electricity consumption | Idemat2023 Electricity Netherlands | 0.094 | 4,195 | 1 | 10% | including heating | 393.84474 |
| | **subtotal** | | | | | | **394** | 0 |
| **total manufacturing** | | | | | | | **3586** | 0 |
| **Transport** | | | **Eco-Intensity (impacts/ ton-km)** | **Mass per item (ton)** | **Distance per item (km)** | **Uncertainty %** | **Notes** | **Calculated Impact** |
| | Truck (upstream) | Idemat2023 Truck+trailer 24 tons net (min weight/volume ratio | 0.091 | 0.16 | 56612 | 30% | | 824.51742 |
| | Boat (upstream) | Idemat2023 Container feeder Handysize 1577 TEU 13 knots | 0.011 | 0.04 | 1003746 | 30% | | 396.62596 |
| | Truck (downstream) | Idemat2023 Truck+trailer 24 tons net (min weight/volume ratio | 0.091 | 1.36 | 707 | 30% | | 87.08493 |
| | | | | | | | | 0 |
| **total transport** | | | | | | | **1308** | 0 |
| **Use** | | | **Eco-Intensity (impacts/MJ or other)** | **Amount per item (MJ or other)** | **Items per func.unit (#)** | **Uncertainty %** | **Notes** | **Calculated Impact** |
| | Electricity use (Europe avg) | Idemat2023 Electricity EU-27 | 0.094 | 236,520 | 1 | 30% | | 22206.655 |
| **total use** | | | | | | | **22207** | |
| **End of Life** | | | **Eco-Intensity (impacts/kg)** | **Mass per item (kg)** | **Items per func.unit (#)** | **Uncertainty %** | **Notes** | **Calculated Impact** |
| | | | | | | | | 0 |
| **total end-of-life** | | | | | | | **0** | |

**Figure 17: Carbon footprint calculations excluding assumptions.**

Figure 18 displays the Excel calculation sheet for the Eco-costs, excluding assumptions.

| Manufacturing | item | database name | Eco-intensity (impacts per kg) | Mass per item (kg) | Items per func.unit (#) | Uncertainty % | Notes | Calculated Impact |
|---|---|---|---|---|---|---|---|---|
| | Aluminium (5754) | Idemat2023 AlMg3 (5754a) | 3.027 | 2.157 | 1 | 10% | | 6.5296973 |
| | Aluminium (Anodized) | Idemat2023 AlMg3 (5754a) | 3.027 | 0.004 | 1 | 30% | | 0.010897 |
| | Aluminium (6082) | Idemat2023 AlMgSi0.5 (6060) | 3.293 | 2.565 | 1 | 30% | | 8.445158 |
| | Aluminium (5083) | Idemat2023 AlMg1 (5005) | 3.066 | 0.211 | 1 | 30% | | 0.6463534 |
| | Aluminium (ALSi9 EN AB-44400) | Idemat2023 Aluminium trade mix (80% prim 20% sec) | 2.210 | 1.759 | 1 | 30% | | 3.8883321 |
| | Aluminium (7075) | Idemat2023 AlZnCuMg (7075) | 3.050 | 0.026 | 1 | 10% | | 0.0780923 |
| | Plastic (PA6) | Idemat2023 PA 6 (Nylon 6, Polyamide 6) | 1.640 | 2.091 | 1 | 10% | | 3.4279662 |
| | Plastic (PVC) | Idemat2023 PVC (Polyvinylchloride, trade mix) | 0.735 | 0.830 | 1 | 10% | | 0.6095766 |
| | Plastic (HMPE) | Idemat2023 PE (Polyethylene) expanded | 1.252 | 7.246 | 1 | 30% | | 9.0699049 |
| | Plastic (HDPE) | Idemat2023 PE (HDPE, High density Polyethylene) | 1.157 | 0.916 | 1 | 10% | | 1.0597818 |
| | Plastic (ABS) | Idemat2023 ABS (Acrylonitrile butadiene styrene) | 1.314 | 10.027 | 1 | 10% | | 13.174652 |
| | Plastic (PA66) | Idemat2023 PA 66 (Nylon 66, Polyamide 6-6) | 1.609 | 0.218 | 1 | 10% | | 0.3507499 |
| | Plastic (3M3690 laminate 3M8993) | Idemat2023 Hylite (1 m2, 1.2 mm thickness, 1.8 ton/m3) | 4.656 | 0.123 | 1 | 30% | | 0.5740457 |
| | Plastic (PC) | Idemat2023 PC (Polycarbonate) | 1.275 | 0.702 | 1 | 10% | | 0.8947005 |
| | Plastic (PE) | Idemat2023 PE (Polyethylene) expanded | 1.252 | 2.152 | 1 | 10% | | 2.6931091 |
| | Plastic (PET) | Idemat2023 PET 30% glass fibre | 0.796 | 0.992 | 1 | 10% | | 0.7896002 |
| | Plastic (POM) | Idemat2023 POM (Polyoxymethyleen, polyacetaal) | 0.854 | 0.335 | 1 | 10% | | 0.2863047 |
| | Plastic (PP) | Idemat2023 PP (Polypropylene) | 1.134 | 0.005 | 1 | 10% | | 0.0051011 |
| | Plastic (PS) | Idemat2023 PS (GPPS, general purpose polystyrene) | 1.254 | 0.190 | 1 | 10% | | 0.2378672 |
| | Plastic (PU) | Idemat2023 PU (polyurethane) rubber for shoe soles | 1.428 | 0.688 | 1 | 10% | | 0.9817579 |
| | Stainless-steel (304) | Idemat2023 X5CrNi18 (304) 70% inox scrap (EU, USA) | 1.381 | 71.741 | 1 | 10% | | 99.073553 |
| | Stainless-steel (301) | Idemat2023 X12CrNi17 7 (301) 70% inox scrap (EU, USA) | 0.725 | 0.029 | 1 | 10% | | 0.0208866 |
| | Stainless-steel (303) | Idemat2023 X10CrNiS (303) 70% inox scrap (EU, USA) | 1.308 | 0.920 | 1 | 10% | | 1.2029698 |
| | Stainless-steel (304L) | Idemat2023 X5CrNi18 (304) 70% inox scrap (EU, USA) | 1.381 | 607.332 | 1 | 10% | | 838.72263 |
| | Stainless-steel (316) | Idemat2023 X5CrNiMo18 (316) 70% inox scrap (EU, USA) | 1.722 | 0.393 | 1 | 30% | | 0.6760427 |
| | Stainless-steel (Unspecified) | Idemat2023 Stainless Steel (secondary), average | 0.427 | 7.986 | 1 | 30% | | 3.412867 |
| | Steel (S235JR) | Idemat2023 Steel (21% sec = trade mix average) EU | 0.210 | 221.386 | 1 | 30% | | 46.386853 |
| | Steel (S235JR Galvanized) | Idemat2023 Steel (21% sec = trade mix average) EU | 0.210 | 4.468 | 1 | 30% | | 0.9362406 |
| | Steel (S235JR Zinc plated) | Idemat2023 Steel (21% sec = trade mix average) EU | 0.210 | 0.253 | 1 | 30% | | 0.0530738 |
| | Steel (S275J2) | Idemat2023 Steel (21% sec = trade mix average) EU | 0.210 | 1.176 | 1 | 30% | | 0.2463857 |
| | Steel (42CrMoS4) | Idemat2023 42CrMo4 | 0.281 | 6.326 | 1 | 10% | | 1.7797875 |
| | Steel (C45) | Idemat2023 C45 | 0.353 | 0.313 | 1 | 10% | | 0.1103916 |
| | Steel (S355J2) | Idemat2023 Steel (21% sec = trade mix average) EU | 0.210 | 59.625 | 1 | 30% | | 12.493258 |
| | Steel (GGG40) | Idemat2023 GGG40 | 0.274 | 13.544 | 1 | 10% | | 3.7044892 |
| | Steel (Springs Class B) | Idemat2023 67SiCr5 | 0.261 | 0.001 | 1 | 30% | | 0.0002866 |
| | Steel (Springs Class C) | Idemat2023 67SiCr5 | 0.261 | 0.463 | 1 | 30% | | 0.1206085 |
| | Steel (40MnB4) | Idemat2023 37MnSi5 | 0.241 | 12.347 | 1 | 30% | | 2.9812761 |
| | Steel (11SMn30) | Idemat2023 9SMnPb (1.0718) | 0.225 | 3.304 | 1 | 30% | | 0.7425392 |
| | Rubber (NBR) | Idemat2023 NBR (nitrile rubber) | 1.510 | 0.057 | 1 | 10% | | 0.0865194 |
| | Rubber (RB10) | Idemat2023 BR (butadiene rubber) | 1.721 | 0.165 | 1 | 10% | | 0.2834097 |
| | Rubber (EPDM) | Idemat2023 EPDM (ethylene propylene diene monomer rubber) | 1.303 | 0.196 | 1 | 10% | | 0.2549174 |
| | Rubber (Unspecified) | Idemat2023 NBR (nitrile rubber) | 1.510 | 12.400 | 1 | 30% | | 18.723221 |
| | **subtotal Bill of Materials (BOM)** | Incl. packaging | weight check: | 1057.6577 | | | **1086** | 0 |
| **Manufacturing** | | | **Eco-intensity (impacts per MJ)** | **Energy per activity (MJ)** | **Items per func.unit (#)** | **Uncertainty %** | **Notes** | |
| | Electricity consumption | Idemat2023 Electricity Netherlands | 0.020 | 4195 | 1 | 10% | including heating | 85.142251 |
| | **subtotal** | | | | | | **85** | 0 |
| **total manufacturing** | | | | | | | **1171** | 0 |
| **Transport (upstream and downstream)** | | | **Eco-Intensity (impacts/ ton-km)** | **Mass per item (ton)** | **Distance per item (km)** | **Uncertainty %** | **Notes** | **Calculated Impact** |
| | Truck (upstream) | Idemat2023 Truck+trailer 24 tons net (min weight/volume ratio 0,32 ton/m3) (tk | 0.026 | 0.16 | 56612 | 30% | | 236.86086 |
| | Boat (upstream) | Idemat2023 Container feeder Handysize 1577 TEU 13 knots | 0.003 | 0.04 | 1003746 | 30% | | 115.58138 |
| | Truck (downstream) | Idemat2023 Truck+trailer 24 tons net (min weight/volume ratio 0,32 ton/m3) (tk | 0.026 | 1.36 | 707 | 30% | | 25.017072 |
| | | | | | | | | 0 |
| **total transport** | | | | | | | **352** | 0 |
| **Use** | | | **Eco-Intensity (impacts/MJ or other)** | **Amount per item (MJ or other)** | **Items per func.unit (#)** | **Uncertainty %** | **Notes** | **Calculated Impact** |
| | Electricity use (Europe avg) | Idemat2023 Electricity EU-27 | 0.020 | 236520 | 1 | 10% | | 4800.6851 |
| **total use** | | | | | | | **4801** | |
| **End of Life** | | | **Eco-Intensity (impacts/kg)** | **Mass per item (kg)** | **Items per func.unit (#)** | **Uncertainty %** | **Notes** | **Calculated Impact** |
| | | | | | | | | 0 |
| **total end-of-life** | | | | | | | **0** | |

**Figure 18: Eco-costs calculations excluding assumptions.**

# K Calculations Including Assumptions

Figure 19 displays the Excel calculation sheet for the Carbon Footprint, including assumptions. The areas highlighted in green show the changes compared to the calculations excluding assumptions.

| Manufacturing | item | database name | Eco-intensity (impacts per kg) | Mass per item (kg) | Items per func.unit (#) | Uncertainty % | Notes | Calculated Impact |
|---|---|---|---|---|---|---|---|---|
| | Aluminium (5754) | Idemat2023 AlMg3 (5754a) | 11.851 | 2.157 | 1 | 10% | | 25.565645 |
| | Aluminium (Anodized) | Idemat2023 AlMg3 (5754a) | 11.851 | 0.004 | 1 | 30% | | 0.0426647 |
| | Aluminium (6082) | Idemat2023 AlMgSi0.5 (6060) | 12.945 | 2.565 | 1 | 30% | | 33.20164 |
| | Aluminium (5083) | Idemat2023 AlMg1 (5005) | 11.735 | 0.211 | 1 | 30% | | 2.4737944 |
| | Aluminium (ALSi9 EN AB-44400) | Idemat2023 Aluminium trade mix (80% prim 20% sec) | 7.631 | 1.759 | 1 | 30% | | 13.426069 |
| | Aluminium (7075) | Idemat2023 AlZnCuMg (7075) | 11.584 | 0.026 | 1 | 10% | | 0.2965502 |
| | Plastic (PA6) | Idemat2023 PA 6 (Nylon 6, Polyamide 6) | 6.700 | 2.091 | 1 | 10% | | 14.00836 |
| | Plastic (PVC) | Idemat2023 PVC (Polyvinylchloride, trade mix) | 2.104 | 0.830 | 1 | 10% | | 1.7454784 |
| | Plastic (HMPE) | Idemat2023 PE (Polyethylene) expanded | 2.397 | 7.246 | 1 | 30% | | 17.366531 |
| | Plastic (HDPE) | Idemat2023 PE (HDPE, High density Polyethylene) | 1.800 | 0.916 | 1 | 10% | | 1.64916 |
| | Plastic (ABS) | Idemat2023 ABS (Acrylonitrile butadiene styrene) | 3.100 | 10.027 | 1 | 10% | | 31.08246 |
| | Plastic (PA66) | Idemat2023 PA 66 (Nylon 66, Polyamide 6-6) | 6.400 | 0.218 | 1 | 10% | | 1.3952 |
| | Plastic (3M3690 laminate 3M8993) | Idemat2023 Hylite (1 m2, 1.2 mm thickness, 1.8 ton/m3) | 12.759 | 0.123 | 1 | 30% | | 1.5731915 |
| | Plastic (PC) | Idemat2023 PC (Polycarbonate) | 3.400 | 0.702 | 1 | 10% | | 2.38612 |
| | Plastic (PE) | Idemat2023 PE (Polyethylene) expanded | 2.397 | 2.152 | 1 | 10% | | 5.1566101 |
| | Plastic (PET) | Idemat2023 PET 30% glass fibre | 1.905 | 0.992 | 1 | 10% | | 1.8891885 |
| | Plastic (POM) | Idemat2023 POM (Polyoxymethyleen, polyacetaal) | 3.200 | 0.335 | 1 | 10% | | 1.07232 |
| | Plastic (PP) | Idemat2023 PP (Polypropylene) | 1.630 | 0.005 | 1 | 10% | | 0.007335 |
| | Plastic (PS) | Idemat2023 PS (GPPS, general purpose polystyrene) | 2.250 | 0.190 | 1 | 10% | | 0.426825 |
| | Plastic (PU) | Idemat2023 PU (polyurethane) rubber for shoe soles | 4.359 | 0.688 | 1 | 10% | | 2.9975148 |
| | Stainless-steel (304) | Idemat2023 X5CrNi18 (304) 70% inox scrap (EU, USA) | 3.939 | 71.741 | 1 | 10% | | 282.58833 |
| | Stainless-steel (301) | Idemat2023 X12CrNi17 7 (301) 70% inox scrap (EU, USA) | 3.244 | 0.029 | 1 | 10% | | 0.0934196 |
| | Stainless-steel (303) | Idemat2023 X10CrNiS (303) 70% inox scrap (EU, USA) | 3.838 | 0.920 | 1 | 10% | | 3.5298733 |
| | Stainless-steel (304L) | Idemat2023 X5CrNi18 (304) 70% inox scrap (EU, USA) | 3.939 | 607.332 | 1 | 10% | | 2392.2956 |
| | Stainless-steel (316) | Idemat2023 X5CrNiMo18 (316) 70% inox scrap (EU, USA) | 4.021 | 0.393 | 1 | 30% | | 1.5786593 |
| | Stainless-steel (Unspecified) | Idemat2023 Stainless Steel (secondary), average | 1.965 | 7.986 | 1 | 30% | | 15.693356 |
| | Steel (S235JR) | Idemat2023 Steel (21% sec = trade mix average) EU | 0.958 | 221.386 | 1 | 30% | | 211.99206 |
| | Steel (S235JR Galvanized) | Idemat2023 Steel (21% sec = trade mix average) EU | 0.958 | 4.468 | 1 | 30% | | 4.2787031 |
| | Steel (S235JR Zinc plated) | Idemat2023 Steel (21% sec = trade mix average) EU | 0.958 | 0.253 | 1 | 30% | | 0.2425521 |
| | Steel (S275J2) | Idemat2023 Steel (21% sec = trade mix average) EU | 0.958 | 1.176 | 1 | 30% | | 1.1260047 |
| | Steel (42CrMoS4) | Idemat2023 42CrMo4 | 1.245 | 6.326 | 1 | 10% | | 7.8758757 |
| | Steel (C45) | Idemat2023 C45 | 1.120 | 0.313 | 1 | 10% | | 0.3503538 |
| | Steel (S355J2) | Idemat2023 Steel (21% sec = trade mix average) EU | 0.958 | 59.625 | 1 | 30% | | 57.095306 |
| | Steel (GGG40) | Idemat2023 GGG40 | 1.464 | 13.544 | 1 | 10% | | 19.831964 |
| | Steel (Springs Class B) | Idemat2023 67SiCr5 | 1.144 | 0.001 | 1 | 30% | | 0.0012579 |
| | Steel (Springs Class C) | Idemat2023 67SiCr5 | 1.144 | 0.463 | 1 | 30% | | 0.5293304 |
| | Steel (40MnB4) | Idemat2023 37MnSi5 | 1.037 | 12.347 | 10 | 30% | | 128.08288 |
| | Steel (11SMn30) | Idemat2023 9SMnPb (1.0718) | 0.980 | 3.304 | 1 | 30% | | 3.2378272 |
| | Rubber (NBR) | Idemat2023 NBR (nitrile rubber) | 3.688 | 0.057 | 1 | 10% | | 0.211322 |
| | Rubber (RB10) | Idemat2023 BR (butadiene rubber) | 4.083 | 0.165 | 1 | 10% | | 0.6723977 |
| | Rubber (EPDM) | Idemat2023 EPDM (ethylene propylene diene monomer rubber | 2.458 | 0.196 | 1 | 10% | | 0.4807958 |
| | Rubber (Unspecified) | Idemat2023 Natural rubber | 1.412 | 12.400 | 3.3 | 30% | | 57.760659 |
| | Steel Part | Idemat2023 Steel (21% sec = trade mix average) EU | 0.958 | 51.776 | 1 | 30% | | 49.579256 |
| | Electric motor | Idemat2023 Electric motor, less than 500 W, estimate | 2.650 | 34.517 | 1 | 30% | | 91.471075 |
| | Steel Part | Idemat2023 Steel (21% sec = trade mix average) EU | 0.958 | 27.474 | 1 | 30% | | 26.307757 |
| | Steel Part | Idemat2023 Steel (21% sec = trade mix average) EU | 0.958 | 20.733 | 1 | 30% | | 19.853267 |
| | Steel Part | Idemat2023 Steel (21% sec = trade mix average) EU | 0.958 | 11.513 | 1 | 30% | | 11.024486 |
| | Steel Part | Idemat2023 Steel (21% sec = trade mix average) EU | 0.958 | 10.758 | 1 | 30% | | 10.301521 |
| | Stainless steel part (431) | Idemat2023 X22CrNi17 (431) 70% inox scrap (EU, USA) | 3.517 | 10.404 | 1 | 30% | | 36.592379 |
| | Electric motor | Idemat2023 Electric motor, less than 500 W, estimate | 2.650 | 14.023 | 1 | 100% | | 37.162248 |
| | Bumper spring assembly | Idemat2023 67SiCr5 | 1.144 | 6.375 | 5 | 30% | | 36.449355 |
| | New drive wheel MFR | Idemat2023 PU (polyurethane) rubber for shoe soles | 4.359 | 10.210 | 5 | 30% | | 222.54673 |
| | Wheel of Swivel Castor (steel) | Idemat2023 X5CrNi18 (304) 70% inox scrap (EU, USA) | 3.939 | 3.660 | 5 | 30% | | 72.084136 |
| | Wheel of Swivel Castor (plastic) | Idemat2023 PU (polyurethane) rubber for shoe soles | 4.359 | 4.740 | 5 | 30% | | 103.32402 |
| | Swivel wheel ( steel and bearing) | Idemat2023 X5CrNi18 (304) 70% inox scrap (EU, USA) | 3.939 | 7.450 | 3.3 | 30% | | 96.840901 |
| | Accu | Idemat2023 Lead battery cars (39 Wh per kg) | 0.601 | 78.922 | 5 | 100% | | 237.04034 |
| | **subtotal Bill of Materials (BOM)** | | weight check: | 1350.21168 | | | **4398** | 0 |
| **Manufacturing** | | | **Eco-intensity (impacts per MJ)** | **Energy per activity (MJ)** | **Items per func.unit (#)** | **Uncertainty %** | **Notes** | |
| | Electricity consumption | Idemat2023 Electricity Netherlands | 0.094 | 4,195 | 1 | 10% | including heating | 393.84474 |
| | **subtotal** | | | | | | **394** | 0 |
| **total manufacturing** | | | | | | | **4792** | 0 |
| **Transport** | | | **Eco-Intensity (impacts/ ton-km)** | **Mass per item (ton)** | **Distance per item (km)** | **Uncertainty %** | **Notes** | **Calculated Impact** |
| | Truck (upstream) | Idemat2023 Truck+trailer 24 tons net (min weight/volume rat | 0.091 | 1.45 | 56708 | 30% | | 7453.7457 |
| | Boat (upstream) | Idemat2023 Container feeder Handysize 1577 TEU 13 knots | 0.011 | 0.04 | 1003746 | 30% | | 396.62641 |
| | | | | | | | | 0 |
| | Truck (downsteam) | Idemat2023 Truck+trailer 24 tons net (min weight/volume rat | 0.091 | 1.36 | 774 | 30% | | 95.281608 |
| **total transport** | | | | | | | **7946** | 0 |
| **Use** | | | **Eco-Intensity (impacts/MJ or other)** | **Amount per item (MJ or other)** | **Items per func.unit (#)** | **Uncertainty %** | **Notes** | **Calculated Impact** |
| | Electricity use (Europe avg) | Idemat2023 Electricity EU-27 | 0.094 | 236,520 | 1 | 30% | | 22206.655 |
| **total use** | | | | | | | **22207** | |
| **End of Life** | | | **Eco-Intensity (impacts/kg)** | **Mass per item (kg)** | **Items per func.unit (#)** | **Uncertainty %** | **Notes** | **Calculated Impact** |
| | | | | | | | | 0 |
| **total end-of-life** | | | | | | | **0** | |

**Figure 19: Carbon footprint calculations including assumptions.**

Figure 20 displays the Excel calculation sheet for the Eco-costs, including assumptions.

| Manufacturing | item | database name | Eco-intensity (impacts per kg) | Mass per item (kg) | Items per func.unit (#) | Uncertainty % | Notes |
|---|---|---|---|---|---|---|---|
| | Aluminium (5754) | Idemat2023 AlMg3 (5754a) | 3.027 | 2.157 | 1 | 10% | |
| | Aluminium (Anodized) | Idemat2023 AlMg3 (5754a) | 3.027 | 0.004 | 1 | 30% | |
| | Aluminium (6082) | Idemat2023 AlMgSi0.5 (6060) | 3.293 | 2.565 | 1 | 30% | |
| | Aluminium (5083) | Idemat2023 AlMg1 (5005) | 3.066 | 0.211 | 1 | 30% | |
| | Aluminium (ALSi9 EN AB-44400) | Idemat2023 Aluminium trade mix (80% prim 20% sec) | 2.210 | 1.759 | 1 | 30% | |
| | Aluminium (7075) | Idemat2023 AlZnCuMg (7075) | 3.050 | 0.026 | 1 | 10% | |
| | Plastic (PA6) | Idemat2023 PA 6 (Nylon 6, Polyamide 6) | 1.640 | 2.091 | 1 | 10% | |
| | Plastic (PVC) | Idemat2023 PVC (Polyvinylchloride, trade mix) | 0.735 | 0.830 | 1 | 10% | |
| | Plastic (HMPE) | Idemat2023 PE (Polyethylene) expanded | 1.252 | 7.246 | 1 | 30% | |
| | Plastic (HDPE) | Idemat2023 PE (HDPE, High density Polyethylene) | 1.157 | 0.916 | 1 | 10% | |
| | Plastic (ABS) | Idemat2023 ABS (Acrylonitrile butadiene styrene) | 1.314 | 10.027 | 1 | 10% | |
| | Plastic (PA66) | Idemat2023 PA 66 (Nylon 66, Polyamide 6-6) | 1.609 | 0.218 | 1 | 10% | |
| | Plastic (3M3690 laminate 3M8993) | Idemat2023 Hylite (1 m2, 1.2 mm thickness, 1.8 ton/m3) | 4.656 | 0.123 | 1 | 30% | |
| | Plastic (PC) | Idemat2023 PC (Polycarbonate) | 1.275 | 0.702 | 1 | 10% | |
| | Plastic (PE) | Idemat2023 PE (Polyethylene) expanded | 1.252 | 2.152 | 1 | 10% | |
| | Plastic (PET) | Idemat2023 PET 30% glass fibre | 0.796 | 0.992 | 1 | 10% | |
| | Plastic (POM) | Idemat2023 POM (Polyoxymethyleen, polyacetaal) | 0.854 | 0.335 | 1 | 10% | |
| | Plastic (PP) | Idemat2023 PP (Polypropylene) | 1.134 | 0.005 | 1 | 10% | |
| | Plastic (PS) | Idemat2023 PS (GPPS, general purpose polystyrene) | 1.254 | 0.190 | 1 | 10% | |
| | Plastic (PU) | Idemat2023 PU (polyurethane) rubber for shoe soles | 1.428 | 0.688 | 1 | 10% | |
| | Stainless-steel (304) | Idemat2023 X5CrNi18 (304) 70% inox scrap (EU, USA) | 1.381 | 71.741 | 1 | 10% | |
| | Stainless-steel (301) | Idemat2023 X12CrNi17 7 (301) 70% inox scrap (EU, USA) | 0.725 | 0.029 | 1 | 10% | |
| | Stainless-steel (303) | Idemat2023 X10CrNiS (303) 70% inox scrap (EU, USA) | 1.308 | 0.920 | 1 | 10% | |
| | Stainless-steel (304L) | Idemat2023 X5CrNi18 (304) 70% inox scrap (EU, USA) | 1.381 | 607.332 | 1 | 10% | |
| | Stainless-steel (316) | Idemat2023 X5CrNiMo18 (316) 70% inox scrap (EU, USA) | 1.722 | 0.393 | 1 | 30% | |
| | Stainless-steel (Unspecified) | Idemat2023 Stainless Steel (secondary), average | 0.427 | 7.986 | 1 | 30% | |
| | Steel (S235JR) | Idemat2023 Steel (21% sec = trade mix average) EU | 0.210 | 221.386 | 1 | 30% | |
| | Steel (S235JR Galvanized) | Idemat2023 Steel (21% sec = trade mix average) EU | 0.210 | 4.468 | 1 | 30% | |
| | Steel (S235JR Zinc plated) | Idemat2023 Steel (21% sec = trade mix average) EU | 0.210 | 0.253 | 1 | 30% | |
| | Steel (S275J2) | Idemat2023 Steel (21% sec = trade mix average) EU | 0.210 | 1.176 | 1 | 30% | |
| | Steel (42CrMoS4) | Idemat2023 42CrMo4 | 0.281 | 6.326 | 1 | 10% | |
| | Steel (C45) | Idemat2023 C45 | 0.353 | 0.313 | 1 | 10% | |
| | Steel (S355J2) | Idemat2023 Steel (21% sec = trade mix average) EU | 0.210 | 59.625 | 1 | 30% | |
| | Steel (GGG40) | Idemat2023 GGG40 | 0.274 | 13.544 | 1 | 10% | |
| | Steel (Springs Class B) | Idemat2023 67SiCr5 | 0.261 | 0.001 | 1 | 30% | |
| | Steel (Springs Class C) | Idemat2023 67SiCr5 | 0.261 | 0.463 | 1 | 30% | |
| | Steel (40MnB4) | Idemat2023 37MnSi5 | 0.241 | 12.347 | 10 | 30% | |
| | Steel (11SMn30) | Idemat2023 9SMnPb (1.0718) | 0.225 | 3.304 | 1 | 30% | |
| | Rubber (NBR) | Idemat2023 NBR (nitrile rubber) | 1.510 | 0.057 | 1 | 10% | |
| | Rubber (RB10) | Idemat2023 BR (butadiene rubber) | 1.721 | 0.165 | 1 | 10% | |
| | Rubber (EPDM) | Idemat2023 EPDM (ethylene propylene diene monomer rubber) | 1.303 | 0.196 | 1 | 10% | |
| | Rubber (Unspecified) | Idemat2023 NBR (nitrile rubber) | 1.510 | 12.400 | 3.3 | 30% | |
| | Steel Part | Idemat2023 Steel (21% sec = trade mix average) EU | 0.210 | 51.776 | 1 | 30% | |
| | Electric motor | Idemat2023 Electric motor, less than 500 W, estimate | 1.341 | 34.517 | 1 | 30% | |
| | Steel Part | Idemat2023 Steel (21% sec = trade mix average) EU | 0.210 | 27.474 | 1 | 30% | |
| | Steel Part | Idemat2023 Steel (21% sec = trade mix average) EU | 0.210 | 20.733 | 1 | 30% | |
| | Steel Part | Idemat2023 Steel (21% sec = trade mix average) EU | 0.210 | 11.513 | 1 | 30% | |
| | Steel Part | Idemat2023 Steel (21% sec = trade mix average) EU | 0.210 | 10.758 | 1 | 30% | |
| | Stainless steel part (431) | Idemat2023 X22CrNi17 (431) 70% inox scrap (EU, USA) | 0.881 | 10.404 | 1 | 30% | |
| | Electric motor | Idemat2023 Electric motor, less than 500 W, estimate | 1.341 | 14.023 | 1 | 100% | |
| | Bumper spring assembly | Idemat2023 67SiCr5 | 1.144 | 6.375 | 5 | 30% | |
| | New drive wheel MFR | Idemat2023 PU (polyurethane) rubber for shoe soles | 4.359 | 10.210 | 5 | 30% | |
| | Wheel of Swivel Castor (steel) | Idemat2023 X5CrNi18 (304) 70% inox scrap (EU, USA) | 3.939 | 3.660 | 5 | 30% | |
| | Wheel of Swivel Castor (plastic) | Idemat2023 PU (polyurethane) rubber for shoe soles | 4.359 | 4.740 | 5 | 30% | |
| | Swivel wheel (steel and bearing) | Idemat2023 X5CrNi18 (304) 70% inox scrap (EU, USA) | 3.939 | 7.450 | 3.3 | 30% | |
| | Accu | Idemat2023 Lead battery cars (39 Wh per kg) | 0.601 | 78.922 | 5 | 100% | |
| | **subtotal Bill of Materials (BOM)** | Incl. packaging | weight check: | 1350.21168 | | | **2024** |
| **Manufacturing** | | | **Eco-intensity (impacts per MJ)** | **Energy per activity (MJ)** | **Items per func.unit (#)** | **Uncertainty %** | **Notes** |
| | Electricity consumption | Idemat2023 Electricity Netherlands | 0.020 | 4,195 | 1 | 10% | including heating |
| | **subtotal** | | | | | | **85** |
| **total manufacturing** | | | | | | | **2109** |
| **Transport (upstream and downstream)** | | | **Eco-Intensity (impacts/ ton-km)** | **Mass per item (ton)** | **Distance per item (km)** | **Uncertainty %** | **Notes** |
| | Truck (upstream) | Idemat2023 Truck+trailer 24 tons net (min weight/volume ratio 0,32 ton/m3) (tk | 0.026 | 1.45 | 56708 | 30% | |
| | Boat (upstream) | Idemat2023 Container feeder Handysize 1577 TEU 13 knots | 0.003 | 0.04 | 1003746 | 30% | |
| | | | | | | | |
| | Truck (downsteam) | Idemat2023 Truck+trailer 24 tons net (min weight/volume ratio 0,32 ton/m3) (tk | 0.026 | 1.36 | 707 | 30% | |
| **total transport** | | | | | | | **2257** |
| **Use** | | | **Eco-Intensity (impacts/MJ or other)** | **Amount per item (MJ or other)** | **Items per func.unit (#)** | **Uncertainty %** | **Notes** |
| | Electricity use (Europe avg) | Idemat2023 Electricity EU-27 | 0.020 | 236,520 | 1 | 10% | |
| **total use** | | | | | | | **4801** |
| **End of Life** | | | **Eco-Intensity (impacts/kg)** | **Mass per item (kg)** | **Items per func.unit (#)** | **Uncertainty %** | **Notes** |
| | | | | | | | |
| **total end-of-life** | | | | | | | **0** |

**Figure 20: Eco-costs calculations including assumptions.**

# L Results Excluding Assumptions

Figure 21 shows the results in CF excluding assumptions and Figure 22 shows the results in Eco-costs excluding assumptions.

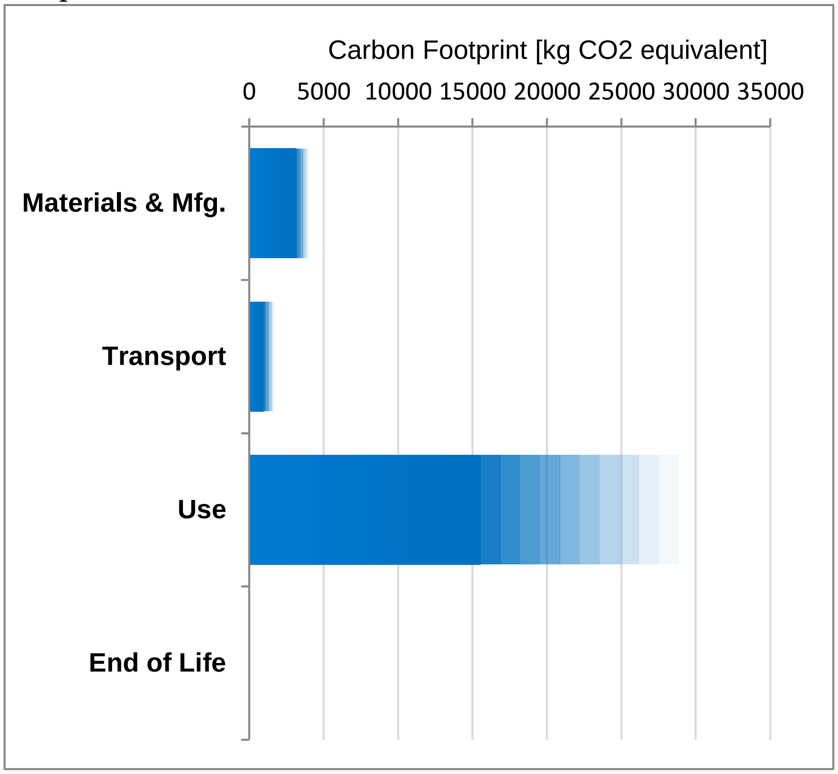


**Figure 21: Results in carbon footprint excluding assumptions. Results**

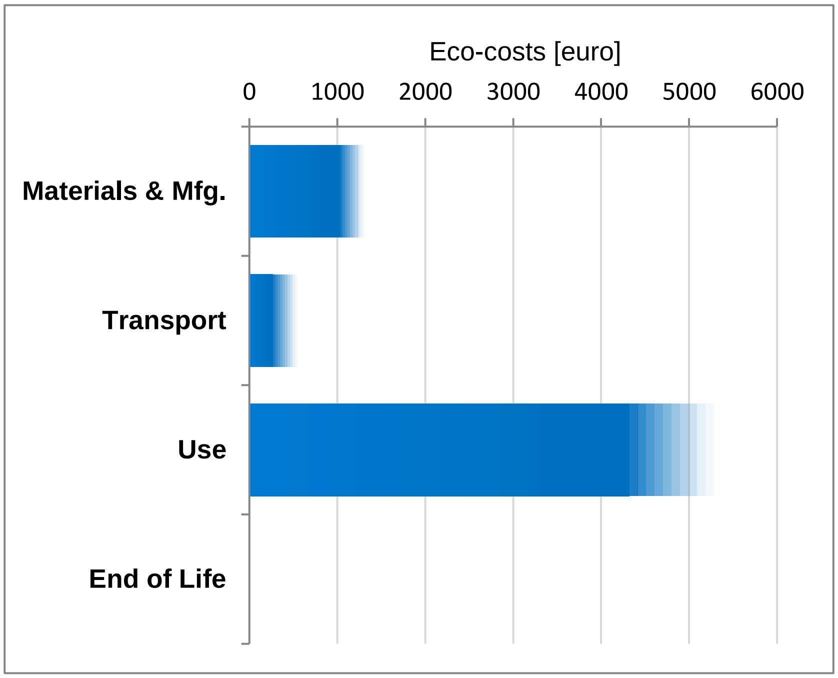


**Figure 22: Results in eco-costs excluding assumptions.**

# M Results Including Assumptions

Figure 23 shows the results in CF including assumptions and Figure 24 shows the results in Eco-costs including assumptions.

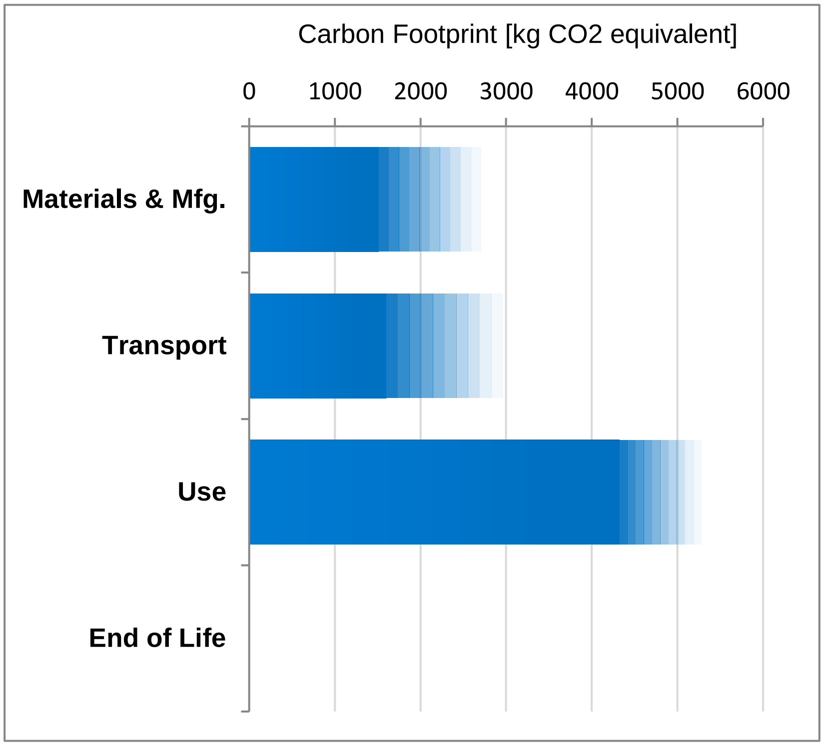


**Figure 23: Results Carbon Footprint including assumptions.**

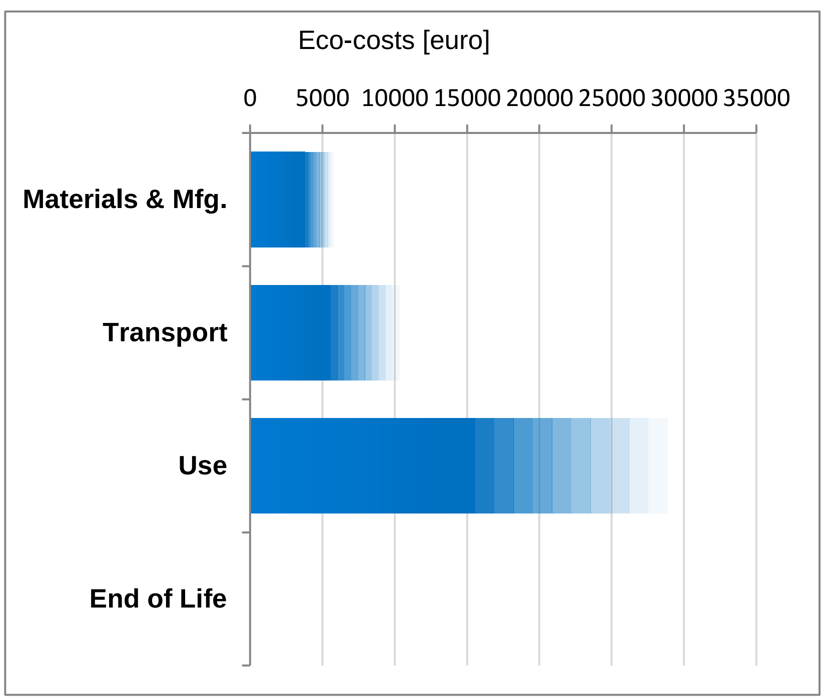


**Figure 24: Eco-costs including assumptions.**