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Using Lifecycle Analysis (LCA) Towards Environmental and Human Health Footprints of Electrically Assisted Velomobile, PODBIKE

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Abstract

The transportation sector is responsible for the second largest ratio of the greenhouse gas emissions that can cause severe effects on human health and the environment. On the other hand, this sector is important by providing human beings with access to education, health care, employment opportunities, etc. and also leads to economic growth. As a result, sustainability is vital for this sector. Many initiatives have been introduced to lead to sustainability for this sector such as electric cars, e-scooters, car-sharing business models, etc. Recent studies have proved that among the current available means of urban transportation, electric cars, conventional bicycles and electric bicycles have the lowest level of environmental and human health impacts. However, the damages associated with the production phase, and energy consumption during the use phase of the electric cars are still too high. Also, lack of safety and comfort of the bicycles can decrease their uptake among the public. Hence, a state-of-the-art concept of velomobile is developed to bridge the gap between the cars and bicycles.

The main purpose of this study was to investigate the undesirable environmental and human health impacts caused by the use of the velomobile. Therefore, in this research, a systematic, comprehensive, and scientific approach is proposed in order to measure and document the sustainability of the velomobile with respect to the environmental and human health footprints, this approach is called Life Cycle Assessment (LCA) or Cradle-to-Grave Analysis. Meanwhile, this methodology can enable the stakeholders of the asset to identify the points with the highest contribution to the environmental and human health damages, and accordingly improve the environmental and human health footprints performance of the velomobile. Also, the study can provide a practical application of the LCA study for four-wheeled pedelecs with electric assist.

Based on the application of the study, the EndPoint LCA was selected to be implemented. The LCA framework is developed for the asset in compliance with two main international standards, ISO 14040 and ISO 14044.

The results and analysis have shown that if the velomobile is ridden using renewable energy, the environmental and human health impacts of the vehicle can be half, and the damages can be mainly attributable to the manufacturing phase of the product, otherwise, the impacts can mainly come from the use phase of the velomobile. Also, the results have demonstrated that the electrical system and rolling chassis assemblies are primarily accountable for the impacts caused during the production phase. Moreover, aluminium components, batteries, electric motors and electronics for control units have the highest environmental and human health impacts potential. In the meantime, the maintenance of the product during the lifetime of the velomobile can lead to the second largest proportion of the damages due to the battery replacement times over the lifetime of the vehicle.

The study concluded that recycling development, technical improvements of the battery packs, aluminium components and electric motors, involvement of the stakeholders in the improvement processes, and continuous follow-up on the environmental and human health footprints performance improvement of the product using the developed mind map can bring about a significant reduction of the impacts.

Key Words: Life Cycle Assessment, Life Cycle Analysis, Velomobile, Sustainability, Environmental impact, Transportation.

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Terms and Definitions

ABS: Acrylonitrile Butadiene Styrene

APP: Application

BEV: Battery Electric Vehicle

BOM: Bill of Material

cm^2: Square Centimetre

E-bike: Electric Bicycle

E-scooter: Electric Scooter

EAB: Electrically Assisted Bicycle

EAV: Electrically Assisted Velomobile

EPDM: Ethylene Propylene Diene Monomer

ERP: Enterprise Resource Planning

EV: Electric Vehicle

EVSE: Electric Vehicle Supply Equipment

GHG: Greenhouse Gas

HDPE: High-Density Polyethylene

IDEF: Integration Definition for Function Modelling

ISO: The International Organization for Standardization

IT: Information Technology

kg: Kilogram

km: Kilometre

kW: Kilowatt

LCA: Life Cycle Assessment/Life Cycle Analysis

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

NBR: Nitrile Butadiene Rubber

PC: Polycarbonate

PCBA: Printed Circuit Board Assembly

pcs: Pieces

Pedelec: Pedal-Electric or a cycle with electric motor assist

PETG: Polyethylene Terephthalate Granule

PHEV: Plug-In Hybrid Electric Vehicle

PMMA: Polymethyl Methacrylate

PO: Purchase Order

Podbike AS: The company developing the Podbike velomobile distinguished by Podbike AS.

PP: Polypropylene

QC: Quality Control

SETAC: Society of Environmental Toxicology and Chemistry

TIM: Thermal Interface Material

tkm: Tone Kilometre

UNEP: United Nations Environment Programme

US: The United States of America

VAS Supplier: Vehicle Assembly Service Supplier

Wh: Watt-hour

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Chapter 1,
Introduction

1.1 Motivation

Greenhouse gases have a large array of adverse impacts on the environment and human health. It has a direct negative impact by trapping solar radiant heat that can cause climate change, and indirect impacts such as respiratory illnesses through airborne pollution, weather and food supply disruption, ecosystem alteration, extinction or migration of species, etc. (NUNEZ, 2019).

Greenhouse gas emissions must be kept at a low level to prevent a dangerous climate change (Sørensen, 2014). In densely populated countries, more people would die of air pollution from cars than from car accidents (Caiazzo et al., 2013). Transportation is one of the major sources of greenhouse gas (GHG) emissions globally, responsible for 15% of the world GHG emissions (World Resources Institute, 2017). Figure number 1 shows the global primary sources of GHG emissions by sector.

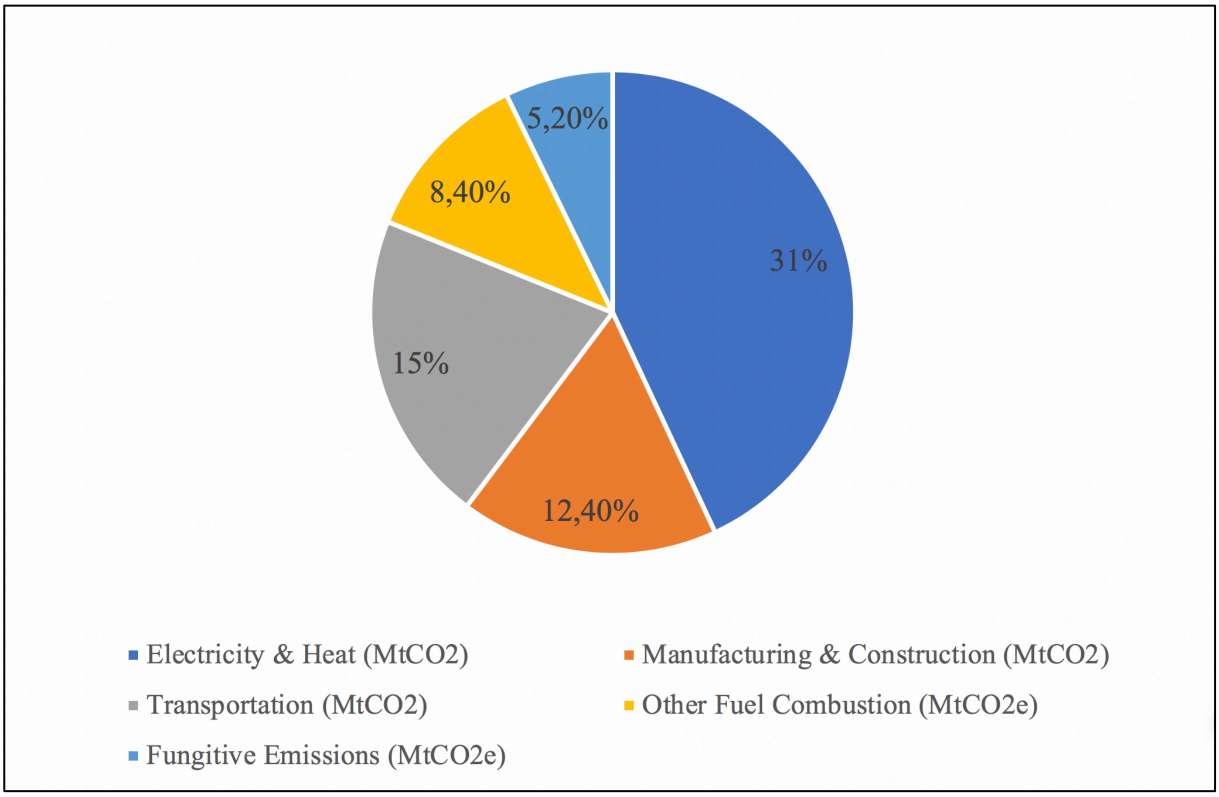

Figure 1, Global Greenhouse Gas Emissions, by Sector, Adopted from (World Resources Institute, 2017)

A recent study shows that obese car commuters have 32% higher risk of death than the ones with a normal weight commuting on bikes (European Association for the Study of Obesity, 2019). Moreover, underutilization of the human body causes more than 20% of deaths in the US (Booth and Hargreaves, 2011).

Regardless of the fact that the electric cars could lead to the lack of exercise and obesity, they require an enormous amount of energy for production and use (Simonsen, 2010), which itself contributes to the GHG emissions.

In 2016, the number of fatalities caused by cycling in the EU (Europe) reached approximately 2,000 reportedly, 8% of all road fatalities in Europe (European Commission, 2018). Most are explained by the lack of proper crash protection on the conventional bicycles. Although, this number decreased from almost 2,700 due to new safety initiatives, the proportion is still too high. The data are depicted through Figure 2.

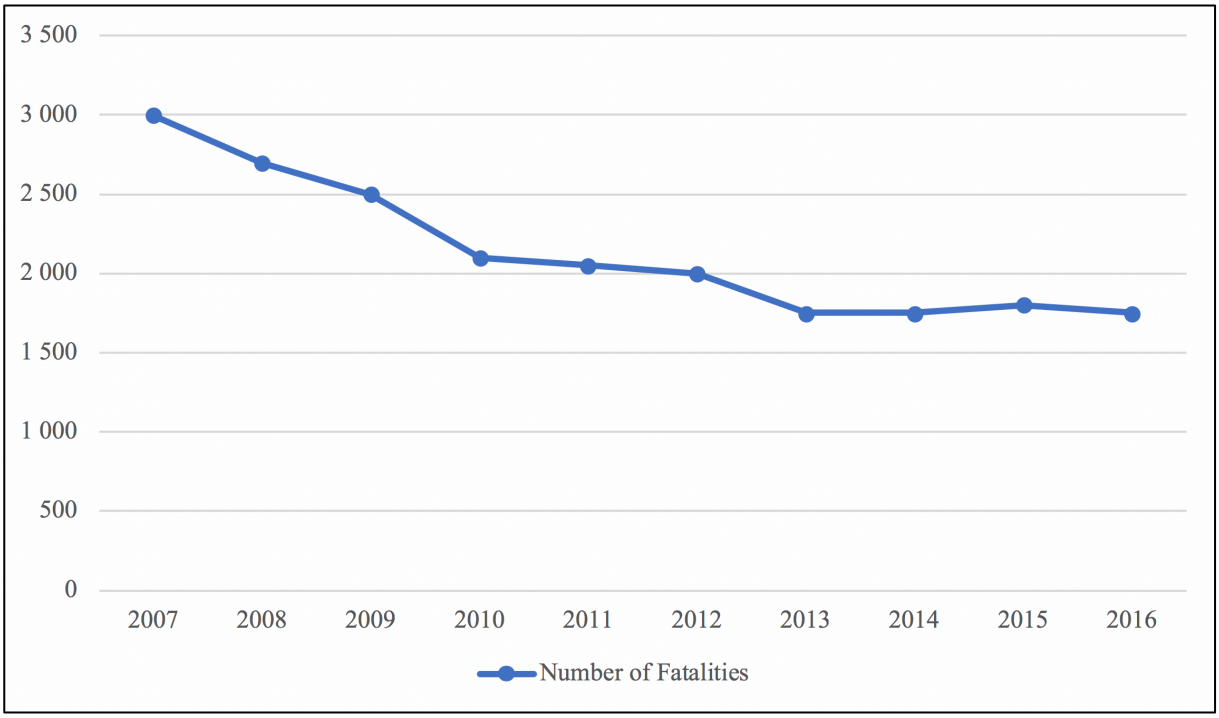

Figure 2, Number of Cyclist Fatalities in EU, 2007-2016, Adopted from (European Commission, 2018)

All the mentioned reasons (e.g. GHG emissions, lack of exercise, crash and weather protection in conventional bicycles, etc.) made Per Hassel Sørensen to develop a four-wheeled electrically assisted velomobile with the aim of high sustainability, improved safety features, and low maintenance, in order to bridge the gap between cars and modern bicycles (Sørensen, 2014).

As mentioned, the product is designed to be sustainable, meaning, material, production methods, transportation, operation, maintenance and finally, disposal and recycling must have low eco-impacts (Sørensen, 2014). These are influenced by the amount of material and energy consumption, and the proportion of wastes and emissions released throughout the whole life cycle of the velomobile. Thus, the LCA (Life Cycle Assessment) method is a scientific way to document the sustainability.

Life cycle assessment, also known as life cycle analysis or cradle-to-grave assessment, is a systematic approach to analyse environmental and human health impacts concerning all the phases of the lifecycle of a commercial product or service (Ilgin and Gupta, 2010). According to the ISO 14044, life cycle is defined as sequential and interlinked phases of a product system, beginning with raw material acquisition or production from natural resources to eventual disposal or decommissioning. ISO is an international federation of national standards bodies Accordingly, this organization defines the LCA as an analysis of the inputs, outputs and the potential environmental and human health impacts of a system product over its whole lifecycle (ISO14044, 2006, ISO14040, 2006).

LCA can enable people to pinpoint the aspects of a product which needs improvements for environmental and human health causes. It guides the decision makers, designers and manufacturers in strategic planning, design and engineering. Besides, it is a positive differentiator in marketing of a product (ISO14040, 2006).

1.2. Aim of the Thesis

The main purpose of this thesis is to provide a distinctive, practical and productive application of the LCA methodology from environmental and human health perspective for electrically assisted velomobile as there are no case study known as LCA of velomobiles. Also, it can be a good guidance on a practical application of LCA for electrically assisted bicycles, since there are many common processes involved in the life cycle of an electrically assisted velomobile and life cycle of a standard electrically assisted bicycle.

There are some claims that riding this velomobile for the urban transportation purposes will reduce the damages to human health and ecosystem and increase the availability of resources. Hence, the secondary objective of this thesis is to study the environmental and human health footprints of the developed velomobile through quantifying the potential environmental and human health impacts with the aim of examining the claims.

This approach will enable Podbike AS (the developer team of the product) in pilot test series production phase to identify the opportunities and improve the environmental and human health footprints performance of the product, not only in the production, but also in the use and disposal stages. Based on the pre-set objectives and strategies of the company which are sustainability, safety, practicality and good design (Podbike AS, 2020b), it is critical to realize the environmental and human health footprints of the product thoroughly, before it goes to the mass production phase.

In addition, qualitative data resulted from this investigation could lead to an in-depth understanding of the environmental sustainability improvements necessity in different production and operation.

1.3. Scope of Work

The present thesis explores the environmental and human health footprints of an electrically assisted velomobile.

In order to understand the importance of transportation and sustainability of this sector, the study begins with the trend of transportation and its impacts on human health, human life and the environment.

Further, asset life cycle analysis is introduced as a scientific and practical methodology for quantifying the products' or services' impacts on human health and environment. A state-of-the-art mean of transportation (i.e. the Podbike velomobile) is described, and the life cycle assessment methodology is developed for the product.

Accordingly, the results of the life cycle analysis are presented and the items with the highest impacts are highlighted. Then, the proposed methods of reducing the impacts and improving the sustainability of the product are outlined.

1.4. Methodology

The researcher has been working in this company for more than one year and he was a part of the research and development as well as the production planning of the company. As a result, some knowledges for this study are gained using day-to-day hands-on experiences.

It is noticeable that the LCA methodology is performed for one single functional velomobile, developed by Podbike AS, which is supposed to be ridden in Norway and Germany.

The LCA methodology complies with the ISO 14040 and ISO 14044. The ISO 14040 includes the principles and framework of environmental management and life cycle assessment. Also, it details the requirements for implementing the LCA methodology (ISO14040, 2006).

The ISO 14044, known as the environmental management and life cycle assessment requirements and guidelines is a complementary international standard to the ISO 14040. This standard benefits from a more detailed instruction for conducting the LCA study including clarification procedure, LCA limitations, selections of LCA values and optional elements, relationships between the LCA phases as well as the structures of review and reporting (ISO14044, 2006).

Both of the standards contain major steps that are required to be taken which are as follows:

- Goal and Scope Definition
- Life Cycle Inventory (LCI)
- Life Cycle Impact Assessment (LCIA)
- Interpretation

1.5. Assumptions and Limitations

Assumptions and limitations are important prerequisites of the study.

The limitations of the study are as follows:

- This study analyses the environmental and human health impacts of the product through its whole life cycle. The economic and social aspects of the product's life cycle are not taken into account and are beyond the scope of this study.
- When implementing an LCA not all relative environmental and human health impacts are taken into account. This is due to the constraints associated with the definition of the system boundaries. As with most of LCAs, the studied system is complex, and the research could argue that the LCA could be more robust and comprehensive through providing a greater level of details and attaining more data. Nonetheless, in spite of almost countless number of facets to each of the phases for the product's lifecycle, a reasonable level of goals, scope and system boundaries is required for the short time frame of the present thesis. Moreover, an LCA study can always use more data, incorporating more details, and expanding the system boundaries in order to increase the accuracy of the results.
- The final packaging of the product is not taken into consideration as it is not designed yet. This can be elaborated in future studies.
- The preparative process activities such as documentation, administration, etc. are not taken into consideration in this study as the inventory data collection requires resources in excess of what this study possess. Also, the environmental and human health impacts caused from these activities are assessed to be negligible compared to the impacts caused from the entire life cycle of the asset.
- The components with low mass and quantity for which the impacts are extremely small in comparison with the other parts, processes and assemblies, are not taken into consideration. For example, there are very small off-the-shelf components for which the masses are less than 0.0001 kg.

- The components for which there are no available data in compliance with the ISO 14040 and ISO 14044 standards on the database regarding the production, transportation, energy consumption and so on, such as small connectors are not considered in this study.
- Concerning the electronic units, especially the PCBAs (Printed Circuit Board Assemblies), standard life cycle data of the electronic control units of standard four-wheeled vehicle is utilized. Because the life cycle analysis model of the control units is so complex and requires an extensive amount of time to be developed for a specific product. Additionally, their impacts are presumed trivial in comparison with the other assemblies (e.g. rolling chassis, motor, battery pack, etc.).
- Since this product is under pilot testing, the BOM (Bill of Material) and technical documents of some assemblies are dynamic. Also, some suppliers and assembly service providers are not selected. This means there will be some changes in the technical specifications of the parts and materials, transportation distances etc. As a result, if considerable changes do occur, this study might not sufficiently reflect the future Podbike velomobile's life cycle assessment.

1.6. Thesis Structure

The present thesis is divided into 9 chapters which are as follows:

1. **Chapter 1, Introduction**

   The main motivations behind the study are presented. The objectives of the study are specified clearly. The scope of the work is explained. The main methodology of the study is illustrated. The assumptions and limitations of the study are delineated, and the structure of the present thesis is explained concisely.

2. **Chapter 2, Literature Review**

   Transportation: Background, history and definition of transportation are explained briefly, and the main focus of this study concerning the type of transportation is specified clearly. Positive and negative impacts of transportation on the environment and human health are described using facts and statistics. The sustainability importance of the sector is described, also, the transition towards sustainability in this sector is scrutinized using concrete examples (i.e. new regulations, projects, business models, products, etc. which are already initiated). The impacts of different means of road transportation are analysed and compared.

   Asset Life Cycle and Life Cycle Analysis Theories and Principles: Background and history of the LCA study are illustrated. Then, theories and principles, as well as the associated ISO standards, are detailed, also, the selected type of LCA study with supporting reasons is determined explicitly.

3. **Chapter 3, State of the Art: Podbike Velomobile**

   The business idea of the product is briefly described. The asset is illustrated from the technical perspective using the technical documentation and prior studies. The asset's production aspects are described coherently using the company's production plan.

4. **Chapter 4, Development of LCA Framework for Podbike Velomobile**

   LCA methodological framework is demonstrated and developed for the product in compliance with the ISO standards. Goal and scope of the LCA study are defined clearly based on the requirements of the study. Life cycle inventory step is defined for the asset. Life cycle impact assessment step is developed for the product. Interpretation step is defined and clarified; the dashboard template of the environmental and human health footprints performance is developed for the assets.

5. **Chapter 5, Analysis and Results Based on the LCA Framework**

   Life Cycle Inventory: The results of the inventory data collection and inventory analysis are explained using the primary and secondary data.

   Life Cycle Impact Assessment: The results of the LCA model and LCIA are presented and analyzed for each individual functional unit (i.e. two different regions are defined as the regions of operation). Then the comparative analysis between the selected functional units is made.

6. **Chapter 6, Recommendation for Further Improvements**

   In this chapter, the main recommendations to the company and developer of the asset are formulated in accordance with the results obtained from the LCA study.

7. **Chapter 7, Discussion**

   The main objectives and the scope of the thesis are explained to examine the consistency of the objectives and the results acquired. The main lessons learned throughout the thesis study briefly described. The major challenges faced during the present thesis are illustrated. The main opportunities for future studies are determined.

8. **Chapter 8, Conclusion**

   The major conclusions and remarks with respect to the results and findings are described.

9. **Chapter 9, Reference**

   The bibliographies which are utilized throughout the whole thesis study are listed.

Chapter 2,
Literature Review

2.1. Transportation

2.1.1. Transportation Background

In the beginning, humans were using their feet to move from one place to another. By 4000 BC to 3000 BC, humans learned that they could benefit from the animals for the movement. After the invention of wheels, boats and the roads across Europe from 3500 BC to 3100 BC, the transportation has seen a great change. By the time of the industrial revolution, and thereafter in the 17th and 18th century, a various array of means of transportation have arisen. Afterwards, in the 19th century, the first internal combustion engines have been developed (Herbst, 2005), following that, the engines have been used in automobiles, boats, aeroplanes, etc. (Nguyen, 2020).

Transportation is defined as the movement of individual(s) and good(s) from one location to another, using a variety of modes (Britannica Academic, 2020). People select different modes (e.g. air, road, water, etc.) depending on their needs (Chakroborty and Das, 2017). For example, for daily commuting, they use their private cars, bicycles, public transportation, etc. or for the long-distance travels, they desire to use air modes, and accordingly aeroplanes to get to their destination quickly.

Transportation is categorised into private and mass transportation (Chakroborty and Das, 2017). However, the main focus of this study is on the road and private transportations in urban areas, since the product is supposed to be a substitute for the private cars, conventional bicycles, etc., used for daily commuting.

2.1.2 Transportation Impacts on Environment

The impacts of transportation on the environment have been great of significance recently. Global warming, air pollution, noise pollution and depletion of energy sources are the most important consequences of transportation (Fuglestvedt et al., 2008).

Air pollution and global warming are caused by a wide range of sources. However, in this investigation, the main attention is taken to the air pollution caused by transportation.

From the pre-industrial times to present, the transportation was accountable for around 16% of the total man-made GHG emissions (Fuglestvedt et al., 2008). After the industrial revolution and the development of the new modes of transportation, this has become one of the most important key contributing factors in the GHG emissions. In Norway, the amount of GHG emissions from the transportation has increased by approximately 33% from 1990 to 2017 (European Environment Agency (EEA), 2019). Following that, road transportation was responsible for almost 82% of the total GHG emissions of transportation in 2014 (European Environment Agency, 2018). CO_2 is the leading greenhouse gas pollutant. From 1990 to 2000, CO_2 emissions have grown by 13% and the CO_2 emissions caused by the road transportation has risen by 25% in this period (Olivier, 2001). Although, in the European union the CO_2 emissions have been reduced over this time, the amount of CO_2 emitted through the road transportation has increased by roughly 21% in this region (European Environment Agency, 2004). Also, the transportation-induced CO_2 emissions are predicted to go up as high as 30-50% until 2050 (Nakicenovic et al., 2000). Another major source of the air pollution is nitrogen oxide that more than 40% of the pollutant comes from the road transportation (European Environment Agency, 2014). The share of the transportation induced GHG emissions in the EU is delineated through figure number 3.

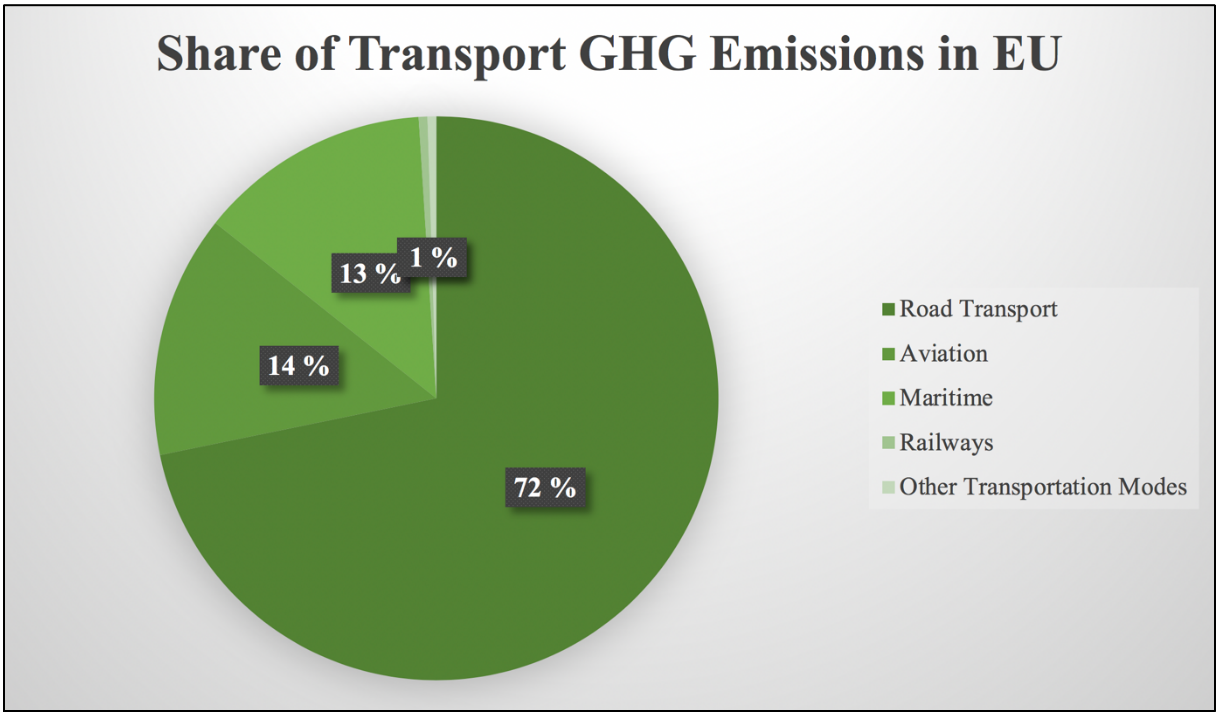

Figure 3, Breakdown of the Transportation Induced GHG Emissions in the EU, Adopted from (European Environment Agency (EEA), 2019)

Figure number 3 shows that the main source of the transportation induced GHG emissions is road transportation with a 72% share. Noticeably, 44% of the road transportation GHG emissions were from private cars (European Environment Agency (EEA), 2019). Moreover, GHG emissions in Norway is around 52 million tonnes, approximately 18% of the emissions is attributable to the road transportation, while the private cars release around 4.7 Mt of the GHG to air (Statistisk sentralbyrå, 2019).

In 2017, one of the greatest energy consumers was the road transportation sector, with 5% of the total energy consumption. Also, energy consumption by the transportation sector has gone up by nearly 5.8%. Hence, recent transport regulations in the EU have been focused on supporting more emission reduction initiatives in this sector (European Environment Agency, 2019).

2.1.3. Transportation Impacts on Human Health

Transportation can have a variety of positive and negative impacts on human health. The useful impacts can be an extensive range of accessibility (e.g. hospitals, educations, employment opportunities, etc.) or physical activities such as cycling. The disadvantages of transportation encompass of well-known health impacts caused by accidents, air pollution, noise pollution, and the GHG emissions (Mindell et al., 2011). A modal shift in transportation from automobiles to cycling and walking can decrease the drawbacks of transportation on human health and increase the beneficial effects.

It has been proven that air pollution generated by transportation has direct impacts on the mortality, respiratory and cardiovascular disease (Dora et al., 2000), cancer and adverse birth outcomes (World Health Organization, 2020). Seven million people die annually due to the air pollution and thus, this has posed a serious threat to human life (Ritchie and Roser, 2017). Air pollution results in 9% of deaths globally (Ritchie and Roser, 2017). It is estimated that the present degree of air pollutants in the EU contributes to the deaths of around 40 000-130 000 adults annually (Dora et al., 2000). Figure 4 is an illustration of the share of premature deaths resulted from air pollution in 2017, globally.

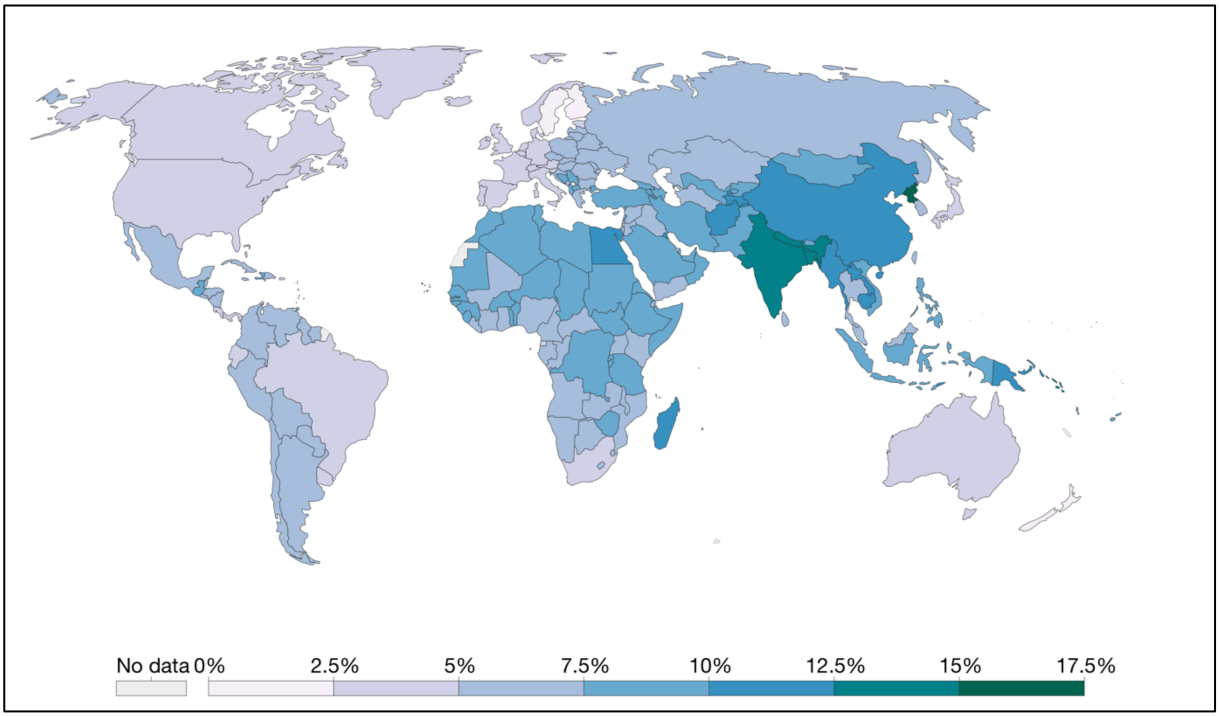

Figure 4, Share of Premature Deaths Attributed to Air Pollution Globally (Ritchie and Roser, 2017)

Road traffic is the main contributor to noise pollution. In addition, According to the most recent data published by the EU's Environmental Noise Directive, the largest source of environmental noise pollution is road traffic affecting approximately 75 million European residents (European Environment Agency, 2018), which could possibly lead to sleep disturbance, annoyance, speech interference, performance difficulties, hearing impairment and hypertension (Dora et al., 2000). Figure 5 depicts the number of European inhabitants exposed to high level of noise pollution generated from different modes of transportation in 2012.

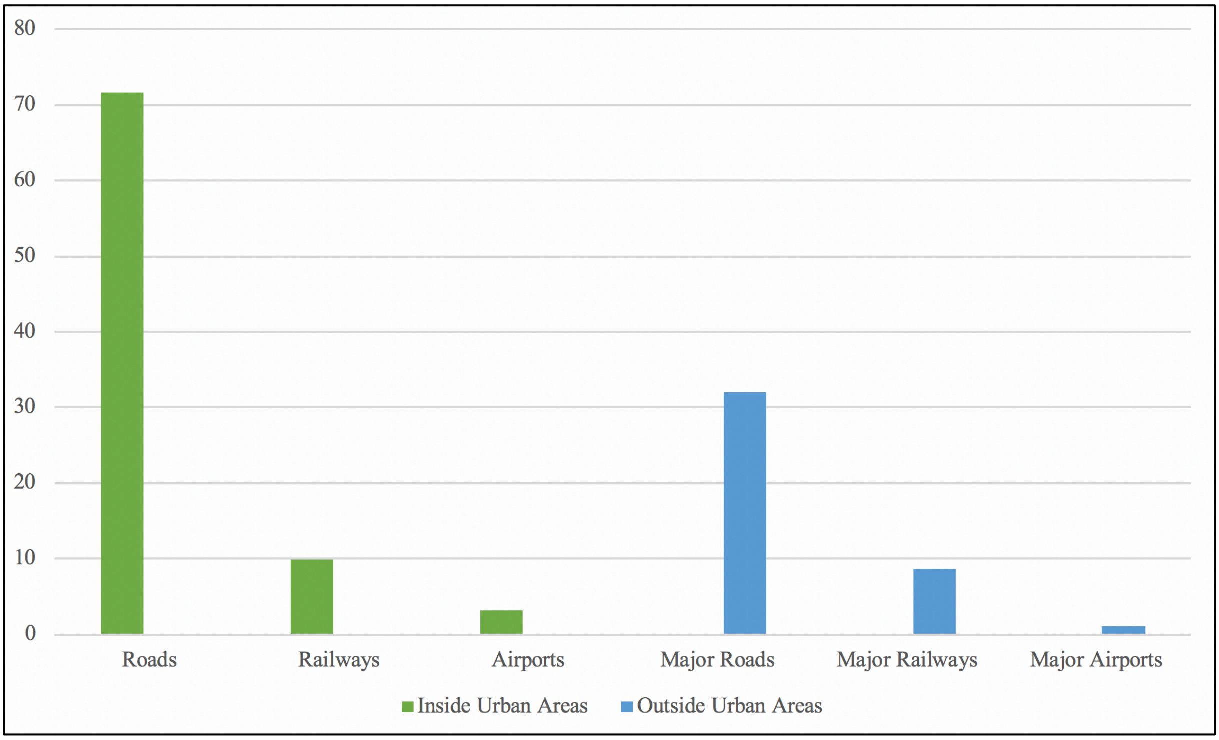

Figure 5, Number of European Residents Exposed to High Level of Noise Pollution Caused by the Transportation Modes, Adopted from (European Environment Agency (EEA), 2018b)

2.1.4. Transition Towards Sustainable Mobility

Transportation plays a main role in global economy, either within countries or between them. Therefore, technological advancement, income rise and growth of competition between suppliers have resulted in a significant improvement of quality and effectiveness of the transportation systems (van Nunen et al., 2011). However, a systematic and transformative approach is left to be taken in order to achieve the 2050 vison of EU, namely 'Living Well Within the Limits of Our Planet'. This vision is determined in the European Unions' Seventh Environment Action Programme. SOER 2015 declared: "*While progress has been made in meeting certain policy objectives, including efficiency and short-term GHG-reduction targets, major challenges remain toward meeting longer-term objectives. The European Commission's target of a 60 % reduction in transport GHG emissions by 2050 will require significant additional measures"* (European Environment Agency (EEA), 2015, p. 1).

There are several regulations impacting the future of the transportation sector. According to 'Effort Sharing Regulation', a proposal, the transportation sector can contribute to a 30% decrease of GHG emissions by 2030. This trend led the EU to evolve policies by which the target can be met (EEA, 2016). Taxation is one of the incentives implemented by several countries to reduce their emissions. Norway's appropriate tax exemptions for BEVs (Battery Electric Vehicle) from acquisition, ownership, charging infrastructure, tolls, etc. have ensured the Norwegian policymakers that the cost of BEV and PHEV (Plug-In Hybrid Electric Vehicle) is similar to the conventional cars. This has resulted in the lowest average CO_2 emissions from the automobiles in Norway at 93g CO_2/km, in 2016. In the Netherlands, the CO_2 emission has dropped even faster than the average emission of EU due to the taxation procedures as well as the provision of benefits in favour of BEVs and PHEVs (European Environment Agency (EEA), 2018).

New industries and business models have been initiated to achieve the EU's targets. Paxter is a company that produces a four-wheeled electric vehicle in Norway. This product provides smart, efficient and environmentally friendly services tailored for post, parcel and newspaper distributions (Kjolberg, 2018). This 394-447 kg vehicle with a range of 40 km or up to 6 hours range is currently being utilized by the Norwegian post (Kjolberg, 2018, PAXSTER AS, 2020). The product is shown in figure 6.

Figure 6, Norwegian Postman Driving the Paxter Product (Kjolberg, 2018)

ZAPTEC is one of the world-leading companies developing smart EV (Electric Vehicle) charging systems in the EU. They produce chargers for the EVs and have delivered charging cables with a designed-in EVSE-controller (Electric Vehicle Supply Equipment Controller) integrated with an ultra-compact transformer. They are currently working on the development of smart home chargers (Figenbaum, 2018). The chargers are meant to provide sufficient charging infrastructures for electric vehicles (ZAPTEC, 2020). The product is displayed in figure 7.

Figure 7, An EV Is Being Charged by the ZAPTEC Charger in UiS Campus, Stavanger, Norway (ZAPTEC, 2018)

Ultra-fast charging is the most recent development. Several fuel stations have already started installing the fast chargers (Figenbaum, 2018). Ionity is the company that are developing the fast chargers, and they plan to install them in a new charging park in Rygge, Norway in cooperation with Circle K. The charging stations can deliver 350 kW (Kilowatt). Also, 51 sites are currently under construction (IONITY, 2020).

Charger installations are increasingly taking place throughout the EU, especially in Norway. The food store KIWI, the furniture shops IKEA and the fast-food restaurants, McDonalds, have started installing the EV chargers (Figenbaum, 2018).

E-scooters sharing is a solution for daily commuting use, which has become popular recently. Through this micro-mobility service, an electric motorized scooter is available for short-term rent. The scooter is “Dockless”, which means that it does not have a permanent fixed location. It can be picked up and then dropped off in an arbitrary place in the service zone (Ajao, 2019). They have shown promising results for daily commuting in an urban area. This product and business model are being utilized in Oslo for short-term hire. The commuters can easily get from point A to B, while the e-scooters can be charged overnight (Inside Scandinavian Business, 2019). The e-scooter product is shown in figure 8.

Figure 8, Riding E-scooters in Oslo, Norway (SANOTRA, 2019)

The Smart City project in Stavanger, Norway is another example. The project is launched with the aim of making Stavanger and two other cities in the Netherlands and the UK more sustainable, smart and liveable. Sustainable mobility through the use of electric buses is one of the most noticeable projects which has been already initiated (UiS, 2014). Autonomous bus is another project which is currently under the development in Forus area, Stavanger with the purpose of the smart and sustainable mobility. The first phase of the autonomous bus project was started in 2017 (Kolumbus, 2018). The autonomous bus is shown in figure 9.

Figure 9, Autonomous Bus Project Testing in Forus, Stavanger, Norway (Kolumbus, 2018)

There are some business models concerning car sharing which are already in operation or are being developed. MoveAbout is an instance, the firm offers business shared BEVs as an option to the conventional automobiles or taxis. Bilkollektivet is a different car sharing solution in

Oslo through which, BEVs and PHVs are recommended to its members for rent as a part of their total offers (Figenbaum, 2018).

Regarding the cycling infrastructures, there have been a number of development and construction projects for the bicycle routes in the EU. EuroVelo is a network of 16 long-distance cycling routes which are developed or under the development throughout the EU (EuroVelo, 2020a). One example is EuroVelo 12 (EV12), the North Sea Cycle Route is a 5 942 km long-distance cycling route surrounding the coastlines of the countries bordering the North Sea. They are Norway, UK, Sweden, Denmark, Germany, The Netherlands and Belgium (EuroVelo, 2020b). Furthermore, the Norwegian Public Road Administration has prioritized the cycling infrastructure development as one of the most critical strategies in their decision making, planning and constructions. Consequently, they have set their strategies to make cycling more attractive through the following measures:

- Improve the safety (e.g. constructing specific routes for bicycles, evolving relevant policies, etc).
- Cycle traffic is given priority over cars and public transportation.
- Easy accessibility to bicycle parking areas in the shopping centres, company buildings, universities, etc.

One of the distinct examples of such a measure taken by the Norwegian Public Road Administration is the construction of continuous cycle path network (Statens Vegvesen Norwegian Public Road Administration, 2003, Statens vegvesen, 2012).

To sum up, a transition has already started with respect to the regulatory evolution, infrastructure construction, business model and product development in order to achieve the great purpose of reducing the GHG emissions and its adverse consequences either on people or environment.

2.1.5. Means of Road Transportation

As it is stated, one of the main sources of GHG emissions is private cars. The GHG emissions have grown in Norway (Statistisk sentralbyrå, 2019), despite the reduction in official fuel consumption per km as a result of more efficient engines as well as hybrid technologies. This is explained by increasing accumulated mileage and traffic congestion in cities (Mock et al., 2013).

Comparative life cycle emissions analysis between electric vehicle and its diesel and petrol counterparts has demonstrated that if the electric vehicle benefits from the electricity that is produced by renewable energy sources, it can substantially contribute to the reduction of GHG emissions and global warming (Hawkins et al., 2013). Figure 10 illustrates the emissions released by different short-distance transport commuters throughout the life cycle of each mean of transportation.

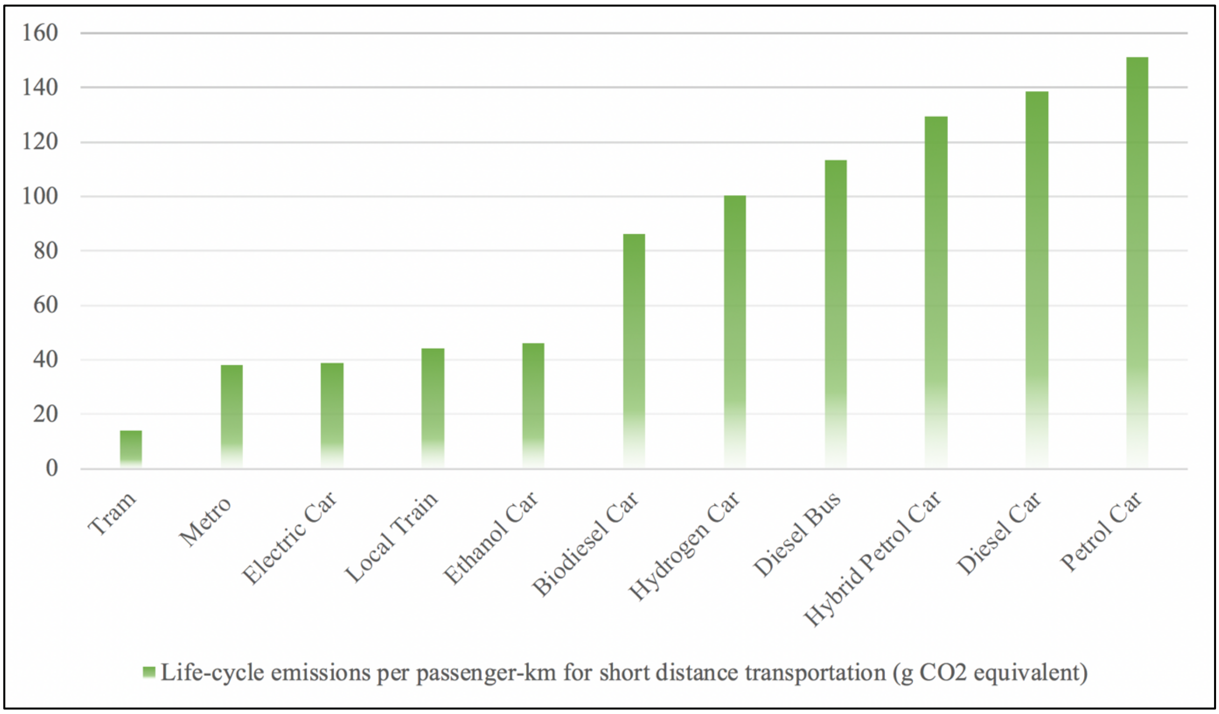

Figure 10, Short Distance Emissions from Current Available Means of Transportation, Adopted from (Simonsen, 2010)

It is perceivable from the figure 10 that, the electric car is a good alternative for the private short distance transportation. Nevertheless, they emit a high amount of GHG over the production phase. Even though electric cars benefit from a charged battery, and have zero emissions during the use, energy consumption per person per km is still quite high because of the automobile's high mass and its dependency on the electricity and road infrastructure (Simonsen, 2010). Particularly, for Norway, the energy efficiency of the short distance transportation should be improved by around 1000% so as to be able to avoid a dangerous level of climate change. This is feasible through the use of electrically assisted human-powered vehicles (Lemire-Elmore, 2004, Simonsen, 2010, Sørensen, 2014). In general, cars can lead to lack of exercise which can cause physical inactivity and obesity. Almost 31% of adults had inadequate physical activity in 2008, this could result in around 3.2 million deaths, globally (World Health Organization (WHO), 2019). According to a report from World Health Organization, the physical inactivity is partly attributable to today's state of transportation which is more passive (World Health Organization (WHO), 2020)

According to an environmental comparative assessment of bicycle with other means of transportation, bicycle has proved the most favourable overall performance, hence it is considered as the best mean of transportation for short distances while train is regarded as the most promising mean of transportation for long distances (Bouwman, 2000). Furthermore, 1 km travel by bike needs about 5-15 Wh (watt-hour) energy, while the same distance by foot needs 15-20 Wh, 30-40 Wh by train and more than 400 Wh by an occupied car (Lemire-Elmore, 2004).

According to a comparative life cycle analysis between electrically assisted bicycle and human-powered one without any electric assistance, electric bikes require 2-4 times less primary energy than the required energy that human receives by eating an ordinary diet (Lemire-Elmore, 2004). An electrically assisted bicycle is shown in figure 11.

Figure 11, An Ordinary Resident Riding an E-bike in England (Stevenson, 2019)

Lack of safety, weather protection and comfort are the major challenges associated with cycling (Goldsmith, 1992, Sørensen, 2014). Bicycle riders get killed in car accidents daily. Because the high mass and speed of the cars release a large amount of energy and impact (Rosen et al., 2011). Even the electric cars have caused the death of cyclists, an example is a cyclist who has been killed by a Tesla Model S, in November 2013, in California (BAXTER, 2014). One of the key factors that prevents people from choosing cycling as their main mean of transportation, especially for short distances and daily commuting is safety. As a result, safe cycling must be prioritized in order to change the transportation behaviours (Elliot et al., 2018), constructing specific infrastructure, lane, or specific structure for the bikes by which the safety of cyclists can be provided are some examples in this regard. Another challenge that prevents people from choosing bicycle as their mean of transportation, especially in a very cold or warm country is lack of weather protection (Goldsmith, 1992, Sørensen, 2014).

As a conclusion, electrical cars have the lowest level of GHG emissions during the use phase provided that the source of energy is renewable, while they still have high level of energy consumption also, their emissions over the production phase is quite high. Electrically assisted bicycles are a better choice considering the environmental aspects and the emissions. Nevertheless, they have some important drawbacks that prevent people from selecting them as their mean of urban transportation which need to be addressed.

2.2. Asset Life Cycle and Life Cycle Analysis Theories and Principles

2.2.1. Life Cycle Assessment History and Background

LCAs were implemented in 1960-1970's for the first time as a result of energy supply crisis. The main purpose of the studies on the LCA implementations was to evolve more reliable LCA methodology and improve the accuracy of them in order to reduce the energy consumption

(Sundström, 1979, Boustead, 1974). However, the main focus of the LCA studies in this period was on packaging alternatives. Afterwards, the public interest in this study decreased.

In the 1980's, the study topic has enjoyed a renewed attention from the scientific and industrial communities. The main challenges concerning the LCA studies from 1970's to 1990's was the lack of international and standard scientific framework (Guinée et al., 1993); this led the outcomes of the studies to be widely different. Consequently, LCA was not accepted as a practical and analytical tool.

In the 1990's many organizations have been established to develop this area of study internationally. SETAC (Society of Environmental Toxicology and Chemistry) as well as ISO (The International Organization for Standardization) were the major organizations which started developing this methodology. Moreover, during this period a variety of scientific papers and journals was published, and LCA became a part of legislation documents (Guinee et al., 2011).

Over the beginning of the 21st century, a significant interest has been shown to LCA. Establishing United Nations Environment Programme (UNEP) and the Life Cycle Partnership initiative between UNEP and SETAC were the most important actions which have been taken to improve the practicality of LCA (Guinee et al., 2011). Also, many European Policies have been developed in the matter of life cycle thinking (Commission of the European Communities, 2003).

In 2005, the European Platform on Life Cycle Assessment was developed to provide quality assured LCA data in order to support decision making in product and service development (Klöpffer, 2014). Furthermore, the recent efforts have been put into the LCA methods and framework for more elaboration and less divergence (Guinee et al., 2011).

2.2.2. Life Cycle Analysis Theories and Principles

Life Cycle Assessment known as Life Cycle Analysis is a scientific and systematic methodology through which the environmental and human health footprints and the eco impacts of a commercial product or service throughout its life cycle can be quantified (Ilgin and Gupta, 2010). The life cycle concept of product or service is illustrated in figure number 12.

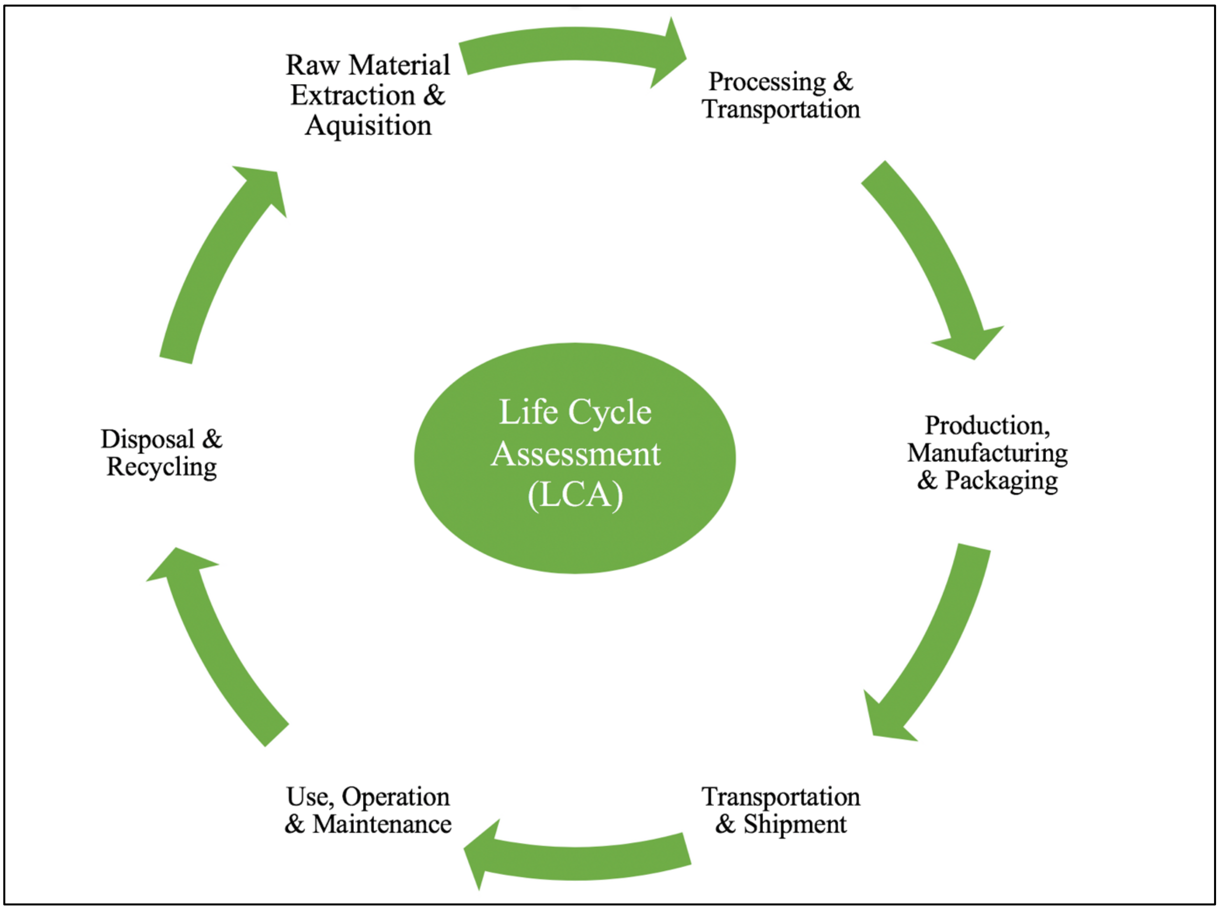

Figure 12, The Life Cycle Concept, Adopted from (European Lime Association, 2020)

ISO 14040 and ISO 14044 are the main standards which define and describe the LCA methodology and its requirements. According to the ISO 14040, life cycle is defined as sequential and interlinked phases of a product system, beginning with raw material acquisition, or production from natural resources to final disposal, recycling or decommissioning. ISO 14040 defines LCA as "*compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle*" (ISO14040, 2006, p. 2). In this definition, the input is interpreted as *"a product, material or energy flow which enters into unit process"* (ISO 14040, 2006, p. 4) and output is defined as "*a product, material or energy flow which leaves a unit process"* (ISO 14040, 2006, p. 4). Also, product system is defined as "*collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product"* (ISO 14040, 2006, p. 4). The principles of the LCA methodology are as follows:

- **Life cycle perspective:** It means the life cycle of product and service from raw material extraction, production and manufacturing, operation and use, maintenance and the end of life treatment must be taken into consideration throughout implementing the whole methodology (ISO14040, 2006).
- **Environmental and human health focus:** The main focus of the LCA study is on the environmental and human health footprints, therefore social, economic and technical aspects are outside of the scope of the study.
- **Relative approach and functional unit:** The LCA study is a relative technique which is organized around a functional unit (ISO14040, 2006), as a result, all the associated examinations must be structured around the functional unit as well.

- **Iterative approach:** Each individual stage of the LCA utilises the outcomes of the other stages (ISO14040, 2006), hence iteration is required for comprehensiveness and consistency through the study.
- **Transparency:** The LCA study is complex (ISO14040, 2006), this means clarification throughout the approach is essential.
- **Comprehensiveness:** All facets and attributes of the methodology must be taken into account, considering the type of LCA.
- **Priority of scientific approach:** The scientific basis of the LCA study must be provided.

LCA is divided into two main categories:

- **MidPoint-oriented LCA:** The assessment of the impact category indicators is carried out at the midpoint level prior to the endpoint such as global warming, ozone depletion, etc. (Goedkoop et al., 2009). At this level, the environmental and human health relevance is evaluated using qualitative data and methods. Also, the results can be realized by environmental experts (BARE, 2000).
- **EndPoint-oriented LCA:** The assessment of the impact category indicators is carried out at the endpoint level such as human health, ecosystem, etc., while the indicators are presented as a result of the midpoint level indicators within a cause-and-effect context (Goedkoop et al., 2009). At this level, quantitative perception can be provided using the midpoint indicators for the investors and decision-makers (BARE, 2000) in order to determine the design, material, production, logistics, etc.

The MidPoint and EndPoint LCA studies are illustrated in figure 13.

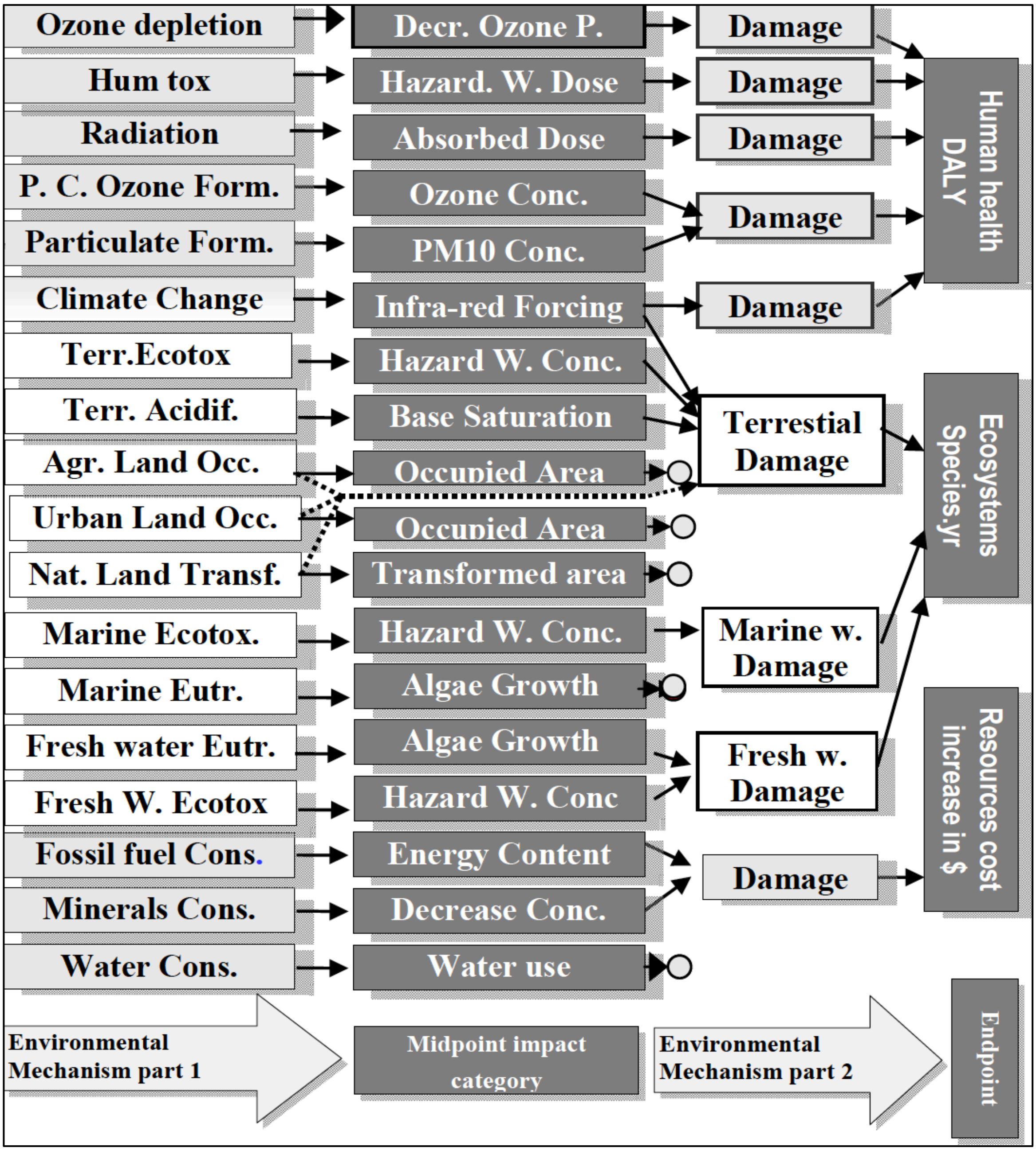

Figure 13, The MidPoint & EndPoint Impact Category Indicators, and Their Relationship (Goedkoop et al., 2009, p. 3)

In this study, the EndPoint-oriented LCA methodology is chosen, since the results are supposed to be utilized by the people who are not environmental experts, such as mechanical or electrical engineers, product designers, etc. Moreover, the results are meant to support the investors' and shareholders' decision making. Therefore, it is important to be understandable to non-experts. At the EndPoint level, most of the MidPoint impact categories are converted and aggregated to the following EndPoint categories (Huijbregts et al., 2017):

- Damage to Human Health (HH)
- Damage to Ecosystem Diversity (ED)
- Damage to Resource Availability (RA)

Chapter 3,
State of the Art: Podbike Velomobile

3.1. Business Idea Description

The adverse effects of today's transportation for short-distance commuting (e.g. GHG emissions, noise pollution, etc.), lack of exercise and high level of life-cycle emissions associated with EVs, lack of comfort, crash and weather protection of electrically assisted bicycles have caused Per Hassel Sørensen to conclude that the society needs a more sustainable, practical, safe and comfortable solution for urban transportation.

It is believed that the concept of velomobile can offset the unsustainable transportation pattern (Sørensen, 2014). The velomobile is defined as a human-powered vehicle, derived from bicycle or tricycle which is partly or entirely enclosed to protect the rider from weather and collisions (Van De Walle, 2004). A velomobile with an electric assist can increase comfort and safety of e-bike, concurrently reduce the negative environmental and human health impacts of car and public transportation (Sørensen, 2014).

The Podbike velomobile is an innovative mobility solution which is supposed to bridge the gap between cars and bicycles while preserving the exercise benefits with an acceptable level of safety, comfort and sustainability (Sørensen, 2014). It maintains the low level of life-cycle emissions for short-distance transportation associated with electrically assisted bicycle, while it enhances safety with improved crash protection and increased comfort with weather protection. The studied product is shown in figure 14.

Figure 14, Riding a Podbike Velomobile in Norway (Podbike AS, 2019b)

3.2. Technical Aspects of Podbike Velomobile

The product is a velomobile with electric assistance. It has an adjustable seat for a single adult and space just behind the main seat, either for an optional child seat or luggage. The body is fully enclosed for the cyclist and the optional passenger, made of recyclable thermoplastic composite material which can absorb energy. The velomobile has four standard bicycle wheels, the rear wheels are covered by the body panels (Sørensen, 2014). Under the main seat, there is a steering handle with rod linkage controlling the front wheels. The chassis is made of a robust self-reinforced aluminium sandwich baseplate. The product benefits from a series-hybrid driveline with a pedal generator and two rear motors propelling the rear wheels. The mechanical parts within the product are made for 10 000-hour operation (Sørensen, 2019). Concurrently, it utilizes a fully independent suspension that can bring about vertical parking (Sørensen, 2014).

All the parts' materials are selected in accordance with the environmental best practices within the designated market. In order to reduce the cost of maintenance, most of the parts can be repaired at reasonable cost excepting the batteries and some electronic sub-assemblies due to the hazardous risks (e.g. fire risks, etc.) or anti-tamper requirements (Sørensen, 2019). Also, the vehicle is designed to be in compliance with EU regulation and safety requirements.

The Podbike velomobile has a wide range of important characteristics which make it unique in its kind:

1. Series hybrid drive with two motors has led the vehicle to have a simpler drive train, with low cost of mass production associated with the motors, uncluttered platform chassis and adjustable pedal position. Also, it is compliant with the legislations concerning the electrically assisted bicycle in the EU.
2. Broad operating temperature and active balancing for the hybrid electric transmission thanks to state-of-the-art battery control system.
3. Thermoplastic composite as a recyclable and environmentally friendly material for the body.
4. A suspension system, offering space-efficient parking, low air drags and comfort for rider.
5. Aerodynamic design, making the product efficient and practical (Sørensen, 2014).
6. Easy enter and exit as an important comfort factor.
7. Light weight with a reasonable cost for the final users.
8. Categorized as electrically assisted bicycle based on the EU and Norwegian policies, meaning it benefits from the priority of bicycles in roads traffic. Also, it can be utilized on the bicycle highways across the EU (Podbike AS, 2020a).

Figure 15, The Space-Efficient Parking Concept of the Podbike Velomobile, (Podbike AS, 2019b)

As it is stated earlier, the Podbike velomobile is designed to bring sustainability to urban transportation. Also, sustainability is defined as an integral part of the company and product (Podbike AS, 2020b). It means the product must have low eco-impacts with respect to design, material, production, transportation, use, maintenance and disposal or recycling.

3.3. Production Process Aspects

The company, Podbike AS includes a number of stakeholders such as suppliers, assembly service partners, customers, employees, investors, etc. Primarily, the supply chain is the representative of the asset's production. The IDEF (Integration Definition for Function Modelling) diagram concept is used to demonstrate the operation use-case scenario of the company under regular circumstances. The main concept of the IDEF diagram is based on five main elements (i.e. function or activity, controlling elements, mechanism and resources, inputs, outputs) (Noran, 2000) are shown through figure 16:

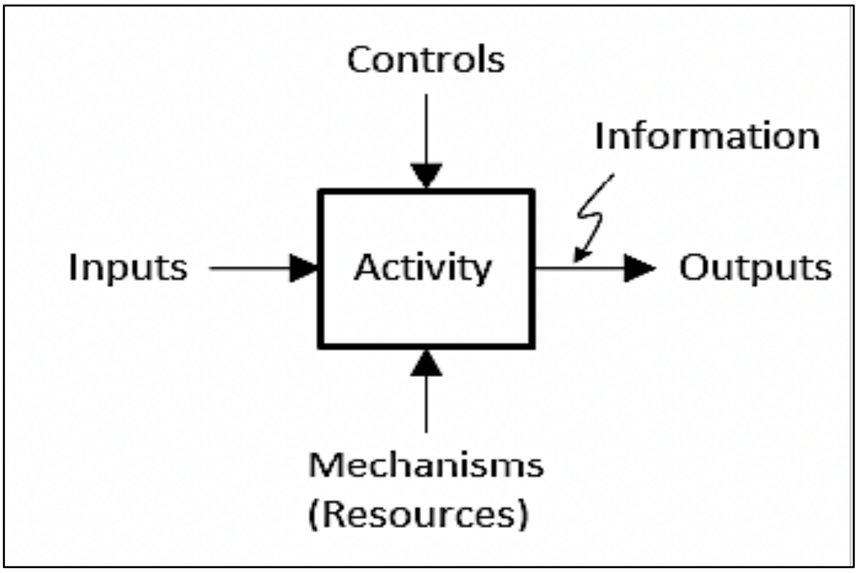

Figure 16, Main Concept of the IDEF Diagram (Lightsey, 2001, p. 51)

Figure 17 is the IDEF diagram, developed for the asset's production and delivery which scrutinizes the main operational aspects of the company. In this figure, the white boxes are the representative of the main functions involved in the operation of the company, the blue boxes at the top represent the controlling elements while the blue boxes at the bottom show the resources and or mechanisms available to carry out the associated function. The inputs and outputs of each individual function as well as the cause-and-effect relationships of the activities are illustrated using the blue arrows.

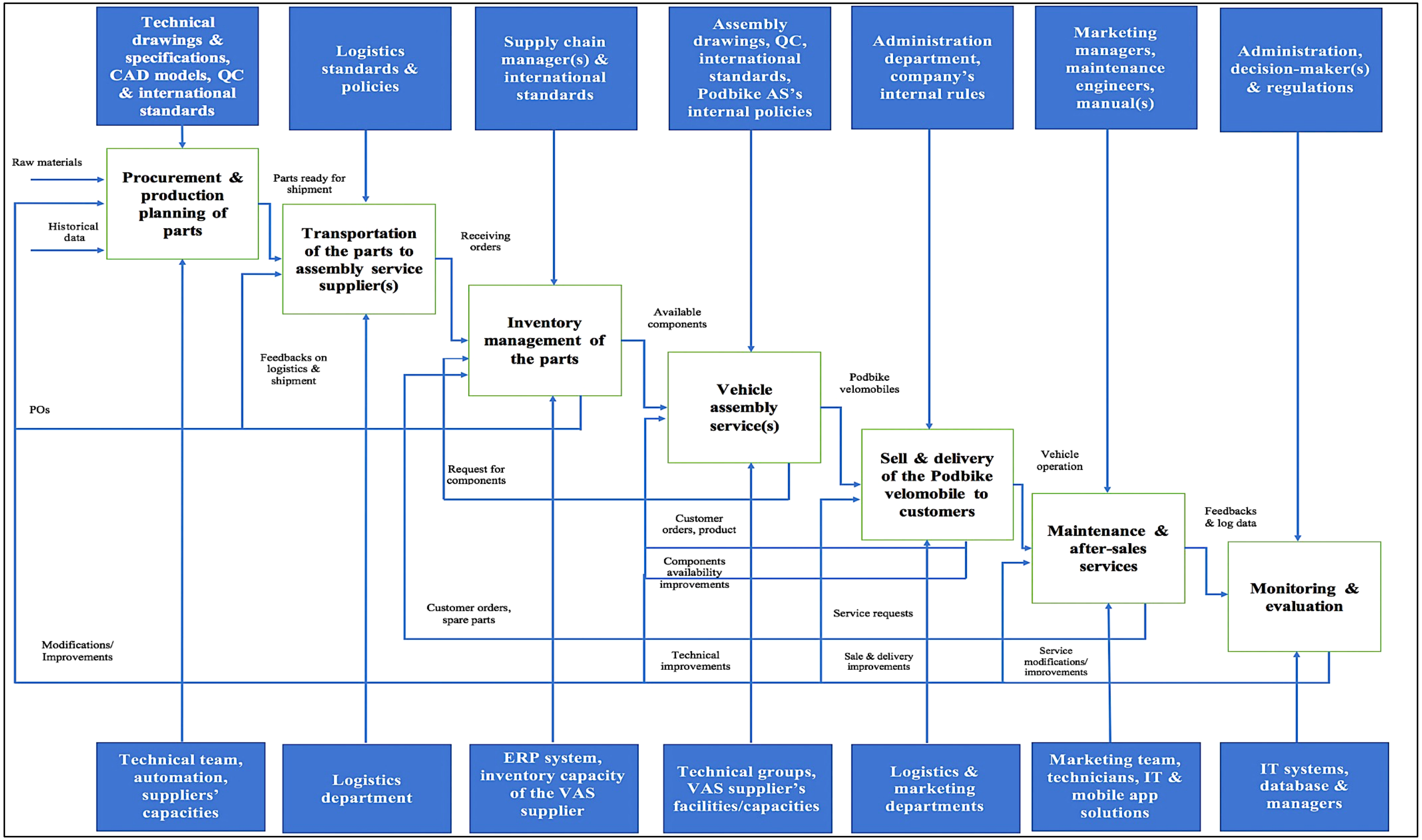

Figure 17, IDEF Diagram of the Podbike AS's Operation, Adopted from (Lightsey, 2001)

Chapter 4,
Development of LCA Framework for Podbike Velomobile

Since one of the main objectives of the Podbike velomobile is sustainability (Podbike AS, 2020b), LCA studies are required in order to quantify the environmental and human health footprints (Sørensen, 2014) of the product and reduce the adverse effects through making modifications and improvements in the development phase. Also, implementing the changes in the product development phase is less costly and more efficient.

Accordingly, since Podbike AS is in the development phase and is transiting towards mass production, it is critical to choose the right design, material, production method and transportation to minimize the environmental and human health impacts and maximize the efficiency.

4.1. LCA Methodology Framework

The Methodological Framework section demonstrates the essential aspects of LCA study in accordance with the ISO 14040 and ISO 14044, and it delineates how the LCA study can be implemented on the product. Also, some of the knowledges and inputs for the development of this framework are gained using practical and hands-on experiences of the researcher since he has been working for more than one year for Podbike AS and he has been involving in the production planning and the product development.

According to the ISO 14040 and ISO 14044 standardised frameworks, an LCA examination consists of four methodological steps in the following order (ISO14040, 2006, ISO14044, 2006):

1. Goal and Scope Definition.
2. Life Cycle Inventory Analysis (LCI).
3. Life Cycle Impact Assessment (LCIA).
4. Interpretation.

The LCA framework is outlined through figure 18.

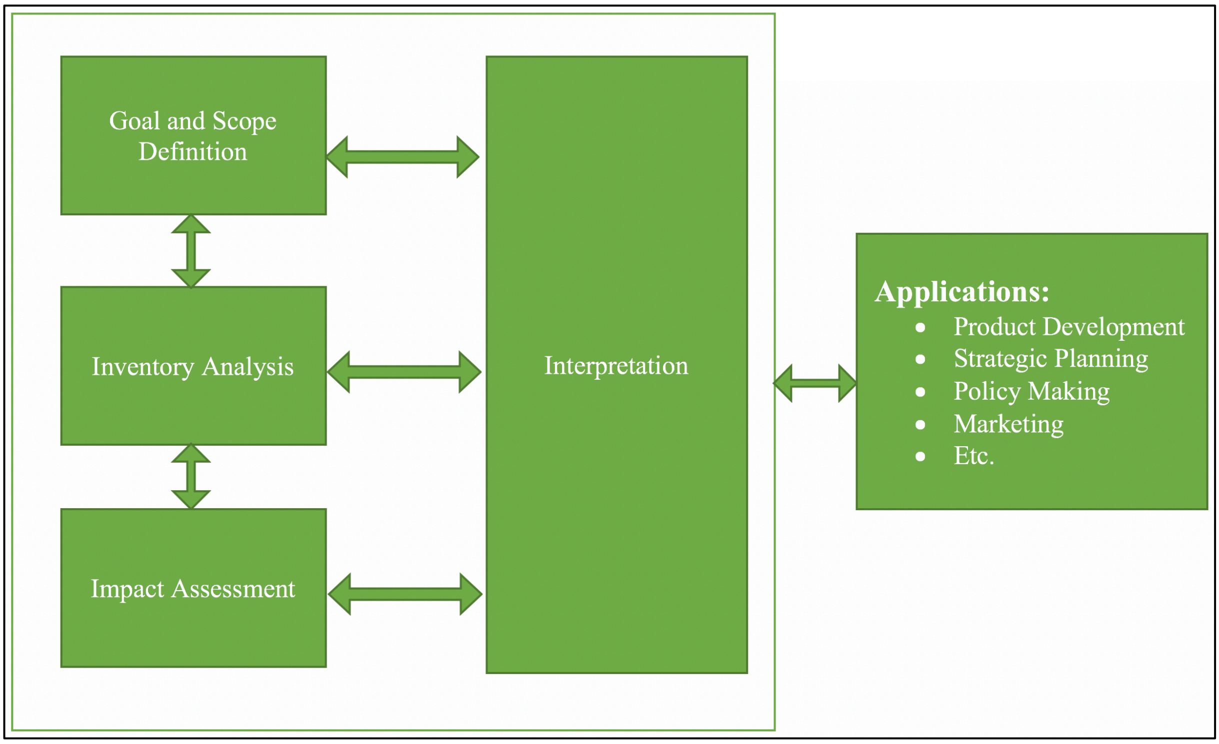

Figure 18, LCA Framework, Adopted from (ISO14040, 2006, ISO14044, 2006)

These steps assist to quantify the environmental energy and material flows that either directly or indirectly affect the energy and material consumption during the production, distribution, use and end of life treatment of the velomobile (Hellweg, 2005).

4.2. Goal and Scope Definition

In this section, the definitions of the following elements must be made:

- All of the products and services to be assessed.
- Functional unit or a functional basis for comparison purposes.
- The unit system boundaries.
- The environmental and human health impact categories of interest.
- The required level of details (Hellweg, 2005, ISO14040, 2006).

The product is a Podbike velomobile delivered to an ordinary end user. Two regions for the operation of the product are selected; Norway and Germany (the main market of the product). There are three reasons for this approach:

1. The main market of the product is in Germany, meaning most of the velomobiles will be used in Germany at least for the first and second series production batches, thereby Germany should be chosen in order to have a sensible overview of the product's environmental and human health impacts in the first years.
2. The original country of the product is Norway. It is planned to start delivery of the pre-order customers in Norway, the Nordics and Germany then followed by the rest of the EU. Also, it is predicted that the orders placed from the Norwegian customers for this product will increase substantially after the test series production. Furthermore, the region of the test series production is Norway (Podbike AS, 2019a). Hence, having Norway as another region of operation is important.
3. Norway and Germany have different electricity generation mix (Holstad et al., 2020), and since the source of energy could alter the results of the study, understanding the

consequences of this mix are necessary for the technical team and the investors of the Podbike company to have a more realistic and comprehensive overview.

As a result, the defined functional units are 200 000 km travelled by one adult in each market. As it is stated earlier, since the LCA study is an EndPoint LCA, the environmental and human health categories of interest are resource depletion, ecosystem damages and human health damages.

The unit system boundaries and the required level of details are illustrated in figure 19. The orange square stands for the entire system boundary under the LCA study and the green squares describe the necessary energy and material inputs and outputs with the specified level of details.

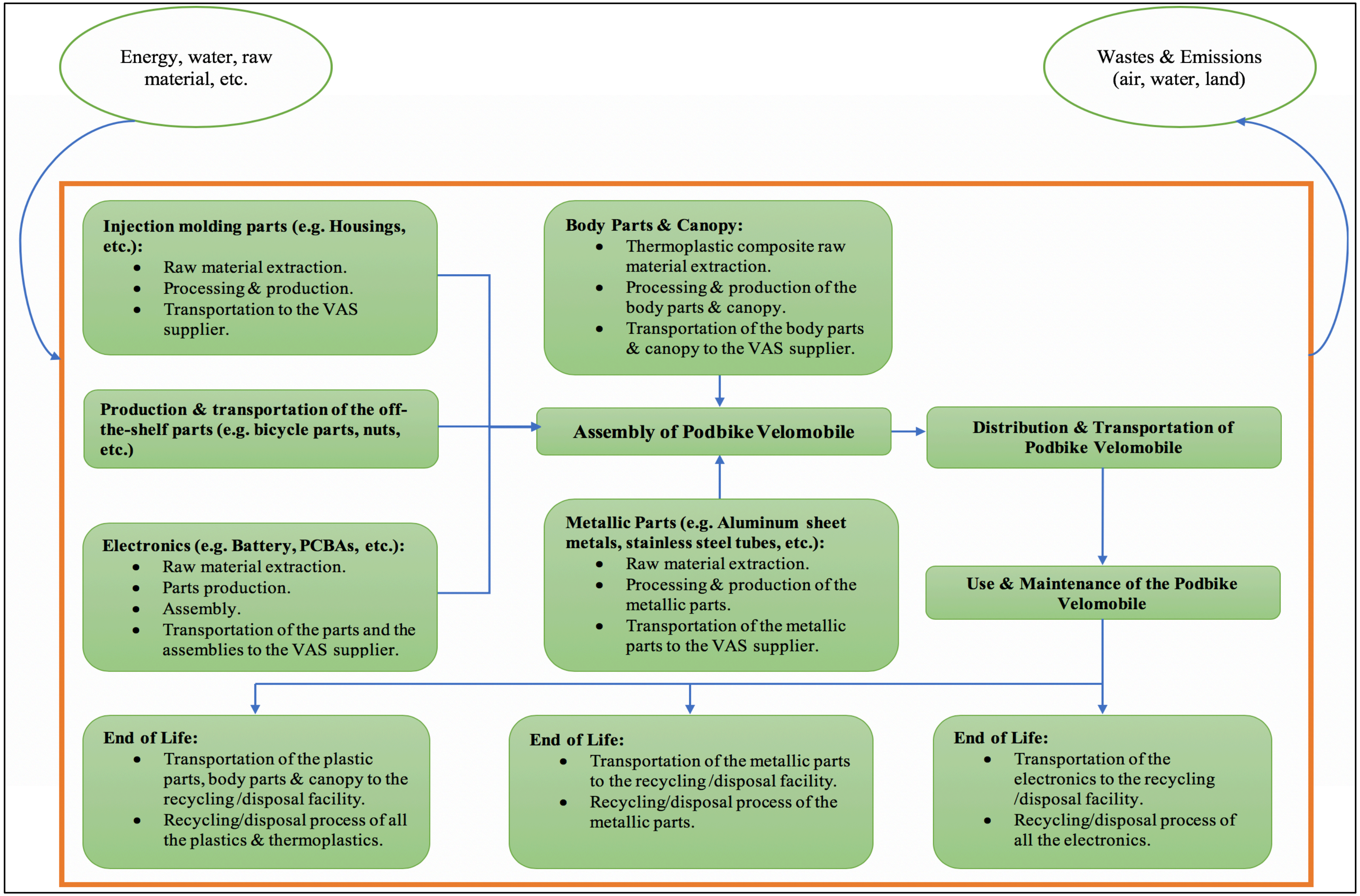

Figure 19, The LCA Stages of the Podbike Velomobile & its System Boundaries

4.3. Life Cycle Inventory (LCI)

The life cycle inventory procedure requires all of the appropriate input and output flows in the Podbike velomobile production. All of the involved inputs and outputs relate explicitly to the defined functional units and the requirements described in the goals and scopes of the study (Hellweg, 2005). An iterative approach is adopted for this study to meet all the requirements (ISO14040, 2006).

The system inputs of this LCA study comprise of the energy and raw material required to manufacture this velomobile. The outputs are considered and recorded as the wastes and emissions caused by the utilization of the energy and raw material resources in order to produce the defined functional units.

First of all, the input and output data were acquired. Thereafter, the product system and process flow charts for implementing the analysis is generated through incorporation of data into the SimaPro software (ISO14040, 2006, ISO14044, 2006). SimaPro software benefits from the data associated with the production and assembly, use and maintenance, transportation and waste treatment which are regionally sensitive. In particular, the processes for the complicated assemblies of e-bike such as Li-ion battery pack, generator, control units, etc. already exist in the database of the software (Goedkoop et al., 2014). Ecoinvent Version 3 database is utilized since this database is one of the most comprehensive and transparent databases used in the EU (Weidema et al., 2013). All the data are updated recently, and they comply with the ISO 14040 and ISO 14044 (SIMAPRO IS, 2020).

According to the scope and goal definition, the product consists of different assembly groups with different suppliers, production processes, average transportation distances, and end of life treatment procedures. As a result, top-level assemblies of the product are used to categorise the data gathering and increase the efficiency of the study.

4.4. Life Cycle Impact Assessment (LCIA)

In this stage, the significance of the environmental and human health impacts is assessed using the LCI results. The inventory data is associated with impact categories and category indicators. Then, the results of this stage can be used for the discussion and interpretation (ISO14044, 2006, ISO14040, 2006). The main framework of the LCIA phase is illustrated in figure 20.

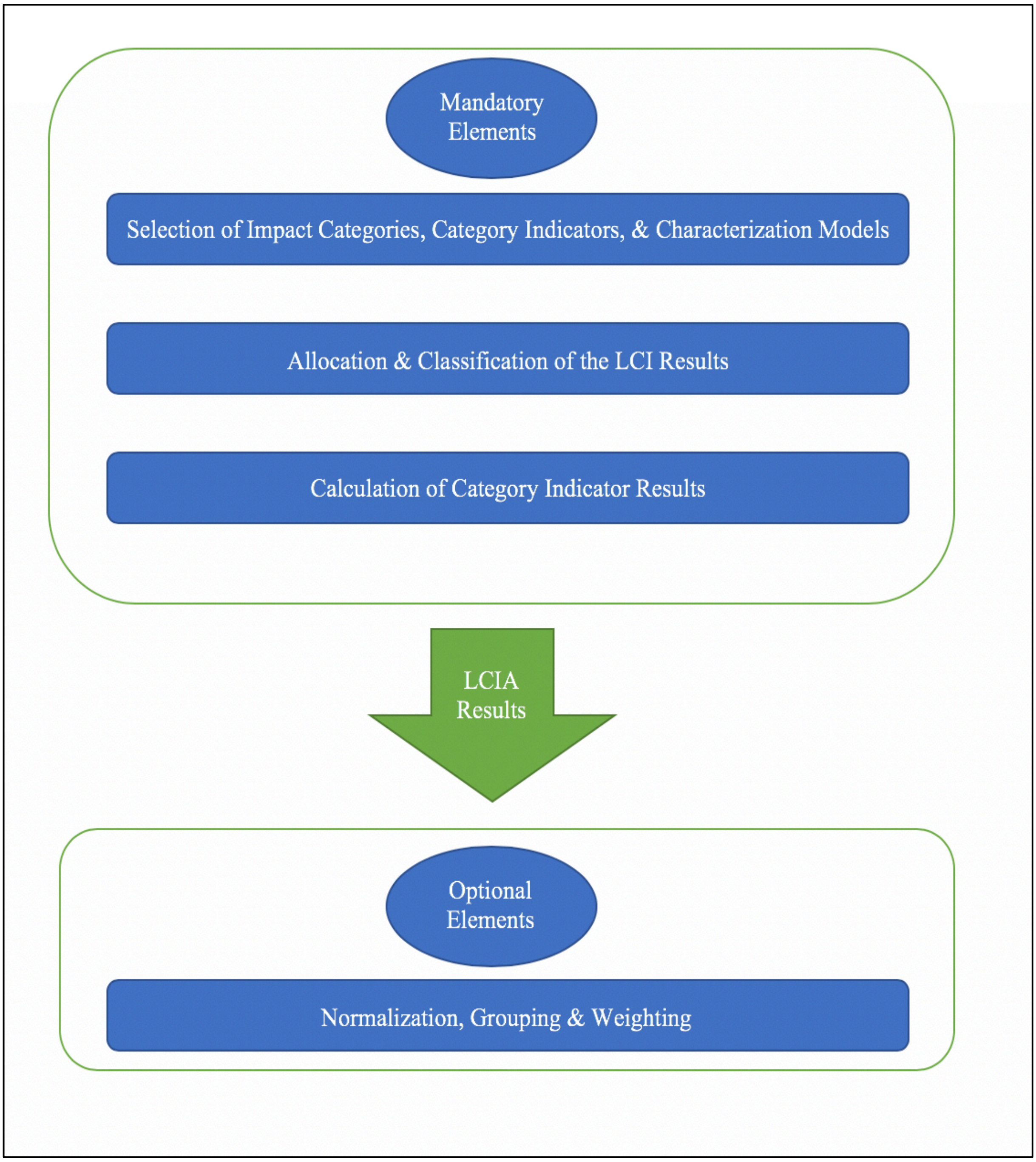

Figure 20, LCIA Framework, Adopted from (ISO14044, 2006, ISO14040, 2006)

Moreover, an iterative approach in this phase enables the researcher to examine the defined goal and scope of the study and verify if the objectives of the study are met.

The Ecoinvent v.3 is incorporated to the SimaPro software (Goedkoop et al., 2014). After the inventory data collection and aggregation, the software was deployed to generate the LCA model. The data inputs were used to build the process flows (inputs and outputs of the life cycle phases). Then the product systems were made to connect the process flows to the LCA model as a whole unit. Afterwards, the software was run to produce the results. Different scientific models based on the inventory data are generated using the software to show the EndPoint environmental and human health impacts caused by the Podbike velomobile's life cycle process of activities.

The impact assessment results show all of the consequences concerning the resources, ecosystem and human health. The results can be indicated either as an integrated single point or a percentage contribution of each process activity (Hellweg, 2005). For the sake of easy interpretation, the results can be normalized and weighted (ISO14040, 2006).

In order to perform the EndPoint LCA, the 'ReCiPe 2016 EndPoint (H) V1.03' method is chosen which is a synchronized impact assessment method. This method, that is the Hierarchist version, is the default ReCiPe EndPoint method and is in compliance with the scientific consensus with respect to the time frame and credibility of impact mechanism. In ReCiPe, it is possible to select using MidPoint or EndPoint indicators. The methodology contains global normalization factors for the reference year of 2010 as well as the weighting sets duplicated from ReCiPe 2008. The single point is calculated using characterization factors. Characterization factors determine the environmental and human health damages with regard to the pre-specified impact categories (i.e. Human Health, Ecosystem Diversity, Resource Availability) per unit of stressors (e.g. per kg of resource exploited). Also, the 2016 version of ReCiPe benefits from the characterization factors that are representative of the global scale rather than the EU scale (Huijbregts et al., 2017).

This method is the latest revision of the EndPoint impact assessment method, incorporated to the SimaPro software (Goedkoop et al., 2014). The method analyses the impact categories stemming from Damage to Human Health (HH), Damage to Ecosystem Diversity (ED) and Damage to Resource Availability (RA).

The impact categories and their MidPoint characterisation factors are detailed in table 1.

Table 1, The Selected Impact Categories of the ReCiPe 2016 EndPoint (H) LCIA Method, Adopted from (Huijbregts et al., 2017)

Item	Damage Category	Impact Category	Factor	Unit
1.	Human Health (HH)	-	-	DALY/DALY
1.1.		Global Warming, HH	1	DALY/DALY
1.2.		Stratospheric ozone depletion	1	DALY/DALY
1.3.		Ionizing radiation	1	DALY/DALY
1.4.		Ozone formation, HH	1	DALY/DALY
1.5.		Fine particulate matter formation	1	DALY/DALY
1.6.		Human carcinogenic toxicity	1	DALY/DALY
1.7.		Human non-carcinogenic toxicity	1	DALY/DALY
1.8.		Water consumption, HH	1	DALY/DALY
2.	Ecosystem Diversity (ED)	-	-	species.year/species.year
2.1.		Global warming, Terrestrial ecosystems	1	species.year/species.year
2.2.		Global warming, Freshwater ecosystems	1	species.year/species.year
2.3.		Ozone formation, Terrestrial ecosystems	1	species.year/species.year
2.4.		Terrestrial acidification	1	species.year/species.year
2.5.		Freshwater eutrophication	1	species.year/species.year
2.6.		Marine eutrophication	1	species.year/species.year
2.7.		Terrestrial ecotoxicity	1	species.year/species.year
2.8.		Freshwater ecotoxicity	1	species.year/species.year
2.9.		Marine ecotoxicity	1	species.year/species.year
2.10.		Land use	1	species.year/species.year
2.11.		Water consumption, Terrestrial ecosystems	1	species.year/species.year
2.12.		Water consumption, Aquatic ecosystems	1	species.year/species.year
3.	Resource Availability (RA)	-	-	USD2013
3.1.		Mineral resource scarcity	1	USD2013/USD2013
3.2.		Fossil resource scarcity	1	USD2013/USD2013

Lastly, the findings from the LCI and LCIA are considered together. Also, the consistency of the results with the goal and scope definition of the LCA study is re-evaluated. The outcomes of the study are transformed into understandable results by non-environmental experts such as design engineers, mechanical and electronic engineers, software specialists, supply chain managers, administrative and marketing departments, and particularly the investors and suppliers because the outcomes of this study should enable different people to find the environmental and human health burdensome associated with their activities. Accordingly, they would be able to look for the solutions to reduce the environmental and human health footprints in each step.

4.5. Interpretation

This stage is the final phase of the LCA procedure. Through this stage, the results of the LCI and LCIA are discussed as a basis for recommendations, conclusions and decision-making according to the defined goal and scope (ISO14040, 2006). The results of this step specify the areas of opportunity where the performance of the environmental and human health footprints of the product can be re-evaluated and improved.

A structured and iterative approach is utilized to recognise, qualify, inspect, assess and present the suggestions and conclusions in accordance with the findings of the LCA study (ISO14044, 2006).

In order to be able to monitor and keep track on the performance of the environmental and human health footprints of the assets (e.g. employees, companies, product, etc.) with regard to the EndPoint impact categories, a dashboard template is developed. This dashboard template is shown in figure 21.

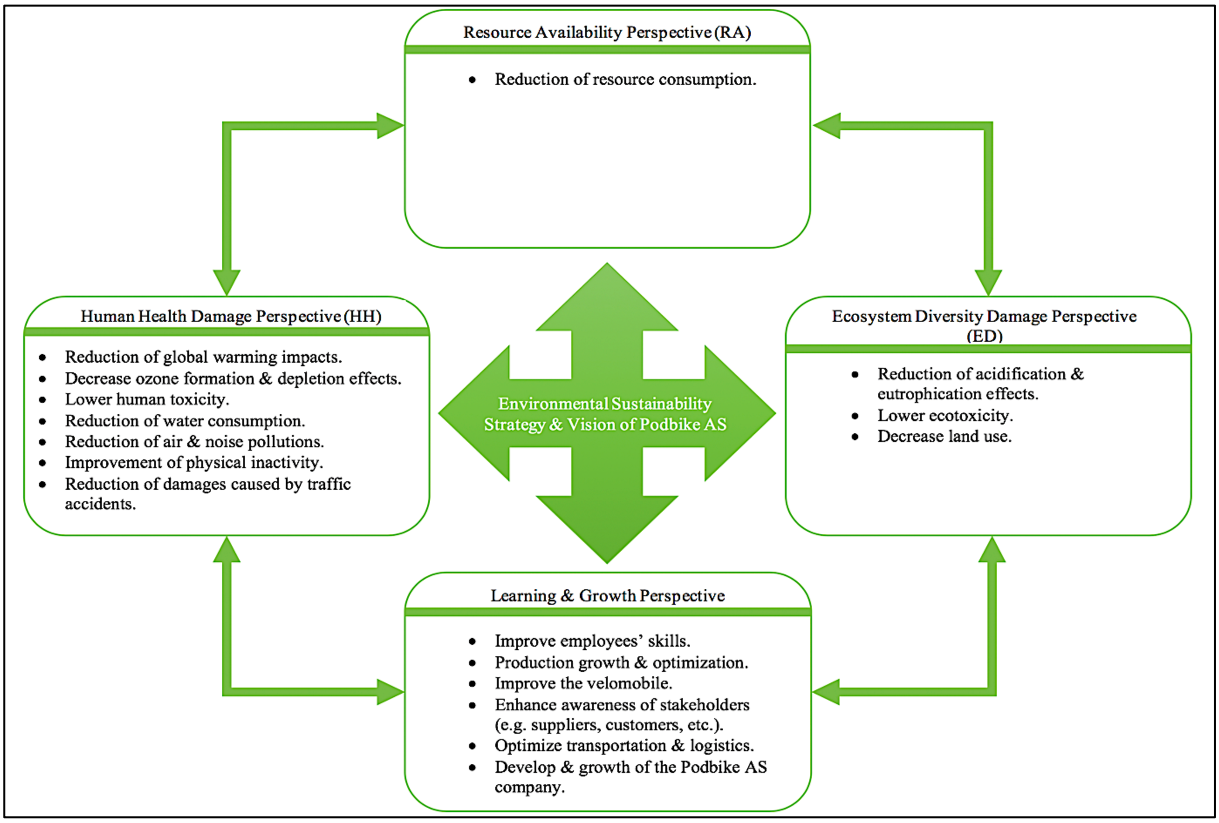

Figure 21, Dashboard Template of the Environmental and Human Health Footprints Performance of the Assets

Also, the above template can enable the manufacturer of the product to observe, measure and control the improvements of the environmental and human health footprints associated with the production of the vehicle based on the selected indicators. Moreover, the improvement measures can be implemented throughout time as a continuous approach using relevant actions and measures.

The interpretation step, which contains recommendations by the researcher as well as the final evaluation of the results consistency with the goal and scope of the study is addressed in Chapter 6 and Chapter 7 respectively.

Chapter 5,
Analysis and Results Based on the LCA Framework

This chapter documents the inventoried data and delineates the impact assessment results for the product's life cycle. The quantification of these results provides evidence for the associated damages to the ecosystem, human health and resource availability stemming from the activities of the Podbike velomobile production, distribution, use, maintenance and end-of-life treatment. Also, this chapter pinpoints where the greatest improvements to lower the environmental and human health footprints could occur.

5.1. Life Cycle Inventory

The product is made of five main master assemblies, which are detailed through the following sections. Only raw materials with the corresponding amounts, the processes involved in the transformation from raw materials to parts are illustrated on the tables below. Other detailed processes (e.g. electricity generations for each production step, transportations involved in the raw material production and distribution, packaging of the parts, etc.) are considered within each process step in the software and not shown here for simplification.

5.1.1. Inventory Data Collection

The primary data related to the production and assembly of different parts (e.g. raw material types, production processes involved, etc.) are collected using detailed technical files (e.g. technical drawings, CAD Models, BOMs, etc.), through close communication and cooperation with different departments of Podbike AS (e.g. marketing department for finding the main market location, etc.) and communication with the suppliers and their experts for more clarification. The data were collected in 2020. The energy consumption and raw material extraction associated with the mould production, manufacturing of each single part, preparation of the production lines and the assembly lines, assembly of the parts, etc. were taken into consideration. The interactions and discussions with the suppliers have been carried out via telecommunications (e.g. emails, phone calls, video-meetings, etc.) to reach different suppliers, located worldwide (e.g. China, Slovenia, Germany, etc.). The primary data were obtained and transformed into more generic data in order to protect the sensitive data from the company.

Once the primary data were accumulated, the secondary data (e.g. standard average amount of electricity required to run the machinery and production line of the thermoplastic body parts in total, etc.) were incorporated and weighted in association with the number of parts needed per velomobile so as to generate the LCA model. Secondary data inputs are achieved using academic peer-reviewed publications and Ecoinvent v.3 LCA databases. Moreover, the data collection has been performed under the inspection of another environmental expert and the inventor of the product (Per Hassel Sørensen). Thus, it is reassured that the validation procedure of the data collection has been carried out in a scientific manner in accordance with the ISO 14040 and ISO 14044.

In the calculation procedures of the data, the relation of the data to the unit process and the reference flow of the functional units is reassured. Also, inputs and outputs associations are re-evaluated.

Manufacturing: In the primary data, the main raw materials for the production of the plastic parts (e.g. the body, canopy, housings, clamps, etc.) are PMMA (Polymethyl Methacrylate), ABS (Acrylonitrile Butadiene Styrene), HDPE (High-Density Polyethylene), PETG (Polyethylene Terephthalate Granule), and PC (Polycarbonate) and the associated production methods are injection moulding and thermoforming. Most of the raw materials for the metallic parts are aluminium alloy with different properties (e.g. 6061-T6), steel and stainless steel. The corresponding production processes consist of rolling and extrusion, anodizing and powder coating. Also, for the complex electronics (e.g. PCBAs, generators, battery, etc.), which are the most challenging assemblies of the product, the primary data are gathered through reviewing all the relevant technical documents to be able to compare with the associated academic publications and adapt the secondary standard data within the database with them.

Transportation and distribution: Average transportation distances data from different suppliers to the VAS (Vehicle Assembly Service) partner, and from the VAS partner to the end users (i.e. Norway and Germany) are achieved through communication with the suppliers (e.g. using their website to find their address) and the marketing department of the Podbike company. The main market is Germany with the majority of the pre-orders. Norway has been chosen as another region of operation. Furthermore, as Podbike AS delivers the product itself, no retailers are considered in the average transportation distances estimations.

Use and maintenance: For the use phase, the only activity which can have the potential environmental and human health impacts, is recharging the battery. According to the product specification, the product is predicted to have at least 20 years of lifetime with 200 000 km operation. Also, it is estimated that the product can be used 10 000 km per year on average (Sørensen, 2019). Regardless of the whole lifetime, the energy consumption for riding the velomobile is 5 Wh/km, including regeneration provided by the product usage. Additional 5Wh/km energy consumption by blower, heater, lights, etc. can increase the total energy utilization of the product up to approximately 10 Wh/km. This shows the product uses 100 kWh/year, indicating almost 2 000 kWh electrical energy consumption by the product through its whole lifetime (Sørensen, 2014).

Norway and Germany are defined as the regions of operation and the sources of electricity are varied in each country. Although electric vehicles can omit the emissions during the operation. If the sources of the electricity to recharge the battery are non-renewable the amount of emissions can be different (Hawkins et al., 2013). Therefore, source of the energy plays a crucial role in the life cycle inventory analysis. The sources of electricity for the specified lands are as follows:

- Germany: 46.3% of the energy comes from renewable sources (i.e. hydro, biomass, wind, solar), 29.4% from coal (i.e. brown and black coals), 13.8% from nuclear and 10.5% from natural gas (Schneider M. A. and Burger, 2020).
- Norway: 97.9% of the electricity is generated by the renewable sources (i.e. hydropower and wind), 2.1% of the energy is produced through thermal power plants (Holstad et al., 2020).

This signifies that the velomobile in Norway is ridden using almost clean energy sources while just about half of the energy source for the vehicles used in Germany is clean. This could potentially lead to a remarkable difference between the results derived from the two different functional units.

For the expected maintenance processes of the product, the standard global maintenance LCA model for four-wheeled electrically assisted pedelec in the database is benefited.

End of life treatment: In order to quantify the environmental and human health impacts of the end-of-life treatment, the data from the standard waste treatment scenarios in Norway and Germany are obtained from the Ecoinvent v.3 database. The end-of-life treatment models contain all the energy and material consumption as well as the emissions associated with the municipal waste treatment scenarios. In this stage, transportation of the wastes, process of sorting the materials, recycling the recyclable parts (e.g. aluminium sheet metals, plastic body parts, etc.), and disposal of the non-recyclable parts are taken into account.

5.1.2. Complete Body Parts Assembly (PBA188)

This assembly, PBA188 contains 31 different parts. They include thermoformed plastic parts made of PMMA, ABS, HDPE and PETG raw materials, injection moulded plastic parts made of PETG, washers, hinges and screws made of steel and stainless steel, aluminium alloy sheet metals as well as the seals and rubbers made of EPDM (Ethylene Propylene Diene Monomer). The inventory inputs exported from the software are shown in table 2.

Table 2, Inventory Inputs for the Complete Body Parts Assembly

Item	Amount	Unit
1. Complete body parts assembly (PBA188), for velo, {GLO} |market for|	1	pcs
1.1. Materials/assemblies	-	-
Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | APOS, U	9.9	kg
Polymethyl methacrylate, sheet {GLO}| market for | APOS, U	1.1	kg
Polyethylene terephthalate, granulate, amorphous {GLO}| market for | APOS, U	0.7	kg
Steel, low-alloyed {GLO}| market for | APOS, U	0.01	kg
Steel, stainless 304 {GLO}| market for | APOS, U	0.02	kg
Polyethylene, high density, granulate {GLO}| market for | APOS, U	2.57	kg
Aluminium alloy, AlMg3 {GLO}| market for | APOS, U	0.0413	kg
Synthetic rubber {GLO}| market for | APOS, U	0.535	kg
1.2. Processes	-	-
Thermoforming, plastic sheet, {GLO}| market for | APOS, U	12.5	kg
Injection moulding, {GLO}| market for | APOS, U	1.7	kg
Transport, freight, lorry, {GLO}| market for | APOS, U	15	tkm
Rolling, aluminium, {GLO}| market for | APOS, U	0.042	kg
Washer, spring, steel, {GLO}| market for | APOS, U	0.009	kg
Screw, steel stainless 304, {GLO}| market for | APOS, U	0.019	kg

5.1.3. Rolling Chassis Complete Assembly (PBA011)

Assembly, PBA011 is made from 71 various parts. The parts consist of rivets, screws, washers, nuts made of aluminium, steel and stainless steel, sheet metals made of aluminium alloys, tubes made of stainless steel and aluminium alloy, thermoplastic parts (e.g. bushings, spacers, etc.) made of ABS, Nylon, PETG, PP (Polypropylene) as well as the rubbers and seals made of NBR (Nitrile Butadiene Rubber) and EPDM. The inventory inputs exported from the software are listed in table 3.

Table 3, Inventory Inputs for the Rolling Chassis Complete Assembly

Item	Amount	Unit
2. Rolling chassis complete (PBA011), for velo, {GLO}	1	pcs
2.1. Materials/assemblies	-	-
Steel, low-alloyed {GLO}| market for | APOS, U	2	kg
Synthetic rubber {GLO}| market for | APOS, U	1	kg
Steel, stainless 304 {GLO}| market for | APOS, U	4	kg
Polypropylene, granulate {GLO}| market for | APOS, U	0.142	kg
Aluminium alloy, AlMg3 {GLO}| market for | APOS, U	13	kg
Aluminium, cast alloy {GLO}| market for | APOS, U	1.232	kg
Aluminium, wrought alloy {GLO}| market for | APOS, U	6.18	kg
Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | APOS, U	0.73	kg
Nylon 6 {GLO}| market for | APOS, U	1.36	kg
Polyethylene terephthalate, granulate, amorphous {GLO}| market for | APOS, U	1.3	kg
Latex {GLO}| market for | APOS, U	2.56	kg
Nylon 6-6 {GLO}| market for | APOS, U	0.005	kg
2.2. Processes	-	-
Powder coat, aluminium sheet {GLO}| market for | APOS, U	600	cm^2
Anodising, aluminium sheet {GLO}| market for | APOS, U	1000	cm^2
Impact extrusion of aluminium, {GLO}| market for | APOS, U	3	kg
Impact extrusion of steel, {GLO}| market for | APOS, U	1.2	kg
Sheet rolling, aluminium {GLO}| market for | APOS, U	15	kg
Washer, steel stainless 304, {GLO}| market for | APOS, U	0.07	kg
Nut, steel stainless 304, {GLO}| market for | APOS, U	0.02	kg
Screw, steel stainless 304, {GLO}| market for | APOS, U	0.3	kg
Rivet, aluminium, {GLO}| market for | APOS, U	0.4	kg
Bicycle tyre, {GLO}| market for | APOS, U	4	pcs
Bicycle, winter tyre, {GLO}| market for | APOS, U	2	pcs
Plastic bicycle wheel, {GLO}| market for | APOS, U	6	pcs
Ball bearing, angular, {GLO}| market for | APOS, U	4	pcs
Mountain bicycle damper & spring, {GLO}| market for | APOS, U	2	pcs
Bicycle inner tube, {GLO}| market for | APOS, U	0.9	kg
Bicycle pedal, {GLO}| market for | APOS, U	2	pcs
Spring, steel stainless 304, {GLO}| market for | APOS, U	0.005	kg
Rod end, M6, ISO 12240-4, {GLO}| market for | APOS, U	0.6	kg
Rod end, M8, ISO 12240-4, {GLO}| market for | APOS, U	0.5	kg
Washer, steel, {GLO}| market for | APOS, U	0.04	kg
Rivet, steel stainless 304, {GLO}| market for | APOS, U	0.016	kg
Screw, steel, {GLO}| market for | APOS, U	0.4	kg
Nut, steel, {GLO}| market for | APOS, U	0.04	kg
Washer, spring, steel, {GLO}| market for | APOS, U	0.01	kg
Injection moulding {GLO}| market for | APOS, U	4.5	kg
Transport, freight, sea, transoceanic ship {GLO}| market for | APOS, U	55	tkm

5.1.4. Electrical System Assembly (PBA042)

Assembly, PBA042 is made from 30 different parts. The parts are screws and nuts made of steel and stainless steel, sheet metals made of aluminium alloys, thermoplastic parts such as electronic housings made of PETG, PP (Polypropylene), and PC (Polycarbonate) as well as the seals and some other small parts like TIMs (Thermal Interface Material or Thermal Conductor). Also, the life cycle of the main EAB's (Electrically Assisted Bicycle) sub-assemblies such as the battery, electronics for control units and generators are already available in Ecoinvent v.3 database and has been used. The inventory inputs exported from the software are listed in table 4.

Table 4, Inventory Inputs for the Electrical System Assembly

Item	Amount	Unit
3. Electrical system assembly (PBA042), for velo, {GLOBAL}|market for|	1	pcs
3.1. Materials/assemblies	-	-
Steel, low-alloyed {GLO}| market for | APOS, U	0.01	kg
Steel, stainless 304 {GLO}| market for | APOS, U	0.064	kg
Polyethylene terephthalate, granulate, amorphous {GLO}| market for | APOS, U	0.5	kg
Aluminium alloy, AlMg3 {GLO}| market for | APOS, U	0.2	kg
Cable, unspecified {GLO}| market for | APOS, U	1.5	kg
Synthetic rubber {GLO}| market for | APOS, U	0.066	kg
Polypropylene, granulate {GLO}| market for | APOS, U	0.05	kg
Polycarbonate {GLO}| market for | APOS, U	0.4	kg
Polyvinylchloride, bulk polymerised {GLO}| market for | APOS, U	0.3	kg
Fan, for power supply unit, desktop computer {GLO}| market for | APOS, U	0.06	kg
Battery, Li-ion, e-bike, rechargeable, standard {GLO}| market for | APOS, U	4	kg
Charger, e-bike {GLO}| market for | APOS, U	0.9	kg
Electronics, for control units, e-bike {GLO}| market for | APOS, U	0.7	kg
Thermal conductor, {GLO}| market for | APOS, U	0.01	kg
Potting resin, polyurethane, {GLO}| market for | APOS, U	0.018	kg
Electric motor, e-bike {GLO}| market for | APOS, U	3	pcs
3.2. Processes	-	-
Anodising, aluminium sheet {GLO}| market for | APOS, U	300	cm^2
Injection moulding {GLO}| market for | APOS, U	1	kg
Transport, freight, sea, transoceanic ship {GLO}| market for | APOS, U	5	tkm
Nut, steel stainless 304, {GLO}| market for | APOS, U	0.0026	kg
Nut, steel low alloyed, {GLO}| market for | APOS, U	0.01	kg
Spring, steel stainless, {GLO}| market for | APOS, U	0.002	kg
Screw, steel stainless 304, {GLO}| market for | APOS, U	0.06	kg
Sheet rolling, aluminium {GLO}| market for | APOS, U	0.16	kg
Washer, steel stainless 304, {GLO}| market for | APOS, U	0.003	kg

5.1.5. Canopy and Hinge System Assembly (PBA151)

Assembly, PBA151 is made using 9 different parts. The parts include washers and nuts made of steel and stainless steel, hinge arms and brackets made of aluminium alloy and stainless steel, thermoformed plastic parts made of PMMA, ABS and PETG, small injection moulded plastic parts as well as the seals and rubbers made of EPDM. The inventory inputs exported from the software are listed in table 5.

Table 5, Inventory Inputs for the Canopy & Hinge System Assembly

Item	Amount	Unit
4. Canopy & hinge system assembly (PBA151), for velo, {GLO}|market for|	1	pcs
4.1. Materials/assemblies	-	-
Steel, low-alloyed {GLO}| market for | APOS, U	0.075	kg
Steel, steel stainless 304, {GLO}| market for | APOS, U	0.343	kg
Aluminium alloy, AlMg3 {GLO}| market for | APOS, U	0.854	kg
Polyethylene terephthalate, granulate, amorphous {GLO}| market for | APOS, U	3	kg
Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | APOS, U	8.1	kg
Polymethyl methacrylate, sheet {GLO}| market for | APOS, U	0.9	kg
Synthetic rubber {GLO}| market for | APOS, U	0.256	kg
Polyvinylchloride, bulk polymerised {GLO}| market for | APOS, U	0.005	kg
4.2. Processes	-	-
Anodising, aluminium sheet {GLO}| market for | APOS, U	1200	cm^2
Injection moulding {GLO}| market for | APOS, U	3	kg
Thermoforming of plastic sheets {GLO}| market for | APOS, U	9	kg
Transport, freight, sea, transoceanic ship {GLO}| market for | APOS, U	12	tkm
Impact extrusion of aluminium, {GLO}| market for | APOS, U	0.5	kg
Sheet rolling, aluminium {GLO}| market for | APOS, U	0.21	kg
Nut, steel stainless 304, {GLO}| market for | APOS, U	0.05	kg
Screw, steel stainless 304, {GLO}| market for | APOS, U	0.06	kg
Washer, steel stainless 304, {GLO}| market for | APOS, U	0.006	kg
Needle bearing, steel, {GLO}| market for | APOS, U	0.012	kg
Rivet, aluminium, {GLO}| market for | APOS, U	0.013	kg
Washer spring, steel, {GLO}| market for | APOS, U	0.006	kg

5.1.6. Brake System Assembly (PBA031)

Assembly, PBA031 is made from 8 different parts. The parts include screws made of steel and stainless steel and sheet metals made of aluminium alloys. In addition, the life cycles of some main bicycle parts such as hydraulic brake system which are already existed within the software are used. The inventory inputs exported from the software are listed in table 6.

Table 6, Inventory Inputs for the Brake System Assembly

Item	Amount	Unit
5. Brake system assembly (PBA031), for velo, {GLO}|for market|	1	pcs
5.1. Materials/assemblies	-	-
Steel, stainless 304 {GLO}| market for | APOS, U	0.13	kg
Bicycle brake disk, steel stainless 304, {GLO}| market for | APOS, U	4	pcs
Hydraulic brake, bicycle, {GLO}| market for | APOS, U	1	pcs
Brake calliper, bicycle, {GLO}| market for | APOS, U	2	pcs
Brake wire, bicycle, {GLO}| market for | APOS, U	2	pcs
Brake lever, bicycle, {GLO}| market for | APOS, U	2	pcs
5.2. Processes	-	-
Transport, freight, aircraft {GLO}| market for | APOS, U	1.2	tkm
Screw, steel stainless 304, {GLO}| market for | APOS, U	0.135	kg

5.2. Life Cycle Impact Assessment

In this section, the LCIA results are modelled using SimaPro software (version 9.0.0.48) and the following impact categories are assessed to generate the environmental and human health impacts of the Podbike velomobile throughout its whole lifecycle.

- Human Health Damages.
- Ecosystem Damages.
- Resource Depletion.

The impacts of the Podbike velomobile's production, distribution, use, maintenance and end-of-life treatment are integrated into a single score using the software.

The red line in each box indicates the level of environmental and human health damages caused by the associated assembly and part production, or processes (e.g. maintenance, waste treatment, etc.). The higher the red line is, the greater the environmental and human health damages are with respect to the defined impact categories. Also, the red arrow marks the environmental and human health damages caused by each box, the thicker the red arrow is, the larger the environmental and human health damages are.

It should be mentioned that the software downsizes the number of parts, processes and assemblies to the most important ones with the highest impacts in order to show it in one page, otherwise the number of sub-assemblies, sub-processes and single parts can become too impractical and complicated for the readers. Thereby, only the processes associated with the production, assembly, use, maintenance, etc. which have a point greater than or equal to 5 pt are shown. For example, the process activities involved in the transportations or packaging of the parts delivered by the suppliers are not displayed by the software and they are hidden because it is not considered having significant environmental and human health damages in comparison with the other assemblies and processes, another instance is the brake system assembly's environmental and human health impacts which are not presented due to the low level of impacts.

The first model is a single score process tree. This model conveys a total overview of each assembly and process contribution(s) to the environmental and human health damages using a single point.

The second model is the second single score process tree where the process activities that have a considerable contribution to the environmental and human health footprints are illustrated in percentage.

The third diagram, a bar chart summarizes the relative contribution of each individual phase of the product's lifecycle to the selected impact categories.

5.2.1. Life Cycle Impact Assessment Results for Norway

The first model called single score process tree of the vehicle with the selected region of operation as Norway that is delineated in figure 22.

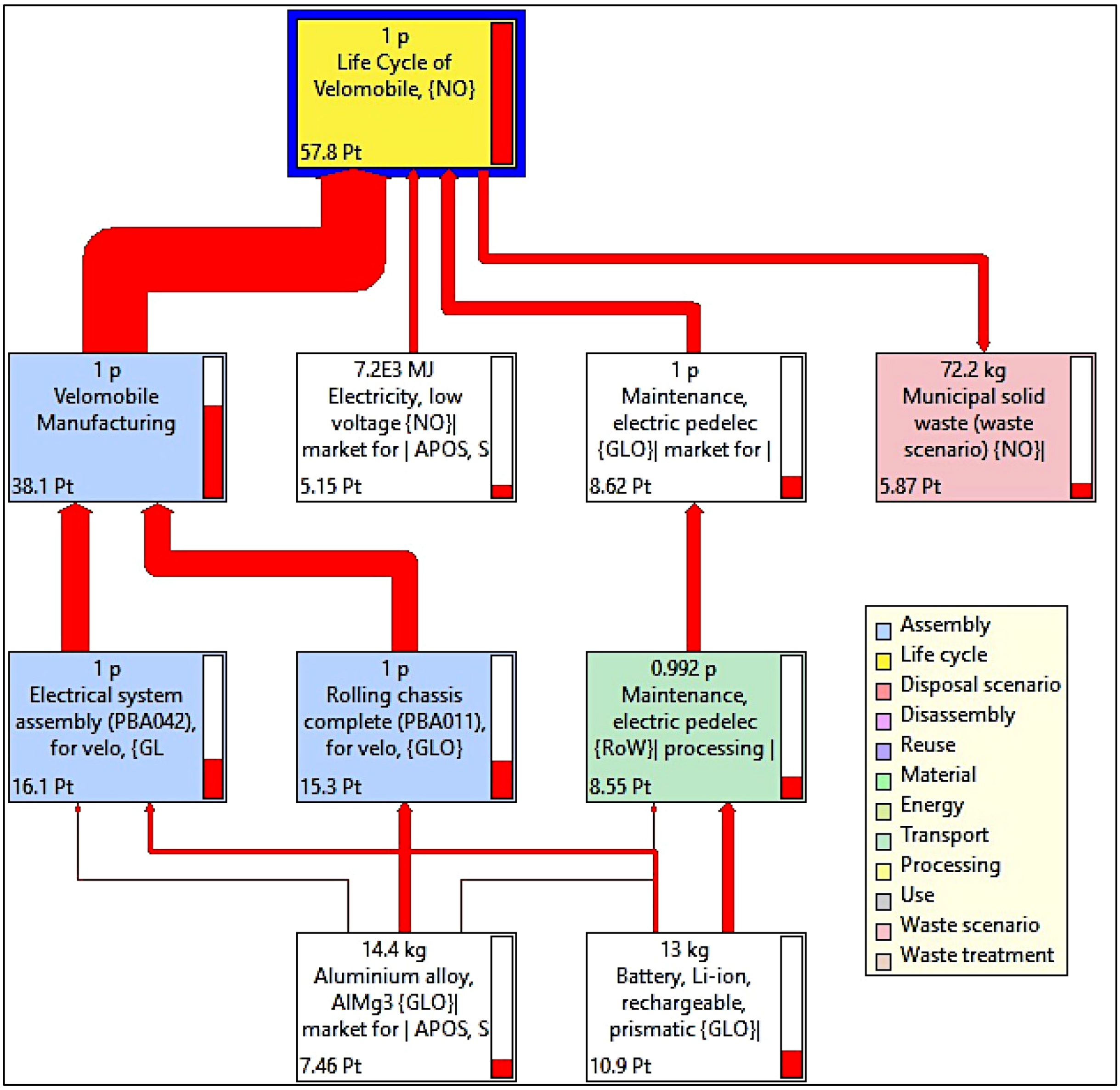

Figure 22, Single Score Process Tree of Podbike Velomobile's Life Cycle with the Functional Unit Defined in Norway

According to the diagram above, the product's lifecycle has a contribution of around 57.8 pt. (the single score) to the environmental and human health impacts with respect to the selected impact categories.

As it is obvious, the manufacturing of the velomobile is mainly responsible for the damages to the environment and human health with 38.1 pt, while the electricity consumption during the use phase throughout the products' lifespan has the lowest level of impacts with a score about 5.15 which is slightly less than the damages caused by the standard municipal waste treatment scenario in Norway that is roughly about 5.87 pt. Also, the graph indicates that the maintenance of the vehicle during its lifetime has an impact with 8.62 pt.

From the red line level, it can be realized that the processes which cause the high level of the environmental and human health impacts through the product's manufacturing are mostly the ones associated with the production of the Electrical System Assembly (PBA042) with 16.1 pt and the Rolling Chassis Complete (PBA011) with 15.3 pt. which are approximately 1-2 times more than the same number resulted from the processes involved in the maintenance of the product.

The parts which are primarily responsible for the high level of environmental and human health impacts are the battery pack with 10.9 pt and the aluminium alloys (AlMg3) with 7.46 pt.

The second model presenting the environmental and human health impacts in percentage for Norway as the region of operation containing more details is outlined in figure 23.

Based on the figure below, approximately 66% of the total environmental and human health footprints of the product is attributable to the manufacturing phase. Also, it is perceivable that the maintenance stands for almost 15% of the environmental and human health damages while this share for the electricity utilization during the use phase is just about 9%. In addition, the end of life treatment scenario accounts for the third-highest proportion which is roughly 10%.

Regarding each assembly production, as it is stated earlier, the electrical system assembly of the product is accountable for the majority of the environmental and human health impacts in the product's manufacturing with almost 28% which is 1.5% more than the impacts resulted from the activities attributable to the production of the rolling chassis complete assembly. The canopy and hinge system assembly has a contribution near 5.43% whereas, the complete body assembly has the least share of the environmental and human health damages with approximately 4.8%.

In addition, the more detailed tree-view figure below demonstrates that 13% of the impacts caused by the maintenance activities due to the predicted battery replacements during the product's lifetime. The parts with the second largest percentage of the impacts are aluminium alloy, AlMg3 that stands for 11.7% of the total impacts stemming from the manufacturing. Also, this is observable that the battery pack and the electronics for control units cause an almost equivalent ratio of the damages which is around 5.5%. Simultaneously, it can be realized from the depiction below that the aluminium wrought alloy is another group of components with an impact close to 7.1% which is roughly just about 0.5% less than the contribution of the electric motors.

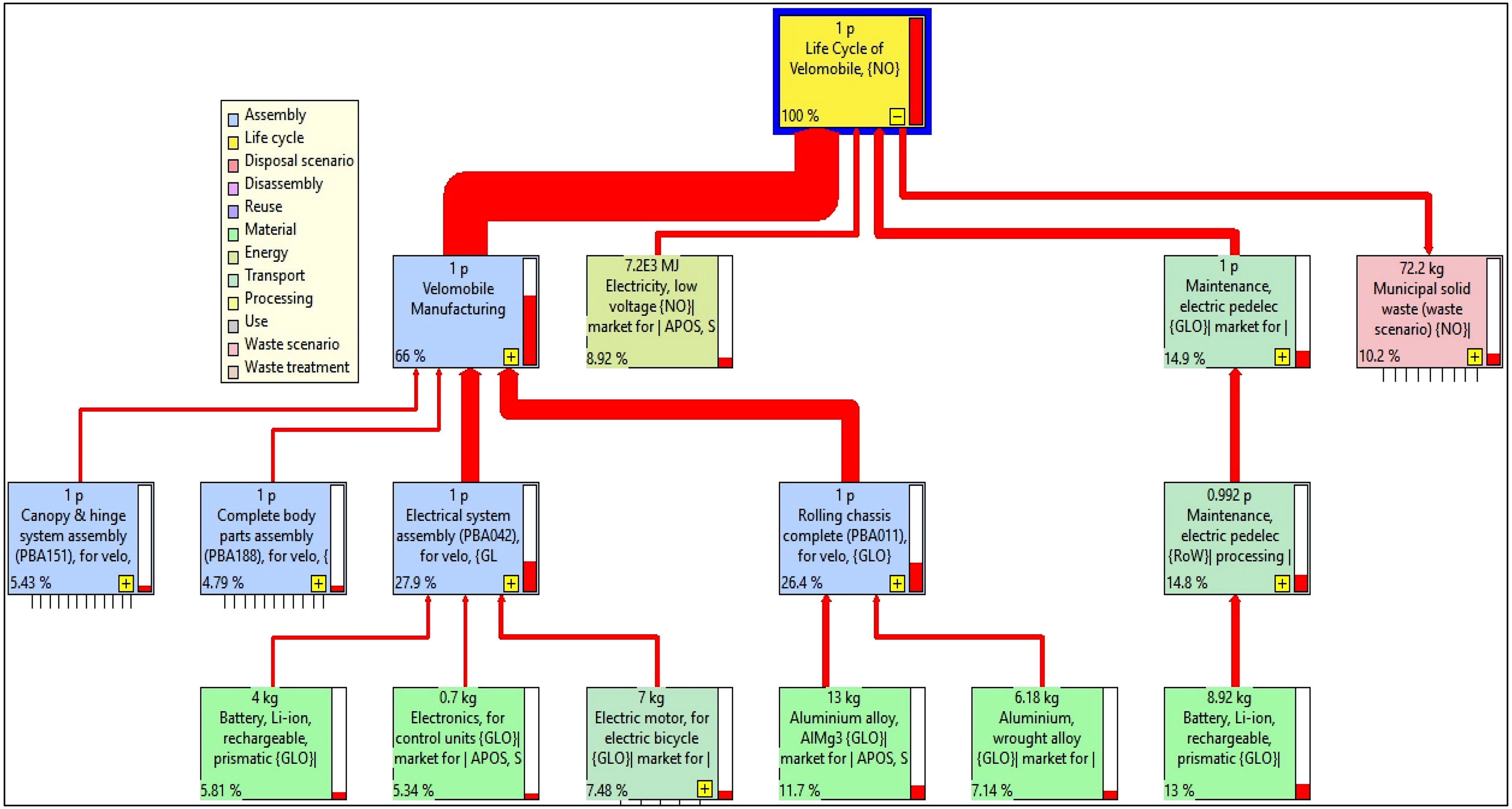

Figure 23, Single Score Process Tree of Podbike Velomobile's Life Cycle with the Functional Unit Defined in Norway, the Contributions Displayed in Percentage

The third graph is represented in figure 24.

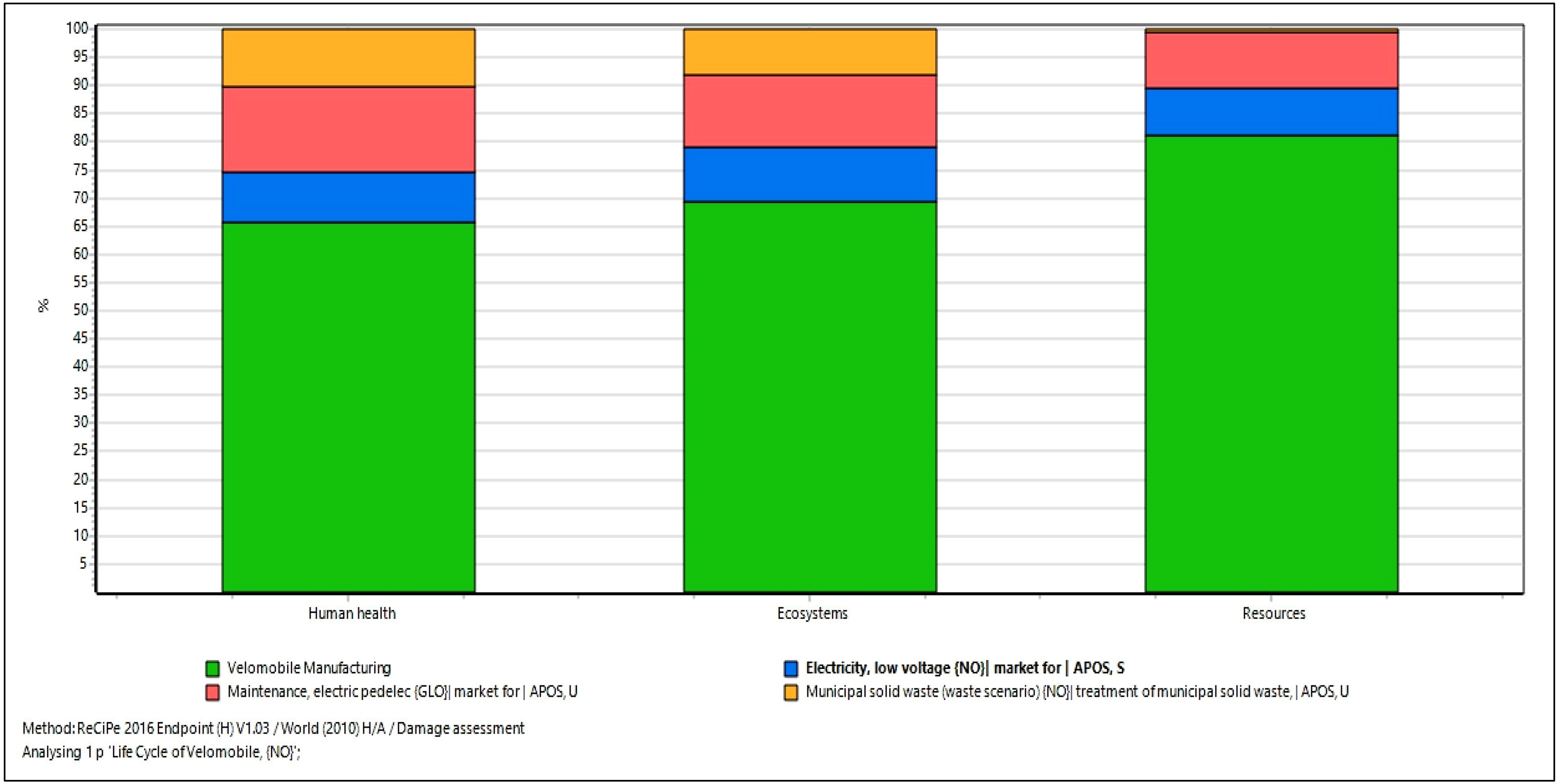

Figure 24, Environmental and Human Health Damages Assessment Bar Chart of the Podbike Velomobile's Lifecycle, with the Functional Unit Defined in Norway

From the chart above, it is clear that the velomobile's manufacturing (in green) is primarily accountable for most of the environmental and human health impacts with respect to the chosen impact categories. It contributes to a little bit more than 65% of the human health impacts which is just about 4% less than the damages to the ecosystem, while it causes slightly more than 80% of the resource depletion.

On average, the processes involved in the maintenance of the product over its lifetime results in a noticeable ratio of the damages, this is shown by the red colour for each impact category. It is quite evident that these processes can result in slightly less than 15% of the human health damages while this contribution to the ecosystem damage and resource depletion impact categories are approximately 13% and 11% respectively.

The blue colour which is the representative of the environmental and human health impacts during the use or operation phase (i.e. electricity consumption for recharging the battery throughout the whole life cycle of the product) has a lower level of the damages in compare to the maintenance and manufacturing processes of the product. On average for the HH and ED impact categories, it is rather 8% which is just about 1% higher than the impacts on the RA impact category.

Regarding the waste treatment scenario, the proportions of the environmental and human health damages for each impact category are indicated using the orange colour, and it demonstrates that the municipal waste treatment scenario in Norway could potentially lead to around 10% human health damages, approximately 7% of the ecosystem damages, and less than 1% resource reduction.

5.2.2. Life Cycle Impact Assessment Results for Germany

The first model which is the single score process tree of the vehicle with the chosen zone of usage as Germany can be found in figure 25.

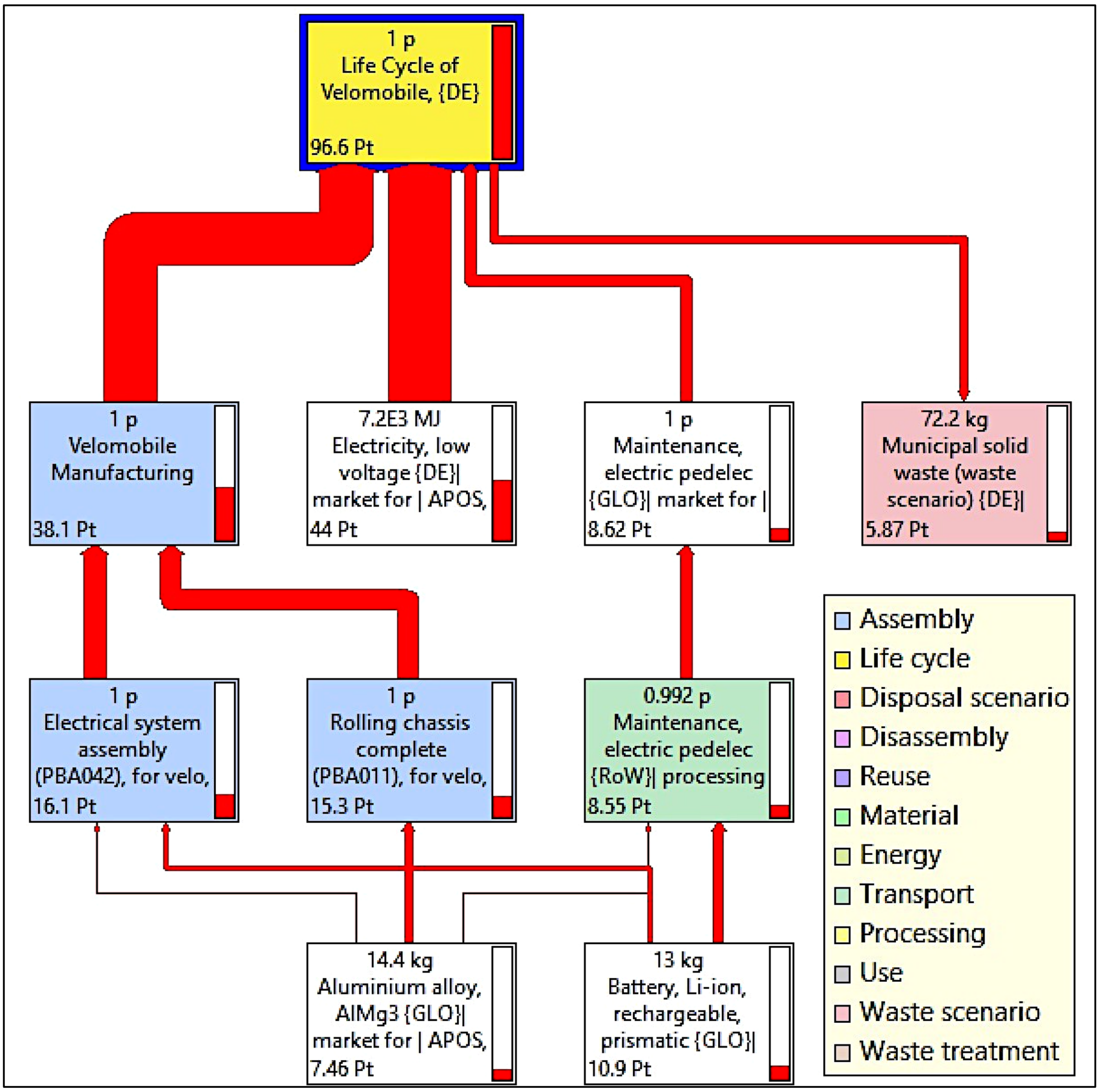

Figure 25, Single Score Process Tree of Podbike Velomobile's Life Cycle with the Functional Unit Defined in Germany

As reported by the depiction above, the product's lifecycle has a contribution of around 96.6 pt. in total to the environmental and human health impacts in association with the selected impact categories which highlights the impacts of changing the region of operation in other words changing the sources of energy.

Obviously, in Germany, the energy consumption over the use phase of the velomobile is primarily accountable for the impacts on the environment and human health with 44 pt, while this proportion for the standard process activities related to the municipal waste treatment scenario in Germany is the least score with a point about 5.87 pt. The second greatest impacts concern the group of activities associated with the vehicle's manufacturing with 38.1 pt. In addition, the diagram indicates that the maintenance of the vehicle throughout its lifespan has an impact with 8.62 pt.

The red line level specifies that the procedures which lead to the most environmental and human health damages of the velomobile's manufacturing are the ones concerning the production of the Electrical System Assembly (PBA042) with 16.1 pt and the Rolling Chassis Complete (PBA011) with 15.3 pt which are approximately 3-4 times more than the same ratio caused by the production, assembly and transportation processes involved in the canopy and hinge system or body parts assemblies since they are made hidden by the software which means that they have a score less than 5 pt.

The components that are mainly responsible for the high level of environmental and human health impacts are the battery pack with 10.9 pt and the aluminium alloys (AlMg3) with 7.46 pt.

The second model describing the environmental and human health impacts in percentage for Germany including more details is shown in figure 26.

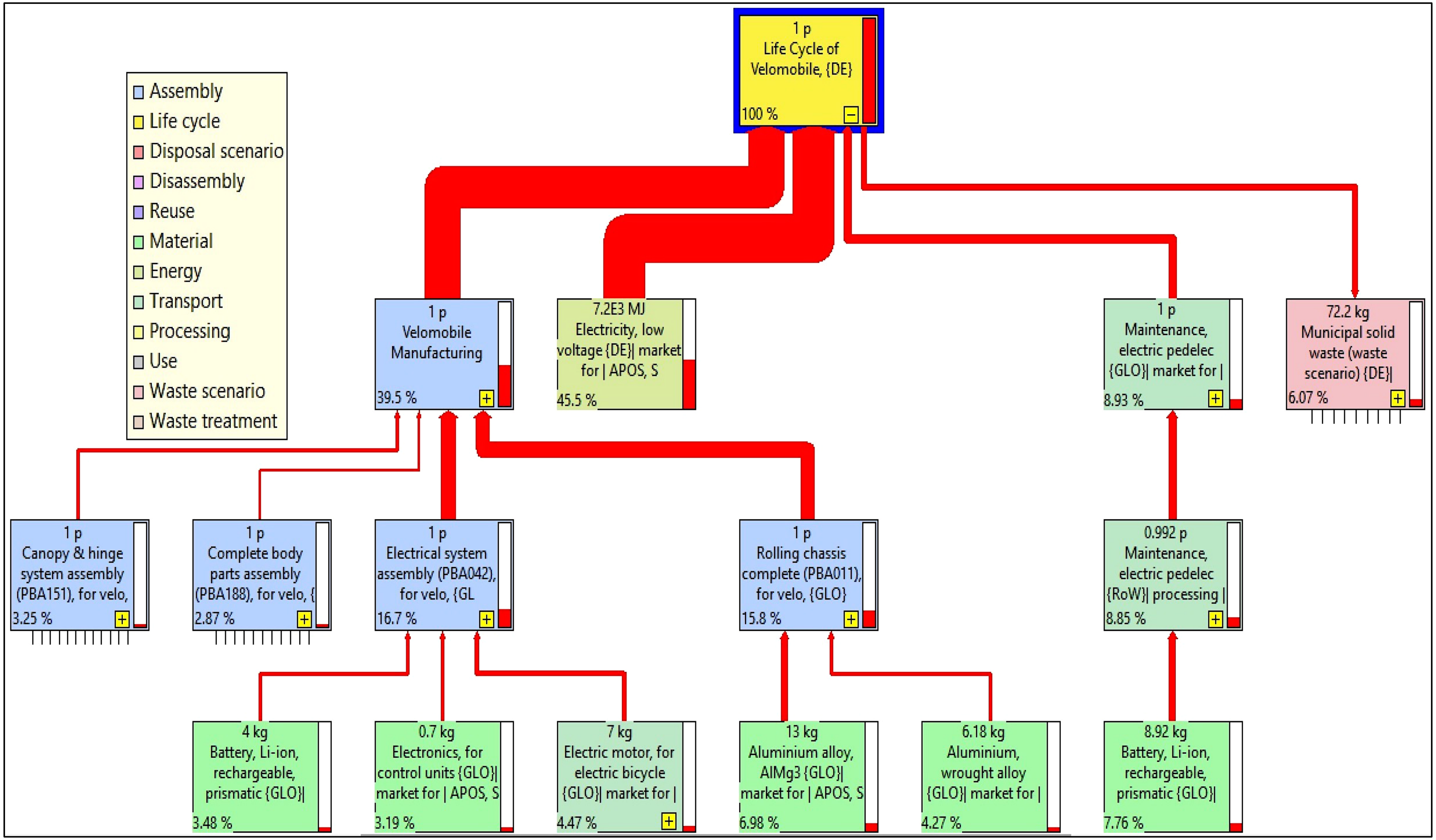

Figure 26, Single Score Process Tree of Podbike Velomobile's Life Cycle with the Functional Unit Defined in Germany, the Contributions Displayed in Percentage

The third graph for the vehicles operated in Germany is illustrated in figure 27.

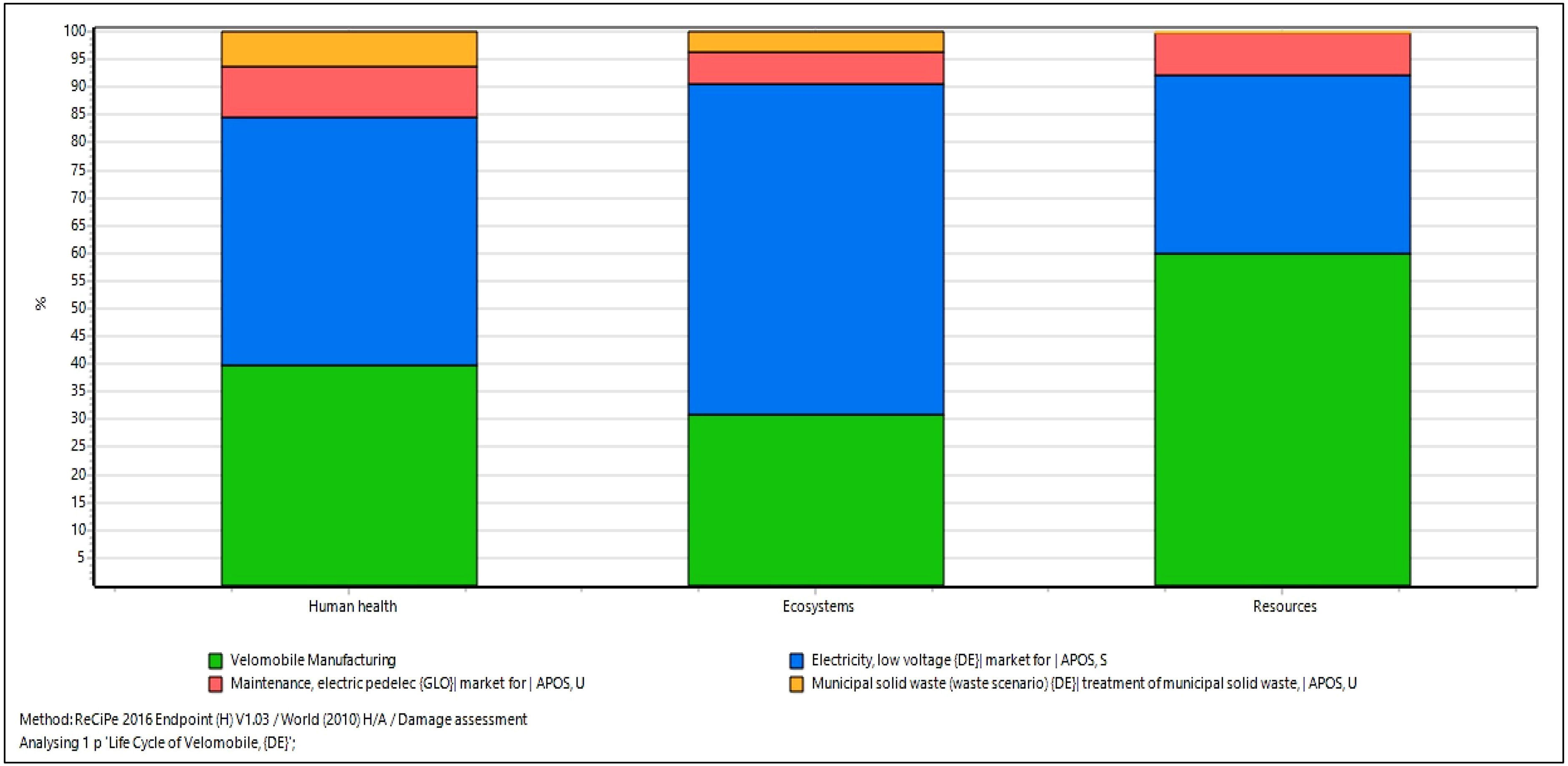

Figure 27, Environmental and Human Health Damages Assessment Bar Chart of the Podbike Velomobile's Lifecycle, with the Functional Unit Defined in Germany

The bar chart above shows that the velomobile's manufacturing (in green) is primarily accountable for the resource depletion with around 60% share. This is almost double the damages it causes the ecosystem, and 20% higher than the impacts on human health.

The blue colour, indicating the environmental and human health impacts during the use or operation phase (i.e. electricity consumption for recharging the battery through the whole life cycle of the product), has the highest impacts on ecosystem (approximately 60%) in compare with its impacts on human health (approximately 45%) or resource availability (approximately 33%). Furthermore, it is noticeable that the impacts of the product's manufacturing on resource availability are about 26% more than the same impacts caused by the use phase, while the ecosystem damages resulted from the manufacturing phase is half of the use phase, and the human health impacts associated with the product's fabrication stage is just about 5% less than the damages concerning the use phase.

The processes involved in the maintenance of the product over its lifetime leads to a ratio of the damages which is shown in red for each impact category. It is clear that these procedures can bring about a little less than 10% of the human health damages while this contribution to the ecosystem damages and resource depletion impact categories are close to 5% and 6% respectively.

With regard to the waste treatment scenario, the shares of the environmental and human health impacts for each impact category are represented in orange, and it describes that the municipal waste treatment scenario in Germany could potentially cause about 6-7% human health damages, slightly less than 5% of the ecosystem damages, and less than 1% impacts on the resource availability.

5.2.3. Comparative Analysis Between the Selected Regions

In this section, the two selected regions within the defined functional units are analysed and compared using comparative damage assessment bar chart. The diagram is shown in figure 28.

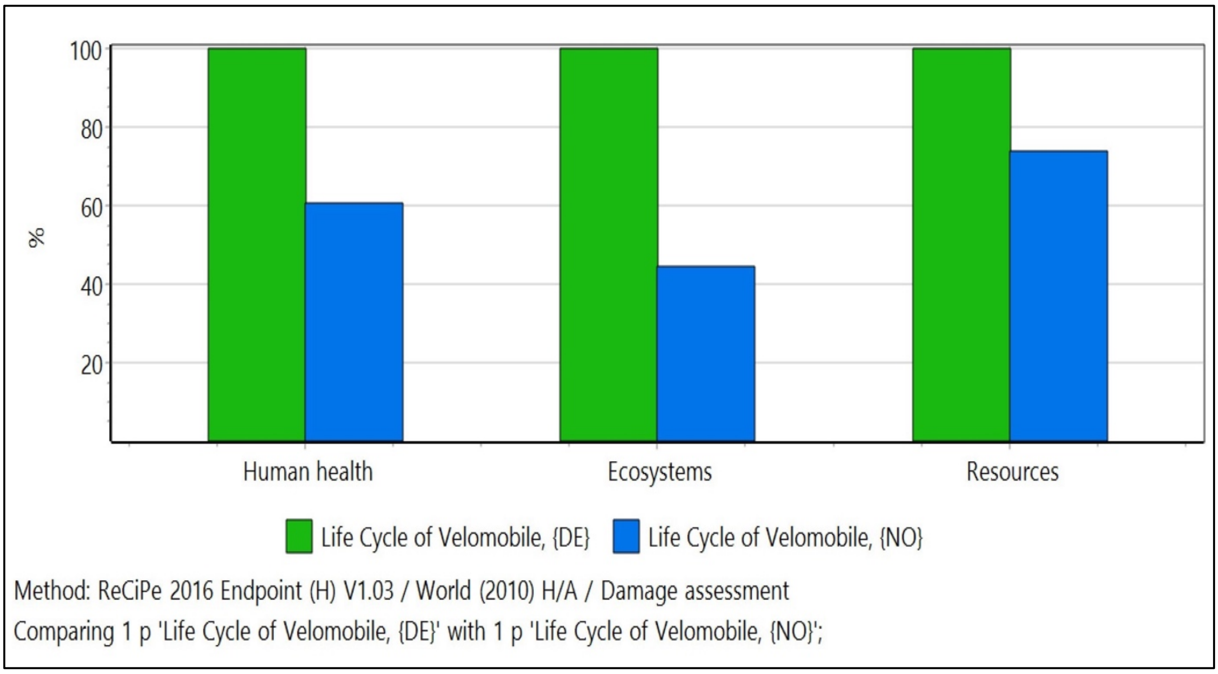

Figure 28, Comparative Damage Assessment for the Two Selected Regions of Operation

In the plot above, the blue bars are the representative of the damages caused by a Podbike velomobile operated in Norway through its lifespan and the green represents the environmental and human health impacts from a Podbike velomobile used in Germany throughout its lifetime.

It can be perceived that the human health damages resulted from a Podbike velomobile in Germany is 40% higher than having this vehicle ridden in Norway, while the unfavourable impacts on the ecosystem for the vehicle in Norway is almost 55% less than the one used in Germany. Moreover, when it comes to the resource availability, this difference decreases up to around 25%.

The main difference between these two countries is the sources of energy that in Norway is primarily renewable while in Germany is a mix of various sources. Accordingly, the different sources of energy play an important role during the use stage of the product’s lifecycle.

Chapter 6,
Recommendation for Further Improvements

Based on the attained results of the LCA study, the following recommendations are formulated:

- **Aluminium Components:**

  These parts have the greatest level of the environmental and human health damages in total. Podbike AS is in the stage of making decision regarding utilization of the powder coating or anodizing all the aluminium components of the chassis in the mass production for the following two reasons: Firstly, for cosmetic purposes secondly, for extra corrosion-resistance. However, since these aluminium components have an acceptable corrosion-resistance, the main reason is cosmetic purposes. In addition, anodizing and powder coating processes of the aluminium sheet metals can intensify the damages to the environment and human health (Sørensen, 2014). Accordingly, it is recommended to avoid the powder coating and anodizing processes involved in the aluminium parts fabrication in order to reduce the measured environmental and human health impacts.

  The supplier of the aluminium sheet metals and the vehicle assembly service are not selected yet, and they are under evaluation. Since there are different potential suppliers in different locations either for the assembly services or aluminium sheet metals fabrication, it is suggested to select both of the suppliers from one region to decrease the environmental and human health footprints associated with the transportation of the aluminium sheet metals.

  Recycling of aluminium needs only approximately 5% of the energy required to fabricate the primary aluminium. CIRCAL 75R is the type of recycled aluminium that contains at least 75% of post-consumer scrap with lightweight and benefiting from the same quality as the primary aluminium. This aluminium type is produced by Hydro, located worldwide which means less environmental and human health footprints are involved due to less transportation (Norsk Hydro ASA, 2019). Thereby, using the aluminium sheet metals fabricated by this product can decline the detrimental impacts of the rolling chassis assembly on the environment and human health.

- **The battery:**

  The battery modules have the second highest contribution (11%) to the environmental and human health impacts over the velomobile's lifecycle in total. As a result, selecting a battery pack supplier in the EU rather than Canada could reduce the environmental and human health impacts of this part considerably with respect to the mean and distance of transportation.

  Developing a specific battery pack for the Podbike velomobile could result in a longer lifetime which means less need for battery replacements. This could yield higher customer satisfaction and less environmental and human health impacts.

  Most of the impacts stemming from the battery can be mitigated through reusing the battery modules and recovering the materials from the battery. Depending on the available technology and developed recycling processes, 50-80% of the lithium-ion battery can be recycled (Elwert et al., 2018). Hence a battery design adapted to recycling requirements at system and module levels as well as planning the recycling procedures of the battery through close cooperation with the firms focusing on the battery's end-of-life treatment can improve the performance of the environmental and human health footprints.

- **Motors:**

    Three e-bike motors which are supplied from China, are other important components with an around 4.5% contribution. Hence, close cooperation with the supplier and the technical team of the company can end up having the supplier of the motors in EU instead of China, this can decrease the damages caused to the studied impact categories through less emissions and less fuel consumption caused by the shipments of the components.

    The motors are off-the-shelf (i.e. ready-made) parts, development of new motors with focus on the environmental and human health consequences through collaboration with the supplier can improve the environmental and human health footprints profile of these parts.

- **Waste treatment scenario:**

    The end of life treatment stage of the asset is a crucial part of the asset's lifecycle. Since this product is made of so many recyclable materials such as the thermoplastic canopy and body parts, aluminium sheet metals, etc. It is important to have close cooperation and collaboration with the companies specialised in recycling procedures for each region in order to develop a new standard recycling process apart from the municipal waste treatment procedures. This can mitigate the environmental and human health damages caused by the asset significantly.

- **Energy sources**

    It is highly recommended to the manufacturer of the product to inform the customers who live in a region in which the sources of electricity are varied (i.e. renewable and non-renewable) regarding the importance of purchasing electrical energy generated through the renewable sources otherwise they could potentially increase the risk of damages imposed to human health and ecosystem and reduce the availability of resources. Hence the involvement of the customers can increase their awareness of the consequences of their choice. Also, this itself can lead to the growth of demands on the clean energy.

- **Designs and Engineering**

    The parts' designs should be adapted into the recyclability needs to increase the recyclability of the parts made of the above materials (Felton and Bird, 2006)

- **Continuous performance monitoring framework**

    When certain improvement measures are taken, the company should have a technique or framework to assess the environmental and human health footprints performance improvement level based on the selected EndPoint impact categories measured using the relevant software(s) (e.g. SimaPro, OpenLCA, etc.) and datasets (e.g. Ecoinvent, ELCD, IDEA, etc.). As a result, a mind map is developed and recommended to Podbike AS which can be found in figure 29.

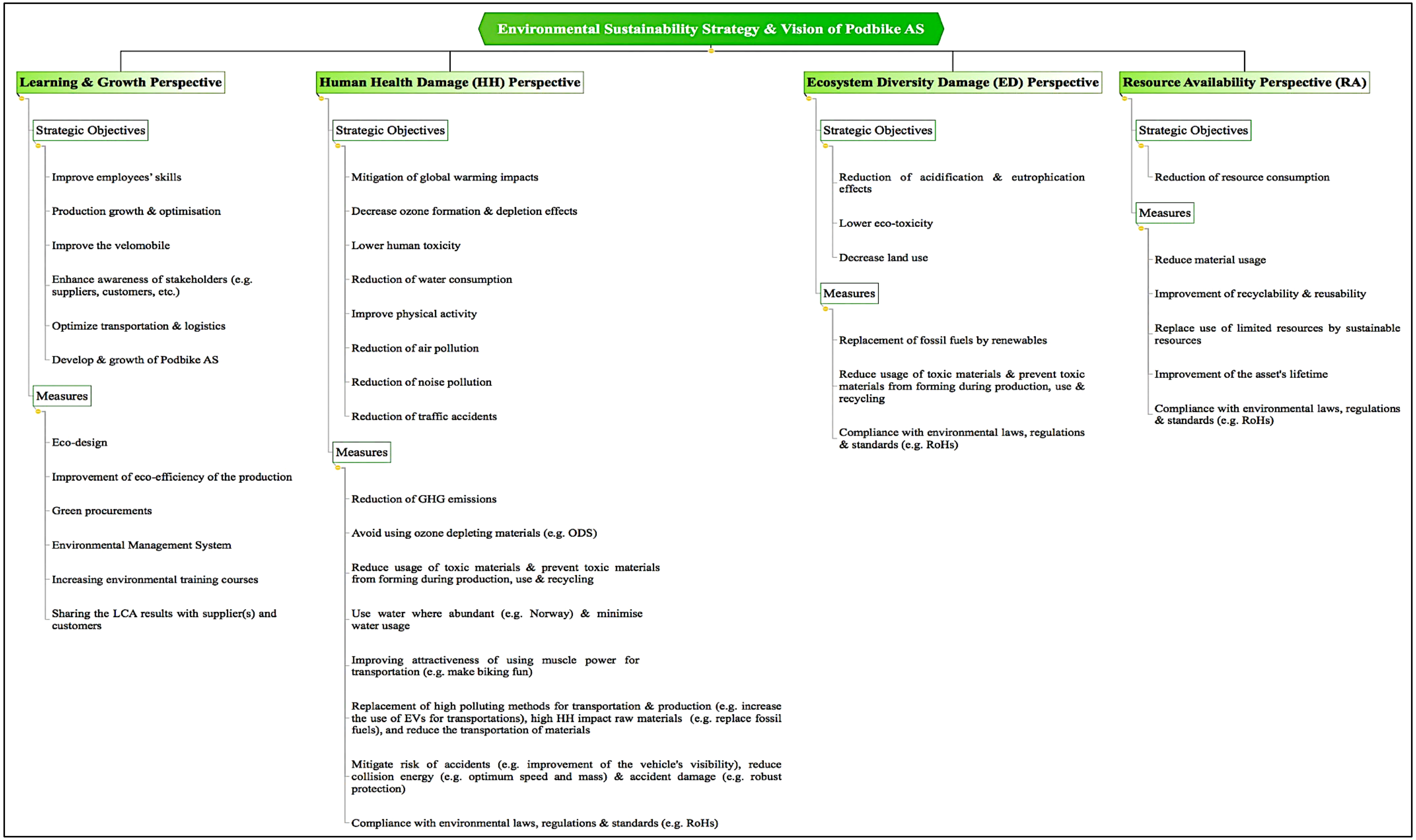

Figure 29, Environmental and Human Health Footprints Performance Improvement Assessment Mind Map

Last but not least, the developers and technical team, suppliers and logistic team of the assemblies and components with the greatest environmental and human health footprints should be informed about the environmental and human health impacts of their activities through a transparent strategy. Accordingly, they should collaborate and cooperate to find the optimum spot of environment, cost and quality through creative solutions. This can enable them to reduce their environmental and human health footprints and improve the sustainability of the business while the quality and practicality of the asset are maintained.

Chapter 7,
Discussion

The main purpose of this chapter is to summarize the important observations throughout the present thesis and examine the consistency of the study.

7.1. In Summary

The principal scope of the project was to contribute to improve the environmental and human health footprints of urban transportation. The main objective of the present thesis thus was to study the use of LCA from an environmental and human health perspectives in order to provide an application of LCA on four-wheeled velomobile with electric assist and thus a fruitful guidance for an LCA-based performance improvement.

In more details, the main purposes of the present thesis were to perform an LCA in order to provide a scientific and practical application of the LCA study on four-wheeled velomobile with electric assist and a beneficial guideline for the LCA study on EABs. Also, this study was aimed to quantify the environmental and human health impacts of the asset that can result in highlighting the spots with the highest contribution to the damages. Thus, the attention can be drawn towards the recognised spots, and identifying possible improvements of the environmental and human health footprints of the asset can be achieved. Moreover, the study was intended to convey a deep and qualitative understanding with regard to the importance of improving the environmental and human health footprints performance of different products and services.

In order to realize the importance of sustainable transportation and the challenges associated with the current available means of urban transportation, a comprehensive literature review was carried out on this sector. Also, to perceive the LCA methodology and its significance, a thorough literature study was implemented on the fundamentals and the principles of this scientific methodology.

The business idea, technical characteristics and the production aspects of the studied velomobile equipped with electric assist were examined to gain knowledge about the asset and the associated operational activities. As a result, the requirements of the LCA study in association with the product were identified.

Then the LCA framework in compliance with the international standards was developed based on the identified requirements of the asset, and the relative steps in accordance with the methodology were taken.

Following the developed LCA framework for the studied product, the results and analysis of the LCA study were presented using the quantified outputs, damage assessment diagrams, single score process trees and comparative graphs. This has enabled the researcher to identify the important spots with the highest environmental and human health impacts.

Hence the recommendations for improvement of the asset with respect to the profile of the environmental and human health footprints were articulated according to the determined spots to reduce the adverse effects of the product on the environment and human health.

7.2. Lessons Learned

In this section, the knowledge gained throughout the research is collected and discussed briefly:

- **Importance of the LCA Study on the Asset:**

  In order to achieve the asset's sustainability, a scientific and standard methodology was required to document the performance of the environmental and human health footprints of the product, this methodology is called life cycle analysis (LCA). To obtain the highest efficiency, this study was conducted in the development phase of the product since in this stage, the company and the asset are more flexible to modifications. As the improvement of the environmental and human health footprints performance of the product is a continuous process, the life cycle assessment needs to be taken as a continuous approach as well.

- **Life Cycle Assessment Steps:**

  The intended application of the study enables the researcher to identify the type, boundaries, level of details, functional units, etc. of the LCA study. So that, all of these factors should be taken into consideration for implementation of any comparative analysis.

  Over the life cycle inventory, all the flows in and out of the product system should be evaluated including raw material extraction and use, energy consumption, water usage as well as emissions and wastes released to the environment according to the materials and process activates involved in the asset's lifecycle. Primarily the materials used in this asset are thermoplastic, aluminium, steel, and stainless-steel parts, synthetic rubbers, and standard EAB's components, while the major production processes involved, were injection moulding, thermoforming, rolling, anodizing, powder coating, extrusion, transportation and standard manufacturing procedures of the global standard e-bike's parts. Also, the standard maintenance processes of the velomobile with electric assist can be utilized and the standard municipal waste treatment scenario of the defined regions should be used to quantify the environmental and human health footprints of the asset concerning the maintenance and end-of-life-treatment stages.

  Through the life cycle impact assessment, the impact categories of the EndPoint LCA were identified as human health damages, ecosystem damages and resource depletion based on the intended application of the study. Then the characterization in accordance with the selected impact categories can be carried out. Afterwards, the magnitude and significance of the potential environmental and human health impacts of the studied asset can be analysed.

- **Importance of the Manufacturing Phase**

  This study has indicated that the activities associated with the manufacturing phase of the asset's lifecycle have the highest contribution to the impact categories measured, provided that the source of energy during the use stage would be renewable. Otherwise, the use phase could have the greatest contribution.

  The electrical system and the rolling chassis complete assemblies were primarily responsible for the damages in the manufacturing phase. This was due to the production of the aluminium alloys, batteries and the electronics. Also, this stage of the product's lifecycle had the largest impacts on the availability of resources, and the lowest impacts on human health.

- **Significance of the Electricity Generation Sources:**

  The study and the previous LCA studies on EVs have demonstrated that the environmental and human health impacts of the asset during the use phase can be substantially reduced using electrical energy. Nevertheless, this can be counterproductive in the regions where electricity generated from non-renewable sources.

The LCA experiment has proved that the environmental and human health footprints over the use phase can be doubled in Germany with a power mix in use. In contrary to the results stemming from Norway, the highest impacts in Germany are on the ecosystem and the lowest are on the human health.

- **Battery's High Contribution to the Environmental and Human Health Impacts Caused by the Asset's Maintenance:**

  The lifetime of the battery can significantly change the environmental and human health impacts of the battery during the maintenance phase. Three to four replacements of the battery throughout the whole lifetime of the asset can add to the damages to the environment and human health. In particular, this part was the main contributor to the damages to the human health.

- **Importance of the Recyclability and Recycling Plan**

  The asset is made of recyclable materials and this can result in the environmental and human health impacts off-set caused by the asset's life cycle.

  As it is stated, the aluminium alloys represented the highest contribution to the environmental and human health impacts, while this material is almost fully recyclable, the second greatest contributors are Li-ion batteries which are 50-80% recyclable. PETG, ABS and PC thermoplastic materials resulted in a notable ratio of the environmental and human health damages while they have the potential of close to 100% recyclability. Also, low-alloyed and stainless steels are almost fully recyclable materials.

  The environmental and human health adverse effects of the mentioned materials can be significantly offset. However, in this LCA, the standard municipal waste treatments of Norway and Germany have been taken into consideration where the recycling percentage of the materials are extremely limited and most of this recycling are delegated to the private firms.

  Three lessons can be learnt from this:

  1. The product should be made of recyclable materials in order to have low eco-impacts.
  2. The design of the components made of the recyclable materials should be adapted into the recyclability needs.
  3. A structured recycling plan of the parts is as important as the recyclability of them.

7.3. Challenges Encountered

This section describes the challenges faced in this thesis:

- The impacts of the asset's lifecycle on the environment and human health was an interesting and beneficial topic to the company and the researcher, however, the study has been initiated with little prior knowledge about the topic, and the learning curve over the thesis study was significant.

- The technical specifications and the suppliers of the parts were changing asynchronously over time since the asset was in the development stage. The adjustments and changes were due to the feedbacks from the pilot test series, certification and regulatory requirements for each region in EU, limitations of the suppliers, etc. These challenges were addressed through an iterative approach and constant follow-ups, consequently, the adjustments have been made to the study iteratively for each change made to the asset.

- The vehicle was a brand-new product fabricated from new components. Accordingly, the author had few prior reference points known as the LCA of electrically assisted velomobile. Nonetheless, this challenge has been dealt with through using the LCA studies of e-bikes and electric cars. In the meantime, using the knowledge of the inventor of the vehicle who was specialised in environmental engineering was a great help in tackling this challenge.

- Data collection was another challenge. Due to the constant development of the vehicle, it was difficult for the company and the suppliers to be able to provide the author with accurate technical inputs (e.g. the electricity consumption during the injection moulding processes), therefore a generalization approach has been taken, and the global standard data were extracted from the datasets. Also, the pandemic situation (i.e. COVID-19) has been arisen during this study, and this affected the pace of the work.

7.4. Further Research

There are a lot of opportunities for further study on the environmental and human health impacts and advantages of using the Podbike velomobile for urban transportation purposes, particularly because this new micro-mobility solution is an emerging and developing mean of transportation. Some of these opportunities are described briefly below:

- The life cycle assessment of the Podbike velomobile offers insight into the complexities of the asset's production, environmental and human health impacts. Understanding the procedures associated with the production can provide a basis for comparing any future study on the environmental and human health impacts of electrically assisted velomobile.

- This LCA study does not consider social and economic aspects of the asset throughout its whole lifecycle, hence, it is recommended for future work that the LCA could be potentially utilized in combination with the three factors, thus it can enable the stakeholders to optimize the sustainability by finding the sweet spot including the benefits for shareholders, environment and society.

- In this study, the main focus was on the production of the vehicle. Since the company is evaluating the packaging alternatives to reduce the environmental and human health impacts and increase the cost-efficiency, further studies should prioritize the performance of the environmental and human health footprints of the product's delivery and transportation by focusing on multiple alternative packaging options.

- In this study, only the life cycle assessment of the Podbike velomobile is carried out. A comparative life cycle analysis between this vehicle and its counterparts for the urban transportation such as electric bicycle, conventional bicycle, different means of public transportation (e.g. bus, train, etc.), electric cars, etc. is interesting to learn how much the overall profile of the environmental and human health footprints can be improved by using this vehicle for the urban transportation purposes.

- As discussed earlier, recycling is important. Forthcoming studies should aim to investigate the recyclability and recycling plan of the asset in order to increase the recyclability of the parts and make a well-organized recycling plan.

- Since it is predicted that more orders will be placed for this product in the future due to the growth of the company's production capacities; and the main markets would extend beyond Norway and Germany, thus future LCA studies are required for the emerging regions.

Chapter 8,
Conclusion

Due to the adverse impacts of the available means of urban transportation on human health and environment, the state-of-the-art velomobile concept is developed. The main objective of the present study was to develop a life cycle assessment of the velomobile, identify the points with the highest contribution to the environmental and human health damages caused by the product, and look for different solutions to improve the performance of the environmental and human health footprints of the asset. Hence the following conclusions according to the results and discussion of the study are articulated:

- It is concluded that the velomobile should be ridden using the electricity, generated through the renewable sources of energy, otherwise the environmental and human health impacts of the vehicle can potentially be doubled, and the damages can be mainly attributable to the energy consumption during the use phase.

- The study shows that although the velomobile is primarily made of recyclable material, the electrical system and rolling chassis assemblies stand for the greatest ratio of the environmental and human health damages which is mainly due to the environmental and human health impacts caused by the aluminium components, batteries, electric motors and electronics for control units. However, the undesirable impacts can be significantly reduced through development of the recycling plan.

- It is inferred that the maintenance of the velomobile can have substantial impacts. This is resulted from the number of battery replacement during the whole lifetime of the asset. Therefore, developing new battery pack and improving the lifetime of the batteries can substantially decrease the impacts, particularly on human health.

- The study demonstrates that the transportations involved in the life cycle of this product are other contributors to the environmental and human health damages. Minimizing the number of transportations through shortening the distances between the suppliers of the parts and the assembly service suppliers can improve the profile of the product with respect to its environmental and human health footprints. Also, using electric vehicles for short distance shipments can lower the damages.

- The research shows that the impacts caused by the aluminium components can be mitigated provided that the anodizing and powder coating procedures would be reduced, and the proposed green aluminium would be benefited as the raw material.

- This study concludes that the transparency, information sharing and increasing the awareness of the stakeholders can result in the reduction of the impacts. According to the results all the stakeholders such as customers, investors, suppliers, employees, etc. should be involved to improve the velomobile's environmental and human health footprints performance.

- The research infers that the improvement of the environmental and human health footprints performance of the asset is a continuous process, thus in order to control and keep tracking on the performance improvements, the developed mind map should be followed by the stakeholders.

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