Development of a decision support for the selection of a sustainability assessment method for technology development in the aviation industry

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Elena Peters

Student number: 5393132

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Graduation committee

Chairperson	: Dr.ir. R.A. Hakvoort, Section Energie and Industie
First Supervisor	: Dr.ir. R.A. Hakvoort, Section Energie and Industie
Second Supervisor	: Dr. E. Schröder, Section Values, Technology and Innovation
External Supervisor	: M.Sc. N. Reich, Airbus Operations

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ABSTRACT

Sustainability is a crucial topic in the day to day life as well as in industries. With the help of innovation and new technologies, the negative impacts on sustainability can be decreased. During the development of technologies, the concept of sustainability should be included at all times. This can be done with the help of sustainability assessment methods. However, companies (like the case company of this study) often only adopt one or a few sustainability assessment methods in their product development process. These methods might not necessarily be suitable for the technology under investigation. Furthermore, guidance on when to use which method can be identified as missing within the literature and in practice.

This thesis study aims to fill this gap by developing decision support for the selection of a sustainability assessment method during technology development. Coming from a comprehensive set of sustainability aspects (social, environmental and economic), during the thesis the focus was put on the environmental aspect exclusively. A literature study is used to identify a set of the possible sustainability assessment method. The identified methods are compared to a set of selection criteria based on the method's acceptance, type of assessment, and sustainability pillar covered. Four methods/method groups are identified as suitable for the defined criteria and the study scope. The selected methods are analyzed in more detail to gain a deeper understanding. Based on the knowledge acquired, a flow chart is developed to support selecting the most suitable sustainability assessment method. In order to be able to compare the selected assessment method with other available method, a ranking is developed. The ranking is based on a qualitative comparison and data obtained from the literature. The ranking is displayed in two ways, by a set of spiderweb diagrams and a ranking with numbers. A partial validation of the developed ranking is done by applying two methods to a use case and comparing the practical results with the theoretical ones. Here a mismatch between the ranking obtained from the theoretical data and the one from practical experience can be identified.

The result of the study is the development of decision support consisting of a flowchart and method ranking. Once both steps are followed, it should be possible to provide a fast and easy method selection for non-experts. Furthermore, the common practice of using only one sustainability assessment method (Life Cycle Assessment) is looked into. It can be seen that no sustainability assessment method is best in all criteria and application cases. Therefore, it is impossible to define one most suitable method in all cases. Choosing the right method depends on the scope (substance, product, or material) and the intended outcome. Thus, relying solely or predominantly on Life Cycle Assessment cannot be recommended. Alternative methods should be adopted and applied, also within the case company.

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LIST OF ABBREVIATIONS

3D	*three-dimensional*
AD	*Axiomatic Design*
CF	*Carbon footprint*
CO2	*Carbon Dioxide*
DfE	*Design for Environment*
DfX	*Design for X*
ECO	*Ecological*
EF	*Environmental footprint*
EIA	*Environmental Impact Assessment*
EMSs	*Environmental Management Systems*
FLM	*Fused Layer Modeling*
FSSD	*Framework for Strategic Sustainable Development*
GDP	*Gross Domestic Product*
GHG	*Greenhouse Gas*
ICAO	*International Civil Aviation Organization*
ISO	*International Organization for Standardization*
kg	*Kilogram*
LCA	*Life Cycle Assessment, Life-Cycle Assessment*
LCC	*Life Cycle Costing*
LCI	*Life Cycle Inventory*
MCDM	*Multi-Criteria Decision Making*
MI	*Total Material Input*
MIPS	*Material Input per Unit of Service*
MIT	*Material Intensity*
ML	*Machine Learning*
MSA	*Material System Analysis*
NPV	*Net Present Value*
OECD	*Organisation for Economic Co-Operation and Development*
PEF	*Product Environmental Footprint*
PSS	*Product Service Systems*
QFD	*Quality Function Deployment*
R&D	*Research and Development*
R&T	*Research and Technology*
RA	*Risk Assessment*
S	*Service unit*
SDGs	*Sustainable Development Goals*
SFA	*Substance Flow Analysis*
SLCA	*Sustainability Life Cycle Assessment*
SPD	*Sustainable Product Development*
SPs	*Sustainability Principles*
SSA	*Strategic Sustainability Assessment*
TMR	*Total Material Requirement*
TOPSIS	*Technique for Order Preference by Similarity to Ideal Solution*
TRL	*Technology Readiness Level*
TSPD	*Templates for Sustainable Product Development*
UEV	*Unit Emergy Values*
VDD	*Value Driven Design*
VDI	*Verein Deutscher Ingenieure e.V.*

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1 INTRODUCTION

The industrial revolution resulted in technologies increasing humans' lifetime but simultaneously leading to destroyed global ecosystems, extinction of species, and disorder of climate systems (Caradonna, 2014). Since the 1980s, the human demand for natural resources has exceeded the level of regeneration possible by Earth (Wackernagel et al., 2002). A continuous growth of population, resource demand, and economies can be observed while the size of the Earth remains the same. If this trend continues, the Earth's resources will not be able to withstand the population (Jaganmohan, 2022).

Additionally, the emission of so-called greenhouse gases, which trap heat in the atmosphere, leads to global warming and climate change (U.S. Environmental Protection Agency, 2022; United Nations, n.d.b). Warmer temperatures influence weather patterns and disrupt nature's balance, leading to risks for life on Earth (United Nations, n.d.b). The largest contributors to climate change are the manufacturing industry, deforestation, and transportation (United Nations, n.d.b). Within the transportation sector, 12% of the carbon dioxide emissions (the primary greenhouse gas emitted by humans) is an output of the aviation sector (Air Transport Action Group, 2020c). On a global level, this industry was responsible for 2.1% of all human-made carbon dioxide emissions in 2019 (Air Transport Action Group, 2020b). As this industry has a high influence on climate change, with a growing trend in the future, attention should be taken and countermeasures established.

A concept that should help to adapt strategies for tackling global warming and enabling economic growth without compromising the environment and society is sustainability. It can be described as an environmental, economic, and social ideal (Caradonna, 2014). Governments play an important role in regard to sustainability by providing standards and regulatory frameworks (Wilkinson et al., 2001). These political tools need to be adopted and complied with by companies. Moreover, adopting sustainability strategies in companies can increase competitiveness (Wilkinson et al., 2001) and create a positive image for customers (Jaganmohan, 2022).

Governments and companies identified the development of new technologies as one possible way to deal with environmental crises and increase sustainability. Especially the innovation phase and the early development process are distinguished as important, as the most significant benefits can be achieved within this phase (Khurana & Rosenthal, 1998). The implementation of sustainability into the development process can be achieved using different methods, tools, and practices named sustainability assessments (Pope et al., 2004). These aim to support decision-makers in deciding on actions that will make society more sustainable (Devuyst, 2001, as cited in Pope et al., 2004).

One company that adopted a corporate sustainability strategy related to technological development and the transportation sector is the company Airbus. "Airbus is a leader in designing, manufacturing and delivering aerospace products, services and solutions to customers on a worldwide scale." (Airbus, 2022c). Within its strategy, Airbus defined four sustainability commitments to guide decision-making within the company (Airbus, 2022a). Tools and methods are established for the innovation process to formally analyze sustainability and contribute towards the company's sustainability ambitions. The adopted sustainability assessment methods should support sustainable evaluation and decision-making during the technology development. However, drawbacks can be identified. The main focus lies on economic and environmental considerations, neglecting social aspects. In addition, the timing for applying the environmental assessment methods is not clearly defined. While the focus is on utilizing the Life Cycle Assessment method, it is questionable if this is always the most suitable method for achieving the strategic sustainability targets, as much criticism of LCA can be found. Therefore, establishing other assessment methods might create additional benefits. To overcome the identified issues, the following research question is proposed:

What decision support can be used to select a sustainability assessment method for technology development in the aviation industry?

1.1 BACKGROUND INFORMATION

93% of European citizens think climate change is a severe problem (European Union , 2019). This is the finding of a study of the Eurobarometer conducted on behalf of the European Commission in 2019. It indicates that the overall society is concerned about the environment. The limits of our planet were brought to the attention by the Club of Rome in 1972. Their report showed that continuing with the current growth in population, resource use, industrialization, and pollution would lead to an overshoot and collapse of the Earth by 2070 (Meadows et al., 1972). The report raised global awareness that resources are not infinite, and that economic growth has ecological impacts. One concept frequently mentioned regarding the limits of our planet is sustainability, which will be explained in the next paragraph.

1.1.1 INTRODUCING SUSTAINABILITY

Sustainability emerged in the late 1970s as an environmental, economic, and social ideal (Caradonna, 2014). Ensuring the well-being of the entire global population now and in the future is the ultimate goal behind the concept (Avesani, 2020). The most established definition of sustainability was published in 1987: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs"(Brundtland, 1987, p.37). Since the 1980s, the academic and political debate on sustainability and sustainable development has risen sharply worldwide (Scoones, 2007). A critical transition of sustainability into practical policy happened in 1992 (Scoones, 2007) when a comprehensive action plan for sustainable development was defined. One hundred seventy-eight countries adopted the plan named Agenda 21, striving for improved human lives and environmental protection (United Nations, n.d.a).

The following decades resulted in several international agreements and goal definitions. One well-known one is the 2015 Paris Agreement, a legally binding treaty adopted by 196 international parties. The aim is to tackle climate change by jointly limiting global warming well below two degrees Celsius compared to pre-industrial levels (United Nations Framework Convention on Climate Change [UNFCCC], n.d.). As it is the first legally binding document, the Paris Agreement is perceived as a landmark for sustainable development.

Another one is the 2030 Agenda for sustainable development. This agenda provides a scheme for prosperity and peace for society and the environment (United Nations, n.d.a). A central component are the Sustainable Development Goals (SDGs), which are an appeal for global partnership and strategic actions. The 17 goals aim to improve health and education, end poverty and other deprivations, reduce inequality, increase economic growth, tackle climate change, and preserve oceans and forests (United Nations, n.d.a).

Overall the concept of sustainability is focused on a long-term perspective and recognizes the interdependence between economic, social, and environmental aspects (Avesani, 2020). Therefore, sustainability is often referred to as the three-pillar approach (people, planet, profit) or triple bottom line. The term triple bottom line was created in 1997 to create a definition for the added value that includes more than solely economic values (Avesani, 2020). It intends to consider the social and environmental costs and benefits that businesses bring to society. Overall the intention is to combine social, environmental, and economic stakes, supporting businesses with the ability to manage them all (Avesani, 2020).

Environmental pillar

Environmental sustainability can be defined as the "maintenance of natural capital" (Goodland, 1995, p. 10). It constitutes the input of renewable and nonrenewable resources and the output of waste and pollution (Goodland, 1995). According to Agenda 21, the actions for environmental sustainability are, among others, the protection of oceans, the atmosphere, biodiversity, soil and forests, water and waste management (United Nations Division for Sustainable Development, 1992).

Economic pillar

Economic sustainability can be defined as economic activities that do not result in disproportional costs for future generations, according to Foy (Foy, 1990).

Social pillar

Environmental and economic issues dominated sustainable development at the beginning (Colantonio, 2011). Social aspects only gained recognition in the late 1990s (Colantonio, 2011). Even though the amount of literature increased afterward, the concept of social sustainability stays fuzzy and is limited by methodological and theoretical constraints (Colantonio, 2011). Additionally, the literature is somewhat chaotic and sometimes confusing or contradictory, according to Vallance et al. (Vallance et al., 2011). Several definitions and key themes describing social sustainability can be found. One way to describe it is: "[…] social sustainability blends traditional social policy areas and principles such as equity and health, with issues concerning participation, needs, social capital, the economy, the environment, and more recently, with the notions of happiness, wellbeing and quality of life" (Colantonio, 2011, p. 40). For a company, this can be referred to as generating profits without harming society (Carter & Rogers, 2008, as cited in Rodríguez et al., 2016). According to Rodríguez et al., social practices can be distinguished into internal and external. While internal practices focus on providing healthy and safe working conditions, as well as freedom for the company's employees, external practices aim for social justice and fairness along the supply chain (Gimenez, Sierra &

Rodon, 2012; Pullman, Maloni & Carter, 2009, as cited in Rodríguez et al., 2016). Social practices include engagement with stakeholders, promoting customer well-being, and certification and auditing of a supplier to prevent poverty, child labor and sweatshops (Rodríguez et al., 2016). In addition, achieving social sustainability can create benefits and opportunities for companies, like attracting new business partners or increasing employee engagement (United Nations Global Compact, n.d.).

Criticism on sustainability

However, while being widely established in today's world, criticism of the concept of sustainability can also be found. One criticism is that the term sustainability is too vague and used for Greenwashing. This describes exaggerating or falsifying the environmental benefits of services, practices, or products (Caradonna, 2014). By using sustainability as a buzzword or for spreading misinformation, it is possible to mislead consumers. Furthermore, an advantage can be taken of the intentions of buyers. Greenwashing leads to the derision and exploitation of the concept of sustainability (Caradonna, 2014).

Another criticism concerns the three-dimensional approach of sustainability. For many authors, this approach on sustainable development is too narrow (Pike et al., 2007, as cited in Avesani, 2020). Sustainable development is considered a holistic approach; therefore, a limitation to three dimensions hides the concept's full potential (Avesani, 2020). How to overcome this issue is not further explained by Avesani.

One way of understanding the critique of sustainability and sustainable development is as a proposed way to strengthen the framework (Dernbach & Cheever, 2015). As no convincing alternatives are proposed by the critics, the identified challenges can be used to improve sustainability and the underlying decision making (Dernbach & Cheever, 2015). Even though sustainability is not straightforward and does not provide the answer to all questions, it can serve as a starting point for decision and law making (Dernbach & Cheever, 2015). It is perceived as such within this thesis: A concept with flaws, but a starting point to mitigate existing threats like climate change.

1.1.2 INDUSTRY-SPECIFIC MITIGATION ACTIONS

Governments have a crucial role in environmental sustainability by providing regulatory frameworks and standards (Wilkinson et al., 2001). Several global regulations, standards, and goals are in place for the aviation industry to counteract the negative environmental impacts. On a global level, alignment is achieved via the International Civil Aviation Organization (ICAO), an administrative and expert bureaucracy financed and directed by 193 national governments (International Civil Aviation Organization, n.d.). The organization provides international standards, policies, and recommended practices to states, which can be implemented nationally. To foster sustainability, they defined a set of goals, like "[…] 2% annual fuel efficiency improvement through 2050 and carbon neutral growth from 2020 onwards […]" (International Civil Aviation Organization , 2019, p. 112). To achieve these goals, the ICAO determined four reduction measures (International Civil Aviation Organization , 2019):

1. Advanced aircraft technology
2. Optimization of air traffic management and operational procedures
3. Sustainable aviation fuels
4. Market-based measures (carbon offsetting and reduction scheme)

On a European level, the European Commission defined a long-term strategic vision for the European continent and the aviation sector. The long-term goal is to achieve climate neutrality by 2050 (European Commission, 2022). A set of policy initiatives is established under the name European Green Deal to achieve this aim (European Commission, 2022). The legislative tools encompass the entire European continent and aspects like energy, land use, taxation policies, and transport.

For the aviation industry, another long-term vision is defined. This vision should help align efforts to tackle present and upcoming challenges, such as climate change, resource scarcity, and globalization (European Commission, 2011). Research and innovation are seen as central to overcoming these challenges and maintaining Europe's competitiveness. Five strategic goals for the year 2050 were outlined to focus the European efforts (European Commission, 2011):

1. Maintaining and extending industrial leadership
2. Meeting societal and market needs
3. Protecting the environment and the energy supply
4. Ensuring safety and security
5. Prioritizing research, testing capabilities and education

Subsequently, it can be seen that environmental standards and regulatory frameworks are in place to guide the transition toward a more sustainable air transportation sector. A common theme which can be identified along those mitigation actions is the focus on research and advanced technology.

1.1.3 SUSTAINABILITY IN THE AVIATION SECTOR

Sustainability in the aviation sector is often intensely focused on environmental criteria (Walker & Cook, 2009) or even limited to the reduction of environmental impacts (ICAO, 2011, as cited in Payán-Sánchez et al., 2018). Additionally, a primary point of attention is carbon dioxide emission, the primary greenhouse gas (GHG) emitted by humans emitted by humans (U.S. Environmental Protection Agency, 2022). In 2019, the civil aviation industry emitted 914 million tons of carbon dioxide (CO2) which is 2.1% of the global artificial total of 43 giga tons (Air Transport Action Group, 2020b). Since 1990 the air traffic sector has grown by 5.33% per year (Air Transport Action Group, 2020a). Although the COVID-19 pandemic led to a drastic decrease in total global passengers (60% decline in 2020 compared to pre-COVID in 2019), the number of passengers is increasing steadily and slowly going in the direction of pre-COVID numbers (24-27% decline estimated for 2022 compared to 2019) (International Civil Aviation Organization, 2022). In addition, history shows that the number of passengers carried increases even after crises occurred (International Civil Aviation Organization, 2022). Therefore, growth in the aviation industry can be expected in the coming years, indicating an increase in CO2 emissions as well. The aviation industry managed to decouple the CO2 emission growth rate to an average of 2.49%, thanks to continuous investments in new technologies, operation improvement, and advanced infrastructure (Air Transport Action Group, 2020a). However, an increase in emissions in the future can be expected due to the overall growth of the sector.

Next to the CO2 emissions and the impact on climate change, more areas of concern can be found regarding environmental sustainability. "[…] aviation has considerable local environmental impacts, including aircraft noise (Postorino and Mantecchini, 2016), local air pollution (Harrison et al., 2015), water use and pollution (Daley and Thomas, 2011), waste production (Hooper and Greenall, 2005), and habitat modification and destruction (Lawton and Fujiwara, 2016) […]" (Payán-Sánchez et al., 2018, p. 537).

Apart from creating negative environmental impacts, these issues can also negatively influence society. Noise and air pollution can intensify existing health concerns or cause harm to mental and physical health (Hume & Watson, 2003, as cited in Budd et al., 2013). Problems like stress, sleep deprivation, disrupted learning, or inhibited communication can arise and decrease social welfare (Hume & Watson, 2003, as cited in Payán-Sánchez et al., 2018). Additionally, industrial noise can be addressed as a matter of public health in the United States and Western Europe (Bröer, 2013). Air pollution with nitrogen dioxide and trioxide can affect human health (e.g., asthma, human cardiovascular and respiratory systems, and mortality), too (Department of the Environment, Transport and the Regions, 2000, as cited in Payán-Sánchez et al., 2018). Furthermore, actions of the aviation industry can cause a threat to water quality (Payán-Sánchez et al., 2018). Ground contamination can lead to groundwater and surface water pollution, negatively influencing agricultural land and drinking water (Payán-Sánchez et al., 2018). Ultimately implications for human health can arise (Payán-Sánchez et al., 2018).

On the contrary, the aviation industry can also create positive effects on society. Cheap air travel can lead to advanced mobility and a spread of social welfare (Budd et al., 2013). For remote communities that lack road and rail networks, air travel enables access to essential services like health care and access to the rest of the world (Air Transport Action Group, 2020a). Air services enable assistance and physical access during emergencies caused by war or natural disasters (Air Transport Action Group, 2020a). In addition, the aviation industry's focus on technological innovation encourages university research and leads to a highly skilled workforce (Air Transport Action Group, 2020a). Research and high skills not only create a positive impact on society but also on the economy.

Additional effects of the aviation industry on global and local economies can be found. The industry provides jobs, facilitates trade and tourism, improves living standards, and generates tax revenues and economic growth (Air Transport Action Group, 2020a). 87.7 million Jobs, consisting of direct, indirect, induced, and tourism-related employment, were supported by the aviation industry before the COVID crisis (see Figure 1) (Air Transport Action Group, 2020a). Economic growth and development are enabled by international trade of services and goods (Air Transport Action Group, 2020a). Additionally, time-critical or sensitive delivery is facilitated, resulting in efficiency and smooth production (Air Transport Action Group, 2020a). A gross domestic product (GDP) of $3.5 trillion, which accounts for 4.1% of the global GDP, was measured prior to the COVID crisis (Air Transport Action Group, 2020a).

In conclusion, the aviation industry highly impacts all areas of sustainability. These effects can be harmful or positive and are often linked to several sustainability pillars. In order to foster positive impacts while diminishing the negative ones, mitigation actions are envisaged by society as well as by policymakers.

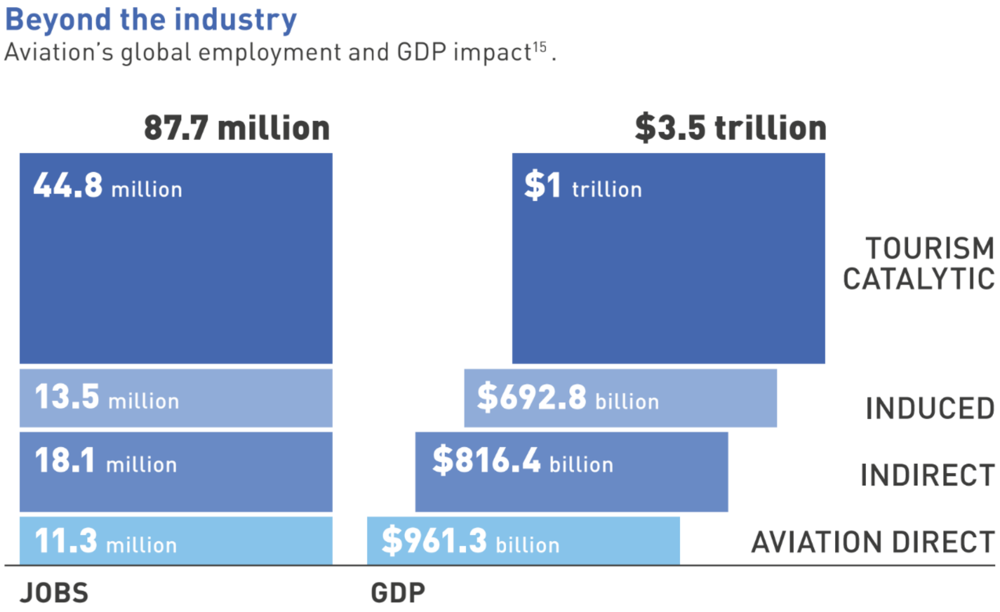


Figure 1 Aviation's global employment and GDP impact. (Air Transport Action Group, 2020a)

1.1.4 CASE COMPANY-SPECIFIC MITIGATION ACTIONS

Governments alone cannot solve environmental problems; the support of economic environment (markets and corporations) is needed (Wilkinson et al., 2001). As described in the previous paragraph, corporations are influenced by policies but they also experience external pressure from customers and the media. (Wilkinson et al., 2001). Hence a reduction in environmental impacts and increased sustainability is inevitable for organizations. Moreover, a focus on sustainability can also become an opportunity for corporations, as their focus might shift from short-term survival towards long-term success, cost and waste can be reduced, and employee satisfaction, productivity, and commitment might increase (Wilkinson et al., 2001). Therefore, integration of sustainability into the business strategy can be observed in many organizations also, within the case company Airbus.

Airbus aims to unite and protect "[…] the world in a safe, ethical, socially and environmentally responsible way" (Airbus, 2022a). To do so, the company integrates sustainability into its corporate strategy. Four sustainability commitments, which guide decision-making within the entire company, are defined (Airbus, 2022a):

1. Lead the journey toward clean aerospace
2. Respect human rights and foster inclusion
3. Build our business on the foundation of safety and quality
4. Exemplify business integrity

Additionally, these commitments are formally adopted to the Sustainable Development Goals (SDGs) to ensure alignment with global strategic actions. In order to ensure transparency and show its commitment to the SDGs, Airbus publishes a progress report annually (Faury, 2021). This document describes the efforts to implement the development goals of the company. Figure 2 shows the journey towards the adoption and the eight SDGs chosen to be contributed to directly by Airbus. The next chapter will present a practical integration of the concept of sustainability.

Figure 2 Airbus SDG journey and goals (Airbus, 2022b)

1.1.5 TECHNOLOGICAL DEVELOPMENT

Innovation and new technologies are identified as ways to increase sustainability and tackle environmental crises (see sections, 1.1.3 & 1.1.2). According to Wilkinson et al., innovation is not only key to competitiveness but also to environmental sustainability (Wilkinson et al., 2001). During innovation, the early phase of the development process is distinguished as crucial, as the most significant benefits can be achieved within this phase (Khurana & Rosenthal, 1998). Within the front-end phase of innovation, the cost of changes is low, and the degree of influence on the outcome and freedom of design is high (Figueiredo et al., 2015). On the contrary, the availability of information is low, and uncertainty is therefore high (Figueiredo et al., 2015), as seen in Figure 3. Decisions that are taken in this early phase influence not only the following innovation phases but also the final product (Figueiredo et al., 2015). Therefore, sustainability considerations should be taken into account as early as possible during the technology development process to ensure that the influence on the future process and product is significant.

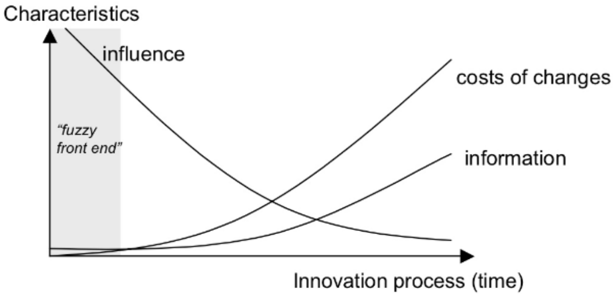


Figure 3 Influence, cost of changes and information during the innovation process (Figueiredo et al., 2015)

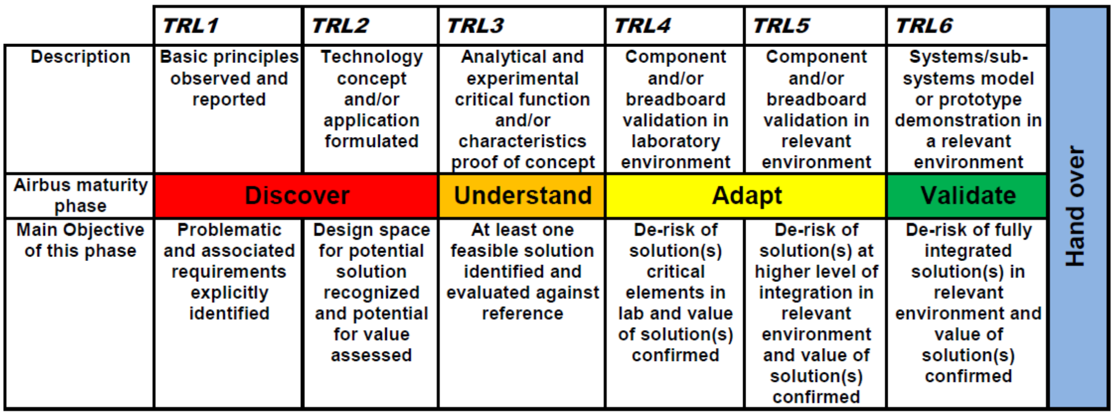
The product design stage determines 80% of the sustainability impacts (Keoleian and Menerey, 1993; Kulatunga et al., 2015; Lewis and Gertsakis, 2001, as cited in Ahmad et al., 2018). In order to deal with this significant influence, the idea of environmentally friendly or ecological (ECO)-design practices was brought to attention (Lofthouse and Bhamra, 2012, as cited in Ahmad et al., 2018). It aims to reduce environmental impacts throughout the life cycle of a product (Sakao, 2007, as cited in Romli et al., 2015). Several tools referred to as eco-design or Design for Environment (DfE) tools were developed to support the product design phase (Navarro et al., 2005; Shi et al., 2017, as cited in Ahmad et al., 2018). However, these tools only include environmental considerations (Ahmad et al., 2018), leaving sustainability's economic and social aspects outside the scope (Knight & Jenkins, 2009). To address this shortcoming the concept of Sustainable Product Design, or Sustainable Product Development (SPD), was introduced. It aims to take the product's functional attributes into account while considering the three dimensions of sustainability at the same time (Bereketli and Genevois, 2013; Hosseinpour et al., 2015, as cited in Ahmad et al., 2018; Gagnon et al., 2012, as cited in Hallstedt & Nylander, 2019). Thus, it is possible to ensure the lowest environmental impacts while enabling economic and social benefits. Furthermore, Sustainable Product Development is defined as integrating and implementing a strategic sustainability perspective and life-cycle thinking into the front end of the innovation process (Hallstedt & Isaksson, 2017). For implementing sustainability into the development process, different methods, tools, and practices named sustainability assessments can be utilized (Pope et al., 2004). Several definitions for sustainability can be found (see Devuyst, 2001, as cited in Pope et al., 2004; Pope et al., 2004). The one used in this thesis is as follows: Sustainability assessment aims to ensure that ''[...] plans and activities make an optimal contribution to sustainable development'' (Verheem, 2002, as cited in Pope et al., 2004).

1.1.6 TECHNOLOGICAL DEVELOPMENT IN THE CASE COMPANY

Technologies and products in the aviation industry can be described as complex products and systems (França et al., 2022). They are usually high-cost, engineering-intensive, highly customized, and rarely rely on self-components (França et al., 2022). Therefore, their development is characterized by extensive design stages, involvement of various companies, long life cycles, and high investments (Bertoni et al., 2020; França et al., 2022).

In order to deal with these characteristics and arising challenges, management tools are in place within the industry. A typical assessment and management tool for technology development within the aerospace industry is the so-called Technology Readiness Level (TRL). This method was developed by the National Aeronautics and Space Administration in the 1970s. It can be compared to a stage gate process for new product development. The Technology Readiness Level " […] are a set of management metrics that enable the assessment of the maturity of a particular technology and the consistent comparison of maturity between different types of technology - all in the context of a specific system, application and operational environment."(ESA, 2008, p. 1). It should inform the management and support decision-making regarding the implementation of technology development projects. As the Technology Readiness Level is defined as a standard metric, it is not linked to one specific technical discipline but can be used in various contexts. This enables consistent comparison of the maturity of different types of technology.

Within the aircraft manufacturing company Airbus the TRL methodology is used in the Research and Technology (R&T) perimeter, aiming to manage risks and uncertainties in the early technology development. The TRLs 1-6 (see Figure 4) can be perceived as the first phase of the innovation process and are the area of interest within this study.



	TRL1	*TRL2*	*TRL3*	*TRL4*	*TRL5*	*TRL6*	Hand over
Description	Basic principles observed and reported	Technology concept and/or application formulated	Analytical and experimental critical function and/or characteristics proof of concept	Component and/or breadboard validation in laboratory environment	Component and/or breadboard validation in relevant environment	Systems/sub-systems model or prototype demonstration in a relevant environment	
Airbus maturity phase	Discover		Understand	Adapt		Validate	
Main Objective of this phase	Problematic and associated requirements explicitly identified	Design space for potential solution recognized and potential for value assessed	At least one feasible solution identified and evaluated against reference	De-risk of solution(s) critical elements in lab and value of solution(s) confirmed	De-risk of solution(s) at higher level of integration in relevant environment and value of solution(s) confirmed	De-risk of fully integrated solution(s) in relevant environment and value of solution(s) confirmed	

Figure 4 Objectives of Airbus maturity phases (Airbus Operations GmbH, 2020)

The TRL methodology and the case company technologies and products are closely linked. At the very early development stages of technology (see TRL2 in Figure 4), the application of the technology is defined. This application formulation can be seen as using the technology inside or as a product for the final outcome (the aircraft). Therefore, technology is seen and defined as a product within this thesis.

Next, the status quo of the sustainability assessment during the R&T phase within the case company will be presented. Currently, some tools and methods are established to analyze sustainability within Airbus formally. They strive to achieve Airbus' sustainability ambitions, as described in chapter 1.1.3. The methods deployed in the technology development process are solely focused on analyzing one aspect of sustainability and are therefore described per pillar.

For the **environmental** impacts, two methods are in place:

- The first one is a simplified environmental assessment, aiming to increase transparency and awareness and incorporate a sustainable mindset within the project team at the beginning of each technology development process. It is composed of quantitative and qualitative considerations. It takes air emissions (carbon dioxide, nitrogen oxide, noise) and resources (recycling, end of life, waste, critical materials, and compliance of substance to regulations) into account. This simplified assessment should provide easy to use guidance and visualization along the development of new technologies.
- The second widely established method is a full-scale Life Cycle Assessment (LCA). LCA is an internationally certified, quantitative assessment method that enables a complete and objective (Lohner et al., 2012) assessment of the environmental impacts created by a technology under development. The timing for applying a Life Cycle Assessment along the technology development process is not specified and depends on the choice of the project leader.

From the **economic** perspective, the following methods are assigned:

- Business case analysis: Created value for the company and customer is analyzed.
  This method is similar to a cost benefit analysis, including net present value calculations. To protect company internal data, the cost benefit method is defined as the status quo method for the case company and this study.

Social impacts are analyzed with the following method:

- Health and safety risk assessment: Identification, assessment, and mitigation of a technology's risk on the health and safety of the case company's employees and the environment (Airbus 2022d).

Additional considerations and trade-offs regarding social aspects are taken into account during the procurement process of new technology. To ensure this, a supplier code of conduct is defined, taking human rights, employment practices, integrity, and business ethics into account (Airbus SAS, 2021). Suppliers are obliged to follow this code of conduct to do business with the case company.

Overall the methods applied within the case company can be described as methods that enable the analysis of one aspect of sustainability (economic, environmental or social). The Health and Safety assessment is an exception, as it considers social and environmental issues. Each assessment analyzes the potential of technology in that specific sustainability aspect. As a result, areas of concern with a high (negative or positive) influence on the sustainability pillar can be identified, and mitigation actions initiated. Additionally, it is possible to compare different (e.g., design) options or technologies with each other based on the findings of the assessment. The assessment outputs, therefore, should enable a prediction about how sustainable a technology is on its own but also in comparison to other technologies or options. Hence, decision-making should be facilitated based on the assessment results.

The established sustainability assessment methods within the case company mainly focus on economic and environmental considerations. It stands out that there are only limited methods for assessing the social dimension of the entire supply chain. In addition, the timing for applying the environmental assessment methods is not clearly defined. While the main focus lies on utilizing the Life Cycle Assessment method, it is questionable if this is always the most suitable method. Much criticism or limitations on LCA can be found. Application of the methodology requires know-how (Woodhouse et al., 2018), which might only be available to some employees or needs to be acquired first. Moreover, conducting an LCA is time-consuming, and a large amount of data must be collected (Woodhouse et al., 2018). The data needed might not exist yet, be challenging to acquire, and thus unreliable or unavailable (Woodhouse et al., 2018). Therefore, implementing other assessment methods might be beneficial for achieving the company's strategic sustainability targets or creating additional benefits. Lastly, assessments and considerations of social impacts are lacking.

1.1.7 LIMITATION OF THE SCOPE

Originally, the idea behind this thesis project was to investigate all three aspects of sustainability (as described in chapter 1.1.1), to overcome the above described shortcomings of the case company's sustainability assessment methods. During the conduction of the project it became evident, that the defined scope exceeds the possible workload within the frame of this thesis. Furthermore, the topic of sustainability is more complex than expected. In order to decrease the workload and to do the complexity of the topic justice, a limitation of the scope is defined. The focus of the thesis is going to be on the environmental pillar and the economic and social pillar are excluded due to the following reasons:

Even though the interest in social pillar and the amount of literature concerning it has increased, the concept of social sustainability stays fuzzy and is limited by methodological and theoretical constraints (Colantonio, 2011). Although various ways of assessing social sustainability are proposed within the literature, a clear definition of quantitative indicators to perform a social sustainability assessment is missing (Popovic et al., 2018; Popovic et al., 2017). Furthermore, a lack of consensus on social impact categories in general, of suitable methods (Garcia et al., 2016; Rahdari & Rostamy, 2015, as cited in Popovic et al., 2017), as well as definitive and agreed-upon targets for social performance (Fauzi et al., 2019), can be observed. Indicators available for the social assessment additionally depend on the type of industry (Popovic et al., 2017; Popovic et al., 2018), are culturally dependent, and very context-specific (Fauzi et al., 2019; Lehmann et al., 2013). This type of information may not be determined in the early stage of technology development, which is a challenge for the implementation of a social assessment (Lehmann et al., 2013). Furthermore, databases containing data on social impacts, which could provide support when conducting the assessment, are still under development. This creates an obstacle to the practical application of assessment methods like Social Life Cycle Assessment (Fauzi et al., 2019). Lastly, Lehmann et al. question the assessment method's applicability for technology analysis on a product level (Lehmann et al., 2013). According to their findings, only a few direct causal links between the process or product and the impact (social issue) could be found (Lehmann et al., 2013). They propose that the Social Life Cycle Assessment is more appropriate for assessing regions or nations and that more suitable indicators need to be defined for assessing technologies (Lehmann et al., 2013). Even though the social dimension of sustainability should be included in technology assessments of companies, a lack of knowledge, suitable indicators, and adoption towards the aviation industry can be identified. In order to overcome this gap, further and more in-depth research is needed, which goes beyond the scope of this research project.

Economic considerations and assessment methods are already implemented and well-known in the case company (for example via business case calculations). However, it is not clear, how the impacts of the other two pillars and sustainability in general are integrated in the economic assessment. Therefore, an investigation of the current integration of sustainability within the existing economic assessment method is needed. Due to the limited scope within the thesis study and to not be depended on confidential company data, it is proposed to exclude the economic pillar. Additionally, it is assumed that the most knowledge about economics and methods in general is available compared to the other two pillar. Thus, it can be assumed that the learning potential is the smallest for the economic pillar.

As the reduction of the scope happened during the execution of the thesis, the focus on all three pillars is still evident in the first two chapters (1 - Introduction and at the beginning of 2 - Phase 1). From the chapter 3 (Phase 2) onwards, the scope will be fully focused on the environmental pillar only.

1.2 LITERATURE REVIEW

Sustainability gains increased interest in society as well as in research. A literature review is conducted to identify the current knowledge base and a knowledge gap. Within this review, sustainability assessment within the development phase in the aviation industry is the field of interest. This chapter is organized into three parts. First, the methodology of the literature review is explained. Second, the literature findings and selected papers on sustainability assessment within the aviation industry are presented and discussed. Lastly, a knowledge gap is identified.

1.2.1 METHODOLOGY

To identify relevant literature, a structured approach using the online database Scopus[1] is chosen. Scopus is selected for the literature review as it is "[…] the largest abstract and citation database of peer-reviewed literature […]" (Scopus, n.d.). Within Scopus, two search strings are designed to identify relevant documents. The search strings consist of keywords related to sustainability assessment, technology development, and the field of interest, the aviation industry. Sustainable product development is selected as the primary search term, as it reflects technological aspects and the three pillars of sustainability. In the Appendix A – Literature study a detailed overview of the first search string can be found in Table 22, and an overview of the second string,

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[1] https://www.scopus.com/

conducted after analyzing the findings of the first search, can be found in Table 23. Furthermore, Appendix A – Literature study provides a detailed description of the search and the findings.

1.2.2 SYSTEMATIC LITERATURE REVIEW RESULTS

According to Hallstedt and Nylander, many tools and methods for sustainable product development are available (Hallstedt & Nylander, 2019). Existing tools that that can be found in literature are e.g. Environmental Management Systems (EMSs), Cleaner Production, Factor 10, Eco-design or Design for Environment, Life-Cycle Assessment (LCA), a Framework for Strategic Sustainable Development (FSSD), a Method for Sustainable Product Development (MSPD), Templates for Sustainable Product Development (TSPD), and a Sustainability Life Cycle Assessment (SLCA) Matrix (Hallstedt et al., 2013). While these instruments and methods take into account the sustainability considerations, they lack practical applicability (Zetterlund, 2016; Held et al., 2018, as cited in Hallstedt & Nylander, 2019). The same is concluded by Moreira et al., while general approaches are available, they are said to miss the practical integration into the design process (Moreira et al., 2015).

To overcome this issue, several methods and frameworks are developed by researchers, which combine existing methods, tools, guiding principles and theoretical strategies. This does not only include sustainability assessment methods but also supportive methods for practical integration like Multi-Criteria Decision Making (MCDM), Stakeholder Analysis or Machine Learning. An overview of the methods, frameworks, and strategies used in the reviewed literature can be found in Table 1.

Table 1 Methods found in literature with defined search string (own source)

Reference	Methods/Tools/Concepts mentioned	Limitations of the study
Lohner et al., 2012	- Environmental footprint (EF) - Qualitative assessment of Environmental Aspects - Life Cycle Assessment (LCA)	- Only environmental consideration - Approach developed for the "coming" years → might be overhauled by now
Hallstedt & Isaksson, 2013	- Environmental Impact Assessment (EIA) - Strategic Sustainability Assessment (SSA) - Risk assessment	- Developed for jet engine design → generalizability questionable
Hallstedt et al., 2013	- Product-service systems (PSS)* - Stakeholder Analysis - Sustainability Life Cycle Assessment (SLCA) Matrix (LCA+LCC+S-LCA) - Value assessment matrix - Risk Assessment - simulation model	- Developed for jet engines → generalizability questionable - Based on product-service systems model →might not be applicable for all products/ technologies
Hallstedt et al., 2015	- Environmental Impact Assessment (EIA) - Strategic Sustainability Assessment (SSA) - Net Present Value (NPV)	- Position the method in the frame of the existing risk assessment methodologies unknown - Robustness and sensitivity not yet tested
Moreira et al., 2015	- Life Cycle Assessment (LCA) - Systemic design approach* - Design for X (DfX) - Product – service systems (PSS)*	- Developed for textile industry →generalizability low - Based on generic product development process → might not be followed by all organizations
Ameli et al., 2016	- Mathematical programming - Life cycle inventory (LCI) - Life Cycle Costing (LCC) - Carbon footprint (CF)	- Developed for complex products with large number of parts and many design alternatives → generalizability questionable - High amount of industry data needed - Developed to make decision between technologies/ parts/ design choices → trade-offs assessment, might not always be the focus
Ashtiany & Alipour, 2016	- Quality Function Deployment (QFD) - Axiomatic Design (AD)	- Developed for airplane tail design - might not applicable to other technologies →generalizability questionable
Bertoni et al.,2018	- Value-driven design (VDD)* - Machine Learning (ML)	- No information about reliability of the results - Uncertainty cannot be quantified within the method
Villamil et al., 2018	- Sustainability principles (SPs)* - Framework for Strategic Sustainable Development (FSSD) - Sustainability Life Cycle Assessment (SLCA) (LCA+LCC+S-LCA)	- Specifically designed for additive manufacturing technologies --> generalizability questionable - Assessment based on multi-functional team → risk of neglecting some important aspects due to the lack of experience and knowledge of the technologies assessed
Wehner et al., 2018	- Life Cycle Assessment (LCA) - Eco risk assessment (RA) - Uncertainty assessment	
Zhang et al., 2018	- Bio inspired design* - Life Cycle Costing (LCC) - Life Cycle Assessment (LCA) - Social impact assessment (S-LCA) - Multi-criteria decision making (MCDM)	- Developed for additive manufacturing technologies - Conceptual model developed →Theoretical suggestion of tools & methods - Only for bio-inspired geometrics
Khan, 2019	- Requirements analysis - Quality function deployment (QFD) - Morphological matrix - Technique for order preference by similarity to ideal solution (TOPSIS) - Pugh matrix.	Only applicable for comparison of different technologies to each other and a baseline technology - Base line tech. must be available - Knowledge about alternative concepts need to be available - No "stand alone" analysis of one technology possible
Bertoni et al.,2020	- Value-driven design (VDD)* - Machine Learning (ML) - Sustainable Product Development (SPD)*	- Particularly suitable for products with a relatively static architecture - concepts with a defined number of parts & geometry that can be parametrically changed in the CAD environment → not applicable to all types of technologies/products → low generalizability

*guiding principles or theoretical strategy, no concrete method or tool

Within Figure 5 the occurrence of a method within the analyzed literature is visualized. This figure shows that life cycle methodologies are often mentioned in the literature. Almost half of the authors (six out of 13) apply the Life Cycle Assessment method, followed by Life Cycle Costing, Social Life Cycle Assessment, and risk analyses. The other methods are only mentioned one or two times in the analyzed literature.

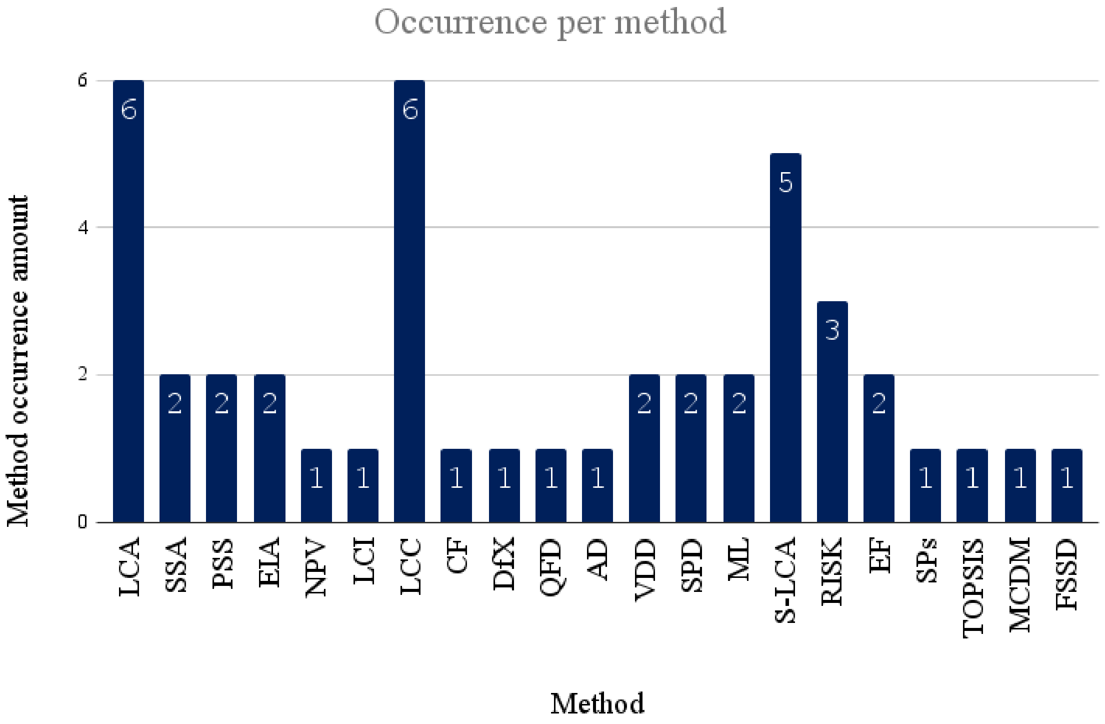


Figure 5 Occurrence per method in studied literature (own source)

These findings can be questioned, as there are some limitations to the identified literature. The methods and frameworks developed by the researchers are mainly developed with the help of one specific use case. Therefore, it is necessary to carefully assess the generic applicability of the findings when applying the proposed method to a different case or technology.

Furthermore, it needs to be taken into account that several papers are composed by the same researchers. Six studies (so almost half of the findings) contain the involvement of one researcher, called Hallstedt. This frequency might lead to biases or a narrow focus on the literature findings. Nevertheless, even if the studies involving Hallstedt are excluded, the Life Cycle Assessment methodology is still the most mentioned, as can be seen in Figure 38 in Appendix B – Occurrence per method without Hallstedt. In addition, the study done by Bertoni et al. in 2020 continues the development of the approach proposed by the same researchers in 2018 (see Bertoni et al., 2018 & Bertoni et al., 2020). Therefore, the combined methods mentioned in the 2020 paper cannot be regarded as a new approach, but a more elaborate version of the 2018 findings. This needs to be considered when assessing the occurrence of methods within the literature finding.

1.2.3 KNOWLEDGE GAP

The literature review shows that several methodological approaches have been proposed to assess sustainability in the development of aviation technologies. While some of these involve similar tools and methods, the combination and application of these varies drastically. Therefore, there does not appear to be a harmonized methodology or framework that the aviation industry could agree upon. In addition, the method used appears to depend on the type of technology or product being developed. Through this literature review, no clear guidance could be found on which method to use when developing new technologies in the aerospace industry.

In addition to this academic knowledge gap, a practical knowledge gap within the case company can be identified. An interest in enhanced sustainability assessment during technology development can be determined from an exchange with Airbus employees from the R&T perimeter and after looking at Airbus company strategy (described in chapter 1.1.3). As described in chapter 1.1.6, the established sustainability assessment methods within the case company mainly focus on economic and environmental considerations. The social dimension is only partly considered yet. In addition, the timing for applying the environmental assessment methods is not clearly defined. Overall, a clear recommendation on methods and tools and the most appropriate application timing during the innovation process (described in chapter 1.1.6) needs to be included. At the same time, the sole focus of the case company on Life Cycle Assessment should be questioned and analyzed.

The gap analysis lead to the need for guidance on which method to apply and when to conduct a particular sustainability assessment method can be identified. To fulfill this need, the following research objective can be derived:

What decision support can be used to select a sustainability assessment method for technology development in the aviation industry?

This thesis project focuses on understanding which sustainability assessment methodologies are available, how they can be integrated into the early development process of aircraft technologies/products and if those are superior than the currently applied methods. The main emphasis lies on the environmental aspects of sustainability. The aircraft technologies in question consist of materials and structures for commercial aircraft parts and processes to manufacture those. Parts for freight transport, system, and software-related technologies, as well as after-sales services, are not included in this research project. This is because these types of technologies differ in their characteristics and requirements. Thus, a different set of sustainability assessment methods is likely needed. Additionally, the after-sales services are not the primary scope of the case company with which this study will be conducted.

1.3 RESEARCH APPROACH

The main research question can be divided into four main components. Firstly, sustainability assessment methods available within the literature need to be understood and analyzed. Suitable methods for innovation within the aviation manufacturing industry should be selected. Secondly, the selected methods need to be transferred into an easy-to-use decision support for non-experts. Non-experts are defined as employees of the case company with no or only limited knowledge about sustainability assessment methods. Thirdly, a comparison of the different methods and the status quo method needs to be provided. Information regarding the capacity and shortcomings of each method should be made available for the non-experts. Lastly, the findings and methods developed within the thesis project need to be verified.

To support solving the main research question, four sub-research questions are developed. Each sub-question is answered within one phase of the thesis. Following the sequential phases will lead to answering the main research question. An overview of the phases, research questions, and methods can be found in Figure 6.

Phase 1: Identification of methods

For the first phase the following sub-research question is identified: ***Which sustainability assessment methods are suitable for an assessment during technology development?***

Various sustainability assessment methods are available, all differing from each other. In order to identify the most suitable ones for the defined study scope, the available methods need to be identified. This lays the foundation of the methods that will be analyzed further within this part of the study as well as throughout the entire study. Besides identifying the different methods, it needs to be checked whether or not they suit the study's scope (technology development in the aviation industry). Several deliverables can be defined to do so. First of all, the requirements of the industry regarding sustainability assessment methods need to be identified. These requirements can be transferred into criteria to check the various methods. Secondly, the methods and tools available in the literature need to be collected. Afterward, these two deliverables can be combined. The identified methods are checked on the criteria. Based on the outcome of this comparison, a selection of suitable methods for the scope of the study can be identified.

To approach this first phase, several research methods are used. First of all, a brainstorming session is organized to deduct the relevant method’s characteristics and knowledge needs of the case company. In addition, a literature study is conducted to identify further industry requirements. A second literature study is used to identify the available sustainability assessment established within the literature. Afterward, a comparison is made to draw a selection of suitable methods.

Phase 2: Method analysis and design of decision support

The sub-research question of the second phase is defined as: ***How can a decision support for the selection of a suitable assessment method be designed?***

The second phase addresses the second part of the main research question: The design of a decision support for non-experts. Several steps need to be taken to achieve this objective. First of all, the selected methods of the first phase are analyzed in more detail. This aims to provide a common understanding of the methods and gain more knowledge about them. The type of information and knowledge that should be addressed in this phase is deducted from the brainstorming conducted in phase 1. These knowledge requirements/characteristics are transferred into criteria. Once the type of information required is defined, additional information about the methods is collected via a literature study. The acquired information is assigned to the respective information criterion and the selected method. Afterward, the data is displayed in a structured way to provide an overview of each method. Lastly, a visual representation of decision support for selecting a method is designed. This visual representation is created based on the knowledge acquired within phase 1 and phase 2. The goal for this part of the decision support is that it should be doable quickly and easily by non-experts.

Phase 3: Development of a ranking

The third sub-research question is defined as follows: ***How can a ranking of the methods to each other be developed?***

The third phase aims to develop a ranking for comparing the different methods. Once the non-expert uses the decision support designed in phase 2 and selects a method, information regarding the capacity of that method needs to be provided. Here awareness regarding the characteristics of the selected method should be given. What are the strong or weak features of the method? Do these feature suit the intended application of the method? If the selected method does not fulfill the user's intentions, the selection of another better-fitting one should be fostered. To do so, a comparison method is developed, and a ranking of the methods to each other is proposed. Furthermore, the different characteristics of each method are visually displayed to enable comparison at one glance.

Additionally, the aim is to compare the selected method (from phase 2) with the case company's status quo sustainability assessment methodology. As the status quo, the Life Cycle Assessment is chosen since this methodology, and the environmental aspects of sustainability are of the utmost importance for the case company at present. In addition, LCA is the most widely used method within the literature (Villamil et al., 2018; Pinheiro Melo et al., 2020).

Research methods proposed for this phase are the development of a qualitative comparison, conduction of a literature review, and the use of pairwise comparison. Additionally, visualization is achieved by using spiderweb diagrams.

Phase 4: Validation of the developed ranking method

The last sub-research question is defined as follows***: What influence does the practical application have on the developed method of qualitative comparison?***

The last phase of the thesis aims to validate the developed method of the third phase. Here a use case is selected on which the sustainability assessment methods are executed. Afterward, the results are used to validate the findings of phase 3 and, with that also, the method developed.

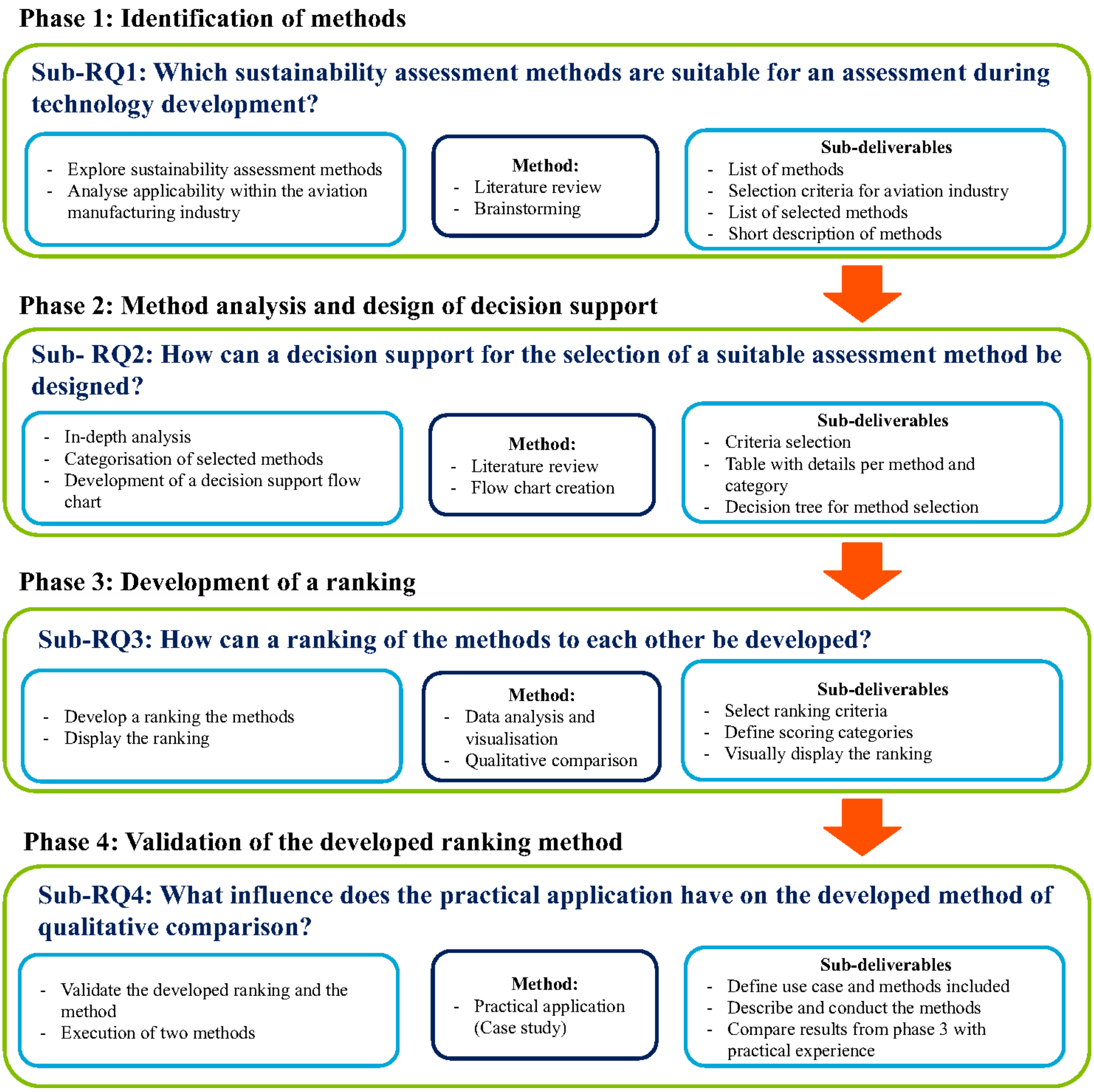


Figure 6 Research flow diagram (own source)

2 PHASE 1 – METHOD IDENTIFICATION

Within this phase sustainability assessment methods suitable for technology development in the aviation manufacturing industry are identified. For this purpose, the criteria that the methods should meet in order to be perceived as suitable for the scope of the study are defined first. Secondly, sustainability assessment methods mentioned within scientific literature are identified. Lastly, these methods are analyzed and selected based on defined criteria.

2.1 CRITERIA DEFINITION

In order to select suitable methods for the scope of the study, criteria are defined. The identified methods are judged on the criteria, and a decision is made based on the judgment. For the criteria definition, a brainstorming session is conducted. Next to the researcher a knowledgeable expert (expertise in R&T and the status quo method Life Cycle Assessment) of the case company participated. The aim of the brainstorming approach is to identify all type of information which might be useful to know about the method. The information gathered in the brainstorming session is used partly in this chapter and partly in other parts of the study. In addition, criteria for categorizing sustainability assessment methods in the literature are examined.

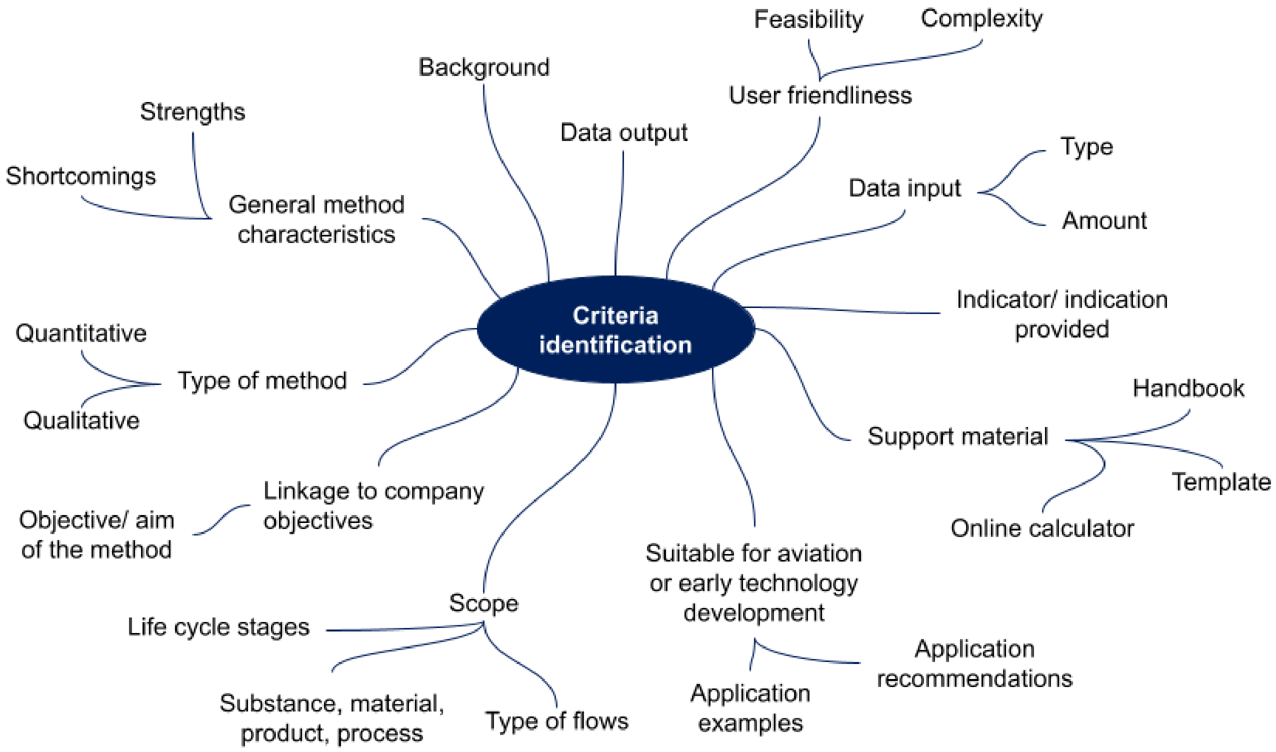


Figure 7 Brainstorming results for criteria identification (own source)

The findings of the brainstorming (see Figure 7) and the literature are transferred into the several criteria. For the first criterion, the establishment of the methodology as a sustainability assessment methodology is defined. As this study aims to identify and analyze sustainability assessment methods, their relevancy within this context is a precondition. Therefore, the identified methods should be referred to or linked to the term *sustainability assessment*. As a criterion for exclusion, methods mentioned less than ten times are chosen. It is assumed that methods mentioned ten or less than ten times in combination with sustainability assessment are irrelevant in this context. Considering all methods, a total of ~44,000 findings could be identified. If mentioned ten times, the method is accountable for 0.02% of the total findings and, therefore, not perceived as relevant. Furthermore, it is assumed that there are not enough application examples available to gain knowledge for adoption quickly.

A second precondition is the need for the identified method to be an assessment method. The study aims to support decision-making on which method to use when analyzing a technology/product's sustainability. Therefore, the method needs to be able to analyze or assess the degree of sustainability of the technology in question. This criterion is reviewed based on the following definition for assessment methods: "[…] the process of reviewing, inspecting, observing, studying, or analyzing one or more assessment objects (i.e., specifications, mechanisms, or activities)."(Johnson, 2020, p. 63). They aim to facilitate understanding, obtain evidence or achieve clarification (Johnson, 2020). Methods that enable analysis or assessment are included. However, methods that do not fulfill this condition are excluded, as they do not meet the aim of analyzing how sustainable a specific technology is. Only if both preconditions described above are fulfilled, the last two criteria are reviewed.

The third criterion categorizes methods and tools according to their focus and areas covered. Here a distinction can be made between tools and methods focusing on policy changes and those focusing on a product level (Ness et al., 2007). To find applicable methods for the study, assessment methods, which are applicable within the innovation phase of a technology, are defined as the ones of interest. Technology and products are closely related to each other within the aviation sector (see chapter 1.1.6), so a focus on a product level is chosen. According to Ness et al., the methods and tools related to this category can also be referred to as product-related assessment (Ness et al., 2007). They focus on flows connected to the production and consumption of services and goods (Ness et al., 2007). Moreover, they assess the usage of resources and environmental impacts along the life cycle of a product or through the production chain (Ness et al., 2007).

Another group of assessment methods that can be distinguished are integrated assessment methods. These are used to support decision-making for policies or projects (Ness et al., 2007). As the focus of the study lies on the assessment of technologies under development, the integrated type of methods is excluded. In order to determine if the assessment methods are focused on products, policy-making, or projects, descriptions of the method or examples of applications within the literature are searched. Alternatively, the background of the study, the defined scope, and the reason for developing the method can be identified if no precise information on the focus can be found. This approach might provide enough information to determine the focus or base an assumption.

As a last criterion, the aspects of sustainability, which will be assessed by the method, are considered. This criterion is proposed by Booysen (Booysen, 2002, as cited in Singh et al., 2009) and adopted by the researcher of this study. In order to provide information on how sustainable technology is, the method should at least address one aspect of sustainability. Therefore, the aspect of sustainability (social, environmental, or economic), which can be directly assessed by the method, will be analyzed. To do so, the aspects of sustainability, which will be measured or assessed by the method, are taken into account. In order to, fulfill the criterion, the environmental pillar of sustainability needs to be directly assessable with the method. If a method consists of several methods (like *Life Cycle Sustainability Assessment*) all methods included need to fulfill the defined criterion. In addition methods are excluded that can help with decision-making or assessing criteria in general, like *multi-criteria decision-making*.

To summarize, the following selection criteria are determined for sustainability assessment methods suitable for the thesis scope:

1. Method often (more than 10 times) mentioned in the context of sustainability assessment
2. Method enables an analysis or assessment
3. The scope of the method is focused on products
    a. If no information is found: Method background, “what was it developed for?”
4. Method assesses at the environmental pillar

2.2 LITERATURE REVIEW

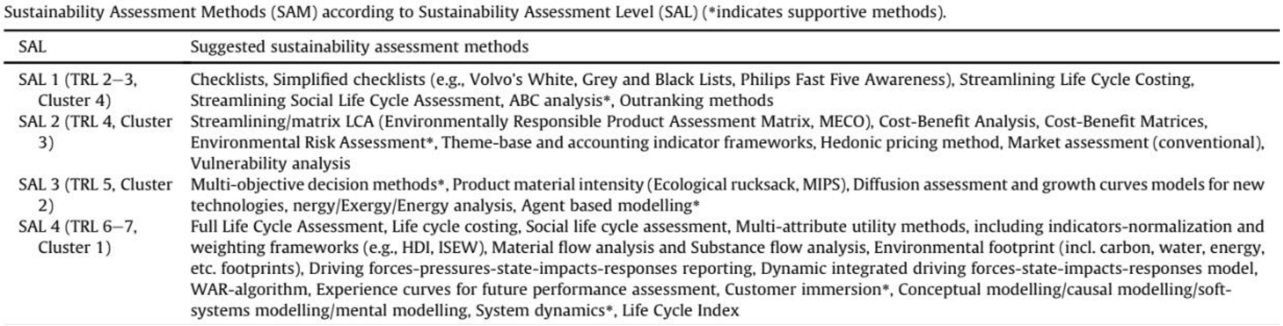
Methodology

The literature study conducted in chapter 1.2.1 provides a starting point for available and suitable methods for the product development within the aviation industry. A further literature review identifies additional methods. As described in chapter 1.1.6, the technology development process within the case company is structured via the Technology Readiness Level. In order to observe if there is a framework available, which combines the TRL with sustainability assessment methods, a structured literature study is performed.

The methodology for the literature study is similar to the one described in chapter 1.2.1; only the search string is modified. The following keywords are used for the search string: *"Sustainability assessment" AND Technology readiness level OR TRL*. These keywords are searched for within the *Title, Abstract, and Keywords*. The database Scopus is used to identify literature. As an outcome of the literature search, five findings are found: two conference papers, two articles, and one review. Due to the low number of findings, a full-text scan of all papers is performed. One article and one conference paper are identified as relevant to the project and are analyzed in more detail within the next paragraph.

Literature Review Results

One article found combining sustainability assessment with the Technology Readiness Level framework is the one of Chebaeva et al. (Chebaeva et al., 2020). In their paper 33 different sustainability assessment methods are classified and clustered into sustainability assessment levels (see Figure 8), a concept derived from and analogous to the Technology Readiness Level method. The 33 methods consist of 27 sustainability assessment methods and six supportive methods, which are organized into clusters based on expert assessment. Their findings indicate that the reviewed methods can be used within different research and development project phases.



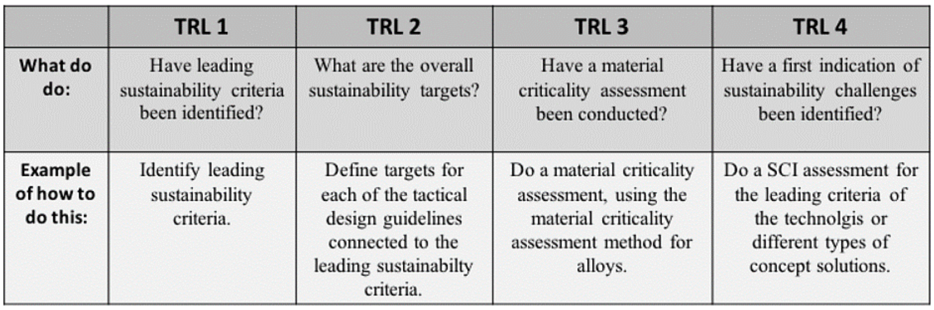
Sustainability Assessment Methods (SAM) according to Sustainability Assessment Level (SAL) (*indicates supportive methods).

SAL	Suggested sustainability assessment methods
SAL 1 (TRL 2–3, Cluster 4)	Checklists, Simplified checklists (e.g., Volvo's White, Grey and Black Lists, Philips Fast Five Awareness), Streamlining Life Cycle Costing, Streamlining Social Life Cycle Assessment, ABC analysis*, Outranking methods
SAL 2 (TRL 4, Cluster 3)	Streamlining/matrix LCA (Environmentally Responsible Product Assessment Matrix, MECO), Cost-Benefit Analysis, Cost-Benefit Matrices, Environmental Risk Assessment*, Theme-base and accounting indicator frameworks, Hedonic pricing method, Market assessment (conventional), Vulnerability analysis
SAL 3 (TRL 5, Cluster 2)	Multi-objective decision methods*, Product material intensity (Ecological rucksack, MIPS), Diffusion assessment and growth curves models for new technologies, nergy/Exergy/Energy analysis, Agent based modelling*
SAL 4 (TRL 6–7, Cluster 1)	Full Life Cycle Assessment, Life cycle costing, Social life cycle assessment, Multi-attribute utility methods, including indicators-normalization and weighting frameworks (e.g., HDI, ISEW), Material flow analysis and Substance flow analysis, Environmental footprint (incl. carbon, water, energy, etc. footprints), Driving forces-pressures-state-impacts-responses reporting, Dynamic integrated driving forces-state-impacts-responses model, WAR-algorithm, Experience curves for future performance assessment, Customer immersion*, Conceptual modelling/causal modelling/soft-systems modelling/mental modelling, System dynamics*, Life Cycle Index

Figure 8 Sustainability Assessment Level (Chebaeva et al., 2020)

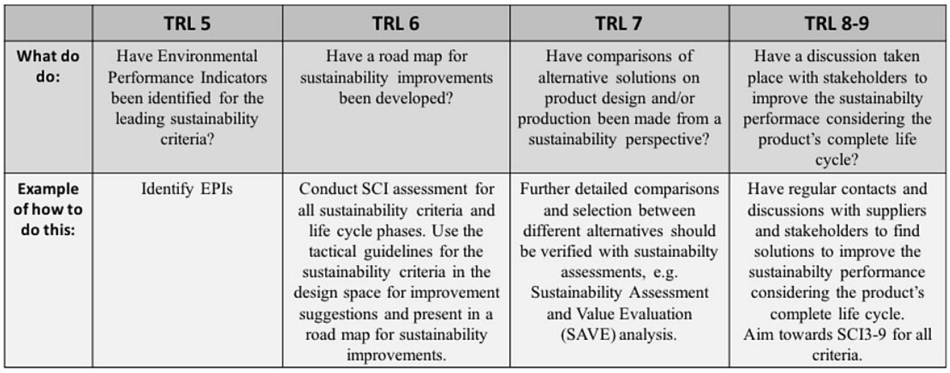
A shortcoming of the study conducted by Chebaeva et al. is the low number of experts taken into account for the analysis. Only three experts are consulted for the first classification of the methods, and eight experts participated in the verification. Furthermore, the verifying eight experts are asked only to review the methods they were familiar with. Thus, no detailed information is given on how many experts verified the classification of each method. Additionally, no information is given about methods initially included in the analysis (based on the literature review) but excluded due to missing experts. Lastly, the framework is developed theoretically, and no application or verification of the findings in practice has been made yet.

The second literature search result is a conference paper published by Hallstedt and Pigosso (Hallstedt & Pigosso, 2017). Their study aims to provide systematic guidance on sustainability in early technology-and product development and to fulfill the requirements of the company the study was conducted with (Hallstedt & Pigosso, 2017). As an outcome, assessment criteria and a proposed way how to meet the criteria are defined for each TRL. Overall, Hallstedt and Pigosso propose an approach that combines the Strategic Sustainability Criterion and the Environmental Performance Indicators to fulfill the defined criteria. An overview of the criteria and proposed answer approach and methods can be found in Figure 9 and Figure 10.



	TRL 1	TRL 2	TRL 3	TRL 4
What do do:	Have leading sustainability criteria been identified?	What are the overall sustainability targets?	Have a material criticality assessment been conducted?	Have a first indication of sustainability challenges been identified?
Example of how to do this:	Identify leading sustainability criteria.	Define targets for each of the tactical design guidelines connected to the leading sustainabilty criteria.	Do a material criticality assessment, using the material criticality assessment method for alloys.	Do a SCI assessment for the leading criteria of the technolgis or different types of concept solutions.

Figure 9 Illustration of the sustainability guidance for TRL1-TRL4 at the studied company (Hallstedt & Pigosso, 2017)



	TRL 5	TRL 6	TRL 7	TRL 8-9
What do do:	Have Environmental Performance Indicators been identified for the leading sustainability criteria?	Have a road map for sustainability improvements been developed?	Have comparisons of alternative solutions on product design and/or production been made from a sustainability perspective?	Have a discussion taken place with stakeholders to improve the sustainabilty performace considering the product's complete life cycle?
Example of how to do this:	Identify EPIs	Conduct SCI assessment for all sustainability criteria and life cycle phases. Use the tactical guidelines for the sustainability criteria in the design space for improvement suggestions and present in a road map for sustainability improvements.	Further detailed comparisons and selection between different alternatives should be verified with sustainabilty assessments, e.g. Sustainability Assessment and Value Evaluation (SAVE) analysis.	Have regular contacts and discussions with suppliers and stakeholders to find solutions to improve the sustainabilty performance considering the product's complete life cycle. Aim towards SCI3-9 for all criteria.

Figure 10 Illustration of the sustainability guidance for TRL5-TRL9 at the studied company (Hallstedt & Pigosso, 2017)

Overall, the study of Hallstedt & Pigosso provides practical guidance on how to implement sustainability assessment within the TRL methodology. The proposed framework starts from a qualitative, more overarching identification of relevant aspects for sustainability towards a more detailed, quantitative assessment of sustainability. Therefore, it incorporates the increasing amount of data available per TRL into the framework. A drawback of the study is the focus on a specific company. The suggested framework is tailored toward the requirements and way of working in the company, which decreases the generalizability and applicability within other companies. However, it could be a starting point for other industries and companies that want to include sustainability in their TRL methodology. Furthermore, parts of the developed framework focus on comparing and selecting between different technologies and technological solutions. This might not be the aim of every company's sustainability assessment. The developed framework is only partly suitable if the goal is to analyze and further improve one technology. Additionally, the identified sustainability criteria and methods mainly focus on environmental aspects. Although the study's goal is to incorporate social sustainability aspects as well, these significantly come short compared to the ecological perspective. Lastly, the study includes many articles and methods published and developed by one of the authors (Hallstedt), which could lead to biases toward choosing and adopting their own methods.

2.3 IDENTIFIED METHODS

Within the literature study conducted in chapter 1.2.1 and chapter 2.2, a total of 56 methods could be identified. These methods and tools are selected based on the used search terms and do not represent a fully comprehensive list of sustainability assessment methods. According to Poveda, there are several hundreds of sustainability assessment tools and methods (Poveda, 2017). Furthermore, an increase in methods can be expected in the future due to the topic's popularity (Poveda, 2017). A different search string or a different database might lead to different results. Therefore, the methods included in this thesis only represent a fraction of the methods and tools available. Additionally, it needs to be taken into account that the identified 56 methods do include sustainability assessment methods and methods that can support decision-making, the application of sustainability assessment methods, and general guiding principles or concepts. This factor will be addressed in more detail in the next chapter.

To assess which methods are suitable for the scope of the study, an understanding of each method needs to be in place. Each method is searched for to acquire this knowledge within Google Scholar and Scopus. The goal is to find a scientific paper containing a description or definition of the method. Due to the high number of methods identified, a list with the name, abbreviation, and a short description of each method is displayed in Table 24 in Appendix C – Description of Methods identified in the Literature.

2.4 ANALYSIS OF IDENTIFIED METHODS

Within this chapter, the 56 identified methods will be analyzed based on the defined criteria. As a result, a selection is drawn from the search results.

For the first criterion, the establishment of the method as a sustainability assessment method is analyzed. This is a precondition because this study aims to propose a framework consisting of sustainability assessment methods. For that purpose, the academic literature is reviewed to check how often each method is referred to or mentioned in combination with the term sustainability assessment. The search is conducted with Scopus, and the search string is structured as follows:

Table 2 Search string 3 (own source)

Connector	Search area	Search term
	Title, Abstract, Keywords	"method name" OR method abbreviation
AND	Title, Abstract, Keywords	sustainability AND (assessment OR analysis)

The search within Scopus is conducted for all methods mentioned in the chapter above (chapter 2.3) and Table 15. Resulting of each search, the number of literature findings is considered. It needs to be pointed out that not the content or quality of the search results is taken into account but solely the number of literature findings. Therefore, not the development level of the method itself but the time it is referred to or linked to the term sustainability assessment is taken into consideration. This analysis should provide information on whether a method is widely perceived as a sustainability assessment method and, therefore, can be assumed as relevant within this context. Additionally, it should indicate if a knowledge base on the considered method is available. If many application examples are obtainable, they can serve as a reference or a pattern to be imitated during the adoption of the method. This could benefit the case company, as the application and usage of the method are assumed to be more accessible. The number of literature search results per method is displayed in Figure 39 in the Appendix D – Number of literature search results per method. A total of 18 methods could not fulfill this criterion.

The data for the second criterion is obtained by the method name and description found within the scientific literature. As a simplification, it is assumed that if the method’s name contains the word “Analysis” or “Assessment”, the respective method fulfills the defined criterion. No information could be found for one method (*Customer Immersion*). This method is perceived as not fulfilling the defined criterion. In addition, some methods partly fulfill the criterion, for example, *Conceptual Modelling*. This method is categorized as a model and should therefore be excluded, but it enables the analysis of quantitative relationships, according to Ness et al. (Ness et al., 2007). In these cases, the methods are excluded, as they do not distinctly fulfill the criterion. Methods that are perceived as not fulfilling the assessment definition are design guidelines, models, concepts, and frameworks. Even though these methods might be able to support assessments, they do not directly conduct an assessment.

Upon further inspection some methods are excluded in addition. These methods are shortly presented hereafter and a justification for their exclusion provided.

Environmental Footprint Family

The environmental footprint family is a set of indicators that enable tracking human pressure on the environment from a consumption-based perspective (Galli et al., 2012, as cited in Matuštík & Kocí, 2021). They aim to prevent burden shifting occurring from the use of single metrics and to develop solutions for systematic problems (Fang et al., 2014, as cited by Wu et al., 2021). The footprint family consists of several single-dimensional indicators. Originally, the footprint methodology was developed from one indicator, the so-called Ecological footprint, which is an area-based indicator. Now there are several footprints available. The most established ones are the Ecological, Carbon, and Water footprint (Matuštík & Kocí, 2021). The water footprint can be used to measure the consumed water for the production of one product unit, or the volume of water polluted. (Murthy, 2022; Wu et al., 2021). The carbon footprint indicates a product’s carbon intensity or quantifies the climate impact (of greenhouse gases) (Murthy, 2022; Wu et al., 2021). Even though the footprint indicators are popular within the media, non-governmental organizations, or businesses, there are various definitions and methodologies for each individual footprint (Matuštík & Kocí, 2021). Therefore, there is no common definition and methodology for each environmental footprint.

Although the environmental footprints are often referred to as sustainability assessment methods (see Ness et al., 2007; Andersson et al., 2016; Vanham et al., 2019) and identified as such within the first part of this project, the more in-depth analysis showed, that the environmental footprint family does not fully fit the scope of this study. Even though they provide an assessment of sustainability, they are in need of other calculation methodologies to do so. According to Fang et al. there are different ways to calculate the footprints of a product (Fang et al., 2014). The LCA method is used frequently. Additionally, it is possible to understand the footprint method as a simplified Life Cycle Assessment, which only focuses on one single impact category (Matuštík & Kocí, 2021). This point of view is also manifested within the Product Environmental Footprint (PEF) methodology proposed by the European Commission (Matuštík & Kocí, 2021). The PEF method is based on Life Cycle Assessment and aims to quantify a product’s (goods or services) environmental impacts (European Commission - Joint Research Centre, 2021). Therefore, the environmental footprint methods can be seen as a part of the Life Cycle Assessment method, or as a method that needs more research regarding an overall and consistent analysis method for products. Due to the above described issues, the environmental footprint method will be handled as a reporting indicator, but not as a standalone sustainability assessment method within this study.

Streamlining/ Matrix Life Cycle Assessment

Streamlining Life Cycle Assessment or also called Simplified Life Cycle Assessment follows the same methodology as Life Cycle Assessment, but should decrease complexity (Beemsterboer et al., 2020). Several simplification practices can be found in the literature. These can be categories into five simplifying logics (Beemsterboer et al., 2020):

1. Exclusion (of e.g. life cycle stages, processes and indicators)
2. Inventory data substitution (e.g. by substituting detailed processes for black-boxes and the use of secondary data from literature or data bases)
3. Qualitative expert judgment (e.g. by the use of matrix approaches to rate the relevance of key environmental issues)
4. Standardization (of methodological standards, guidelines and tools)
5. Automation (e.g. by the use of software or automated data imports from databases)

Simplifications are common in practice but not unproblematic (Beemsterboer et al., 2020). They might introduce inaccuracies into results of the study (Danilecki et al. 2017; Dowson et al. 2012; Soust-Verdaguer et al. 2016, as cited in Beemsterboer et al., 2020). Besides, they can create additional challenges, like the need for a high level of expertise to judge emissions and impacts (as required in the matrix approaches) (Beemsterboer et al., 2020). Other researchers claim, "[…] that there is no essential distinction between full and simplified LCA" (Arzoumanidis et al. 2017; Curran and Young 1996, as cited in Beemsterboer et al., 2020, p. 2165). This approach can be seen in the case company. If necessary, different simplification logics are adopted, like the use of standardized methods, automated software and secondary data. They are not perceived as an own method, but part of a full LCA. The simplifications are taken into consideration during the result interpretation and reporting. Due to the perception of simplified LCAs as full LCAs in the case company, the same point of view is applied in this thesis and the method excluded.

Checklist

Checklists can be described as a series of question. Answering those should help with systematically addressing sustainability issues (Woodhouse et al., 2018). It is possible to find a number of predefined checklists, like Volvo's White, Grey and Black Lists, Philips Fast Five Awareness or Ecodesign checklists (see Byggeth & Hochschorner, 2006). Another possibility is to develop a checklist which matches the exact sustainability assessment needs. An example of individually developed checklist can be found in (Schöggl et al., 2017). In order to further analyze the checklist method, it is necessary to define a concrete checklist, or to develop one on your own. This requires further work that goes beyond the scope of this study. Additional information on checklist can be found in Table 26 in Appendix F – In depth analysis of Checklist method.

2.5 SELECTION OF RELEVANT METHODS

The review of all methods and the respective criteria can be found in Table 3 and in more detail in Table 25 in Appendix E – Method selection with references. A checkmark and green color are shown if a method fulfills the respective criteria. A parenthetical check mark indicates a partial fulfillment of the criterion. If no information can be found regarding the method and the criterion, the cell is colored red. Within the first two columns, the precondition criteria are shown. If both preconditions are fulfilled, the remaining criteria (and columns) are analyzed and filled. In order to be selected as a suitable method, both preconditions need to be fulfilled, the focus/scope needs to be on products, and the environmental pillar needs to be directly assessed. If all criteria are fulfilled, a checkmark and a dark green color is displayed within the last column.

Table 3 Method selection based on criteria (own source)

Criterion	**Pre-condition**		**Scope**	**Sustainability pillar**			**Selected**
Method (abbreviation)	**(1) Findings**	**(2) Assessment method**	**Product**	**Economic**	**Social**	**Environ-ment**	
ABC-Analysis (ABCA)		✓					
Agent-Based Modelling (ABM)	✓						
Axiomatic Design	✓						
Checklists (CL)	✓	✓	✓	✓	✓	✓	(✓)
Conceptual modelling or Causal modelling or Soft-systems modelling or Mental modelling (CM)	✓	(✓)					
Cost-Benefit Analysis (CBA)	✓	✓		✓	(✓)	(✓)	
Cost-Benefit matrices (CBM)		✓					
Customer Immersion (CI)							
Design of X/ design for Excellence (DfX)	✓						
Diffusion assessment and growth-curves models for new technologies (DAGCM)		✓					
Driving Force Pressure State Impact Response Reporting (DPSIR)	✓	(✓)			(✓)	✓	
Dynamic integrated Driving Force State Impact Response Model (DIDFSIRM)							
Ecological Risk Assessment (ERA)	✓	✓				✓	
Energy/Exergy/Emergy Analysis (EEEA)	✓	✓	✓	✓		✓	✓
Environmental Footprint (incl. carbon, water, energy, etc. footprints) (EF)	✓	✓	✓			✓	(✓)
Environmental Impact Assessment (EIA)	✓	✓				✓	
Environmental Risk Assessment (ERA)	✓	✓				✓	
Experience curves for future performance assessment (ECFPA)		✓					
Framework for Strategic Sustainable Development (FSSD)	✓						
Full Life Cycle Assessment (LCA)	✓	✓	✓			✓	✓
Hedonic Pricing Method (HPM)	✓	✓	✓	✓			
Life Cycle Costing (LCC)	✓	✓	✓	✓			
Life Cycle Index (LInX)		(✓)					
Life Cycle Sustainability Assessment (LCSA)	✓	✓	✓	✓	✓	✓	(✓)

Criterion	Pre-condition		Scope	Sustainability pillar			Selected
Method (abbreviation)	**(1) Findings**	**(2) Assessment method**	**Product**	**Economic**	**Social**	**Environ-ment**	
Market Assessment (conventional) (MAUM)	✓	✓	✓				
Material Criticality Assessment		✓					
Material Flow Analysis and Substance Flow Analysis (MFA/SFA)	✓	✓	✓			✓	✓
Mathematical Programming	✓		✓				
Morphological Matrix	✓	✓					
Multi-attribute utility methods (MAUM / MAUT)	✓	✓					
Multi-criteria decision making/ analysis (MCDM/MCA)	✓	✓					
Multi-objective decision methods (MODM)		✓					
Net Present Value (NPV)	✓	✓		✓			
Outranking Methods (OM)	✓	✓					
Pugh Matrix	✓						
(Product) material intensity (Ecological Rucksack, MIPS) (PMI)	✓	✓	✓			✓	✓
Product service systems	✓						
Quality Function Deployment (QFD)	✓						
Simplified Checklists (sCL)		✓					
Social Life Cycle Assessment (sLCA)	✓	✓	✓		✓		
Stakeholder Analysis	✓	✓					
Strategic Environmental Assessment (SEA)	✓	✓				✓	
Strategic Sustainability Assessment (SSA)		✓					
Streamlining Life Cycle Costing (StLCC)		✓					
Streamlining Social Life Cycle Assessment (StsLCA)		✓					
Streamlining/Matrix LCA (StLCA)	✓	✓	✓			✓	(✓)
Sustainability Life Cycle Assessment Matrix		✓					
Sustainable Principles (SP)	✓						
System Dynamics (SD)	✓						
Theme-based and accounting indicator frameworks (TBAIF)							

Criterion	Pre-condition		Scope	Sustainability pillar			Selected
Method (abbreviation)	**(1) Findings**	**(2) Assessment method**	**Product**	**Economic**	**Social**	**Environment**	
Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)	✓	✓	✓				
Uncertainty Assessment	✓	✓					
Value Assessment Matrix		✓					
Value-Driven Design (VDD)							
Vulnerability Analysis	✓	✓				✓	
Waste Reduction (WAR)-Algorithm	✓						

Color coding	✓	Fulfilled
	(✓)	Partly fulfilled
	🟥	No information

Based on the assessment of the method on the defined criteria, a total of four methods are identified as suitable for the further study. Some of these methods include several different methods, which are discussed in more detail in the next chapter.

3 PHASE 2 – IN-DEPTH ANALYSIS

After a first analysis of the methods in the project's first phase, a more in-depth analysis of the selected methods will be conducted within this chapter. The additional information gained within this step should provide the knowledge for developing the decision-support framework and comparing the selected methods.

3.1 METHOD OVERVIEW

The general approach for the in-depth analysis and the development of the decision tree/flow chart is visualized in Figure 11. First, the areas of interest are identified. Within this step the type of information considered relevant or significant for the in-depth analysis is defined. Second, information regarding the selected methods and areas of interest is collected. The data is compiled via literature research using scientific and standard search engines. Afterward, the identified information is organized according to the areas of interest. This organization is done in a table to ensure a structured overview. Forth, a visualization of the methods is drawn to show possible connections between the methods. This should help organize the different methods and show their similarities and differences in an easily understandable manner. Fifth, the flowchart containing the decision tree for method selection is developed based on the findings of the previous steps. As a first validation, the flow chart is shown to an expert in the area of Research and Development to get some feedback. Lastly, the feedback is integrated and a second flowchart is created.

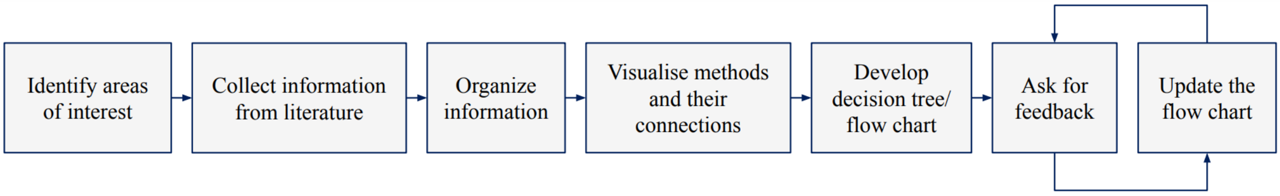


Figure 11 Approach for in-depth analysis and flow chart development (own source)

3.2 IDENTIFICATION OF THE AREAS OF INTEREST

The researcher identifies the areas of interest based on the brainstorming results (see Figure 7). Here assumptions are made about what type of information would be relevant to understand the method better and decide which method to use, when, and how. The following explains the nature of the relevant information and justifies why it is identified as relevant.

Short description:

First of all, a short description of the methods should be provided. Within a few sentences, the characteristics of each method will be explained to obtain and provide a better understanding. This aims to ensure that a common understanding exists and that non-experts can grasp the underlying concept. As the details of each method are only relevant when the assessment itself is conducted, the description is purposely held short.

The objective/aim of the method:

To understand what the method can be used for, the objective or aim of the method is looked into. The objective can be described as the goal of the method towards which the effort of conducting the assessment is directed. This is interesting, as it can provide information about the expected results and suitable application. Additionally, it can support decision-making in choosing an adequate method.

Input data:

In order to carry out an analysis, a specific amount and type of information are required. This information needs to be provided by the method operator and entered into the assessment to apply the method. It is defined as input data within this study. Knowledge about the input data is required to prepare the analysis and estimate the effort of compiling the respective data.

Output data:

The output data is defined within this study as data generated by carrying out the assessment method. It describes the data produced or resulting from the analysis. The output data is interesting for understanding the conclusions and interpretations that can be derived from the assessment. Furthermore, the decision can be deducted from the data whether the method is suitable for the intended application and whether it leads to the desired results. Additionally, it might be necessary to modify the output to a presentable form to draw conclusions from it. Thus, knowledge about further actions that might be needed to achieve the desired results can be derived from the output data, too.

Indicator(s), the indication provided by or derived from the method:

Indicators can quantify information by aggregating diverse and multiple data (Herva et al., 2011). hey help simplify communication, illustration, and analysis of complex and complicated information, as well as show progress and trends over a specific period (Singh et al., 2009; Herva et al., 2011). Furthermore, indicators can be seen as a value representative of the respective phenomenon, as they "[…] arise from values (we measure what we care about), and they create values (we care about what we measure)" (Meadows, 1998, as cited in Singh et al., 2009, p. 281). By looking at the indicators derived from the method, information about the main characteristics (concerning sustainability) of the products and processes under study can be obtained. This information is summarized, focused, and condensed into a readily comprehensible amount of significant information (Singh et al., 2009). Consequently, it can be assumed that information provided via indicators can be communicated with and interpreted by non-experts. To sum up, the look at the indicator should provide knowledge about the information that can be obtained from applying the respective assessment method.

Application examples, and recommendations:

To understand in which cases a method can or should be carried out, it might be helpful to know for which cases the method has been used before or is recommended. This can support choosing the most suitable method for each use case. Additionally, application examples or case studies can support a method by using them to guide the assessment process or function as a reference.

Strength of the method:

Knowing the strength of a method might help to achieve the desired goal of the individual assessment and to successfully analyze sustainability. This might help with deciding on an appropriate application of the method and whether the desired assessment results can be achieved.

Drawbacks/ criticism:

Another area of interest is each method's weaknesses, drawbacks, and criticism. When carrying out an assessment, it is vital to understand what / where the limits of a method are and to raise attention to them. The limits of a method can be significant for choosing the proper application and deciding whether it leads to the desired outcome. Furthermore, it provides information for the interpretation of the results. What are areas of concern, what is excluded from the assessment, and are the results well-funded? Thus, the weaknesses of a method can limit the interpretation and conclusions drawn from the results and should be made evident.

Nature of the method:

Within this study, the nature of the method describes whether it is qualitative or quantitative. This knowledge can help to identify further strengths and weaknesses and evaluate the interpretations drawn from the results. Additionally, conclusions about the compilation effort can be drawn from this information.

3.3 INFORMATION COLLECTION

In order to obtain data for the analysis, literature concerning each method is collected. The search for relevant literature is primarily conducted using scientific search engines. By this, most scientific papers from journals indexed in scientific databases are included in this part of the study. As a database, the search engine *Google Scholar*[2] and the *TU Delft library*[3] are used. Additional information and scientific papers are found using the *ScienceDirect topic* pages[4]. According to the publisher Elsevier, these topic pages provide a comprehensive database of reliable knowledge and function as a tool for discovering further trustworthy reading (Elsevier, 2023). Next to the scientific search, a general search using standard engines is also carried out. The typical search engine *Google*[5] is used to identify further information and guidance documents for the assessment methods. As a search term, the name of each method, as mentioned in Table 3, is applied, and the keywords for the defined areas of interest. The abstracts of the literature search results identified as most relevant by the search engines (the ones stated first after searching) are scanned, and if identified as promising, a full-text scan and analysis are conducted. Lastly, additional literature is obtained via a snowballing approach.

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[2] https://scholar.google.com/

[3] https://www.tudelft.nl/library

[4] https://www.sciencedirect.com/topics

[5] https://www.google.com/

3.4 FINDINGS OF IN-DEPTH ANALYSIS

After identifying relevant literature, the information regarding the areas of interest is extracted and compiled. In order to ensure a common understanding of the remaining ten methods, the description of each method is provided beforehand. Afterward, the information regarding the remaining areas of interest are displayed in a table format per method to increase the visibility of the findings.

Material Flow Analysis Methods

Material flow analysis deals with studying the physical flows of materials and natural resources into, through, and out of a system (OECD, 2008). It helps to analyze the relationships between human activities, material flows, and environmental changes (OECD, 2008). In order to analyze material flows at different scales, material flow analysis consists of a family of tools varying in the issue of concern and objects of interest (OECD, 2008). Here a distinction can be made between two types of methodological tools. The first type of method focuses on issues associated with specific substances, manufactured goods, and materials related to technology development, supply security, and environmental impacts (OECD, 2008). The second type focuses on general economic and environmental concerns related to material flows through a system in a world region, country, economic sector, or company (OECD, 2008). As the scope of the thesis lies in technology development, the second type of method is excluded from further review, and only the first type of method is considered.

3.4.1 SUBSTANCE FLOW ANALYSIS (SFA)

Substance Flow Analysis (SFA): "[…] monitor flows of specific substances […] that are known for raising particular concerns as regards the environmental and health risks associated with their production and consumption." (OECD, 2008, p.12). Examples of such substances are mercury, zinc, or CO2 (OECD, 2008). The accounting principle behind the SFA is based on the mass balance principle (OECD, 2008). It is based on the first law of thermodynamics, which states that matter (mass or energy) cannot be destroyed or created by a physical process (OECD, 2008). In the material flow analysis methods the principle is also referred to as material balancing principle and can be understood as follows (OECD, 2008):

$$\text{Natural resource extraction} + \text{imports} = \text{residual output} + \text{exports} + \text{net addition to man} - \text{made stock} \tag{1}$$

Which means, that the sum of inputs into the defined system needs to equals the sum of its outputs (OECD, 2008). More information is provided in Table 4.

Table 4 In-depth analysis of Substance Flow Analysis (own source)

Area of interest	**Findings from the literature**
The objective/ aim of the method	• Supports of the control and management of substances, which raise concerns (OECD, 2008) • Identification of environmental hotspots along the life cycle of a specific substance (OECD, 2008) • Support of material specific decision making and management (OECD, 2008)
Input data	Substance flows (inflows, outflows and stocks) on a given area over a given time (generally one year) (Loiseau et al., 2012)
Output data	The results are presented as a set of flows and stocks (Loiseau et al., 2012)
Indicator; Method gives indication of	• Indicators available to show which processes are associated with the highest losses of hazardous substances to the environment (when the flow of the critical substance is the indicator) (OECD, 2008) • Indicators to estimate the impacts of flows on the environment in a broad sense (damages to ecosystems, human health, or a loss of functions) (Loiseau et al., 2012) • "Environmental efficiency, environmental load, environmental pressure, pollutant emission ratio, recovery ratio of waste, disposal ratio of dangerous waste, annual scrap generation, pollutant emission and waste generation, CO2 emission, etc." (Huang et al., 2012 p. 107)
Application examples & recommendations	**Studies at national level:** Sweden: studies of metal flows in the Stockholm area; United States: study of substance flows in the New York/New Jersey harbor (OECD, 2008) **Can be applied for:** Chemicals control; Risk assessments; Hazardous waste management; for pollution prevention, pollution control policies, the control of toxic substances and chemicals management (OECD, 2008) **Studies available in the field of**: • Metallic or Biogenic elements; element compounds; toxic and harmful substances etc. (Huang et al., 2012) • Industrial processes (Antikainen et al., 2004, as cited in Herva et al., 2011) • Waste management (Brunner and Ma, 2008, as cited in Herva et al., 2011).
Strength of the method	• Very high level of detail (OECD, 2008) • Give relevant information of the relative magnitude of pollution and can reveal unsuspected losses (Loiseau et al., 2012)
Drawbacks & criticism of the method	• High compilation effort (OECD, 2008) • Indirect and unused flows are not taken into account (OECD, 2008) • Compilation is labor intensive (OECD, 2008) • No standard SFA methodology in place, although several propositions have been put forward. (Loiseau et al., 2012) • Focuses only on a single substance. Therefore the substitution with another substance could lead to burden shifting, as that substance is out of the scope of the study (Loiseau et al., 2012) • Method cannot distinguish different forms of the same substance (gas, liquid etc.) (Loiseau et al., 2012)
Nature of the analysis	Quantitative (OECD, 2008)

3.4.2 MATERIAL SYSTEM ANALYSIS (MSA)

Material System Analysis (MSA): "[…] based on material specific flow accounts. It focuses on selected raw materials or semi-finished goods at various levels of detail and application (e.g. cement, paper, iron and steel, copper, plastics, timber, water) and considers life-cycle-wide inputs and outputs. It applies to materials that raise particular concerns as to the sustainability of their use, the security of their supply to the economy, and/or the environmental consequences of their production and consumption." (OECD, 2008, p. 12). The MSA is based on the mass balance principle (see (1)) as well (OECD, 2008). Information regarding the remaining areas of interest can be found in Table 5.

Table 5 In-depth analysis of Material System Analysis (own source)

Area of interest	Findings from the literature
The objective/ aim of the method	• Analyze the magnitude of given material flows, their economic and environmental consequences (OECD, 2008) • Detection of supply problems (OECD, 2008) • Point at emissions and waste associated with material usage and the related environmental burden (OECD, 2008) • Reveal recycling potentials (OECD, 2008)
Input data	• Input flows; Output flows; Stocks • A map of the material flows through the economy (as raw materials or as parts of basic materials, components or products). Including: entries into the economy (extraction and import); movements through the economy (production, consumption, export); additions to stock; and end of life (BIO by Deloitte , 2015) • Additional information related to: security of supply (governance risk supply, country concentration…); substitutes; future supply and demand changes of materials (BIO by Deloitte , 2015)
Output data	• Map of material flows • physical flows and stocks along the life cycle of the material (European Commission, 2023)
Indicator; Method gives indication of	Indicators to show, which processes from extraction to final disposal are associated with the highest waste and pollutant releases to the environment and the highest resource inputs (OECD, 2008) **Indicators derived from the method:** • "Environmental efficiency, environmental load, environmental pressure, pollutant emission ratio, recovery ratio of waste, disposal ratio of dangerous waste, annual scrap generation, pollutant emission and waste generation, CO2 emission, etc." (Huang et al., 2012, p. 107) • End-of-Life Recycling Rate (EoL-RR): how much of the collected old scrap is functionally recycled (Godoy León et al., 2022) • Recycling Process Efficiency Rate: overall recycling efficiency rate (Godoy León et al., 2022) • Self-Sufficiency Potential: the amount of material entering the use phase which comes from domestic production (Godoy León et al., 2022) • Pre-Consumer Loss Rate: the losses occurring before the use phase (Godoy León et al., 2022) • Total Scrap Recycling Input Rate: how much of the processing and manufacturing inputs come from domestic and imported scrap (Godoy León et al., 2022) • Old Scrap Ratio: the fraction of old scrap in the recycling flow (new and old scrap) (Godoy León et al., 2022)

Area of interest	**Findings from the literature**
Application examples & recommendations	**Example:** MFA study in the automobile and in other industries (iron & steel, cement, chemicals, paper, construction, home appliances) in Japan (OECD, 2008) **Recommended to be used for:** Natural resource management (mineral systems, energy systems); Sustainable materials management; Waste management; Resource conservation; Recycling markets; Trade and supply security; Integrated Pollution Prevention and Control (OECD, 2008) Material Flow Analysis of Aluminum, Copper, and Iron in the EU-28 (Passarini et al., 2018) **Study areas:** Biogenic or metallic mixtures, water, food, fuels, paper, plastic, chemical products, industrial products, agricultural materials, building materials (cement, etc.), discarded electronic motor products, total material flow through transport systems or economic or environmental systems of city, region or nation, etc. (Huang et al., 2012)
Strength of the method	• Can support many different approaches (Fischer-Kowalski et al., 2011) • High level of detail (OECD, 2008)
Drawbacks & criticism of the method	• No direct recommendation is given at the end (Fischer-Kowalski et al., 2011) • The inputs of ecological services are ignored (Hau & Bakshi, 2004b) • Compilation effort is medium to high (OECD, 2008) • Methodology is not standardized (OECD, 2008) • "[…] very little data directly usable for the MSA was available and it was often necessary to fill the data gaps by making extrapolations or assumptions based on the limited data available" (BIO by Deloitte , 2015, p.32) • "In addition, the development of a MSA requires that the input and output flows of each life cycle step balance exactly. In order to present consistent results in terms of mass balance, it was necessary to make some adjustments to the values obtained from the different available data sources, each being independent of each other" (BIO by Deloitte , 2015, p.32)
Nature of the analysis	Quantitative

3.4.3 LIFE CYCLE ASSESSMENT (LCA)

Life Cycle Assessments (LCA): “[…] are based on life cycle inventories. They focus on materials connected to the production and use of specific products (e.g. batteries, cars, computers, textiles), and analyses the material requirements and potential environmental pressures along the full life cycle of the products.” (OECD, 2008, p.12). Although LCA belongs to the group of material flow accounting (together with SFA and MSA), it is not based on the mass balance principle, according to the OECD (OECD, 2008).

The method is standardized by the International Organization for Standardization (ISO) described it in the ISO 140400 and ISO 14044. Recently, the improvement and harmonization of the LCA methodology has been taken a step further. The European Commission proposed the Product and Organization Environmental Footprint methodology. Still following the standardized LCA framework, this updated methodology should provide more robustness, reproducibility, consistency, and comparability within the assessment (European Commission - Joint Research Centre, 2021). Even though the Product Environmental Footprint (PEF) method is still in a transition phase (European Commission, n.d.), the European Commission recommends using the already developed parts of the new methodology (European Commission, 2021). Due to this fact and as it is adoption in the case company, PEF method will be used as the applicable standard within this study.

Further information about the Life Cycle Assessment is provided in Table 6.

Table 6 In-depth analysis of Life Cycle Assessment (own source)

Area of interest	**Findings from the literature**
The objective/ aim of the method	• Identification of material requirements (OECD, 2008) • Identification of potential environmental pressures (OECD, 2008) • To compare different options (Simonen, 2014) • Understanding of environmental impacts along the entire life cycle and throughout the supply chain (Simonen, 2014) • Helps to understand improvement opportunities and trade-offs (Simonen, 2014) • Identification of hotspots (Čuček et al., 2015), where the environmental impacts are the highest (Roy et al., 2009) **Industry objectives** (Owsianiaket al., 2018): • To support decision making in product and process development • For marketing purposes • To develop and select indicators used to monitor environmental performance (of plants or products) • To select suppliers or subcontractors (Owsianiaket al., 2018; Čuček et al., 2015) • For strategic planning
Input data	All in- and outputs (quantified) related to the life cycle of the product (materials, energy, water, waste, emissions etc.)

Output data	• A set of conclusions and recommendations (UNEP, 2012)
	• A single overall PEF score for:
	  ○ The total life cycle (Zampori & Pant, 2019).
	  ○ (ii) The total life cycle excluding the use stage (Zampori & Pant, 2019).

Indicator; Method gives indication of	• Impact category (respective indicator) according to PEF method (Zamboni & Pant, 2019): Climate change (Radiative forcing); Ozone Depletion Potential (ODP); Land use (Soil quality index; Biotic production; Erosion resistance; Mechanical filtration; Groundwater replenishment); Eutrophication terrestrial; (Accumulated Exceedance); Eutrophication, freshwater (Fraction of nutrients reaching freshwater end compartment); Eutrophication, marine (Fraction of nutrients reaching marine end compartment); Photochemical ozone formation human health (Tropospheric ozone concentration increase); Ionizing radiation, human health (Human exposure efficiency relative to U235); acidification (Accumulated Exceedance); Human toxicity, cancer (Comparative Toxic Unit for humans); Human toxicity, non-cancer (Comparative Toxic Unit for humans); ecotoxicity, freshwater (Comparative Toxic Unit for ecosystems); Water use (User deprivation potential); Particulate matter (Impact on human health); Resource use, minerals and metals (Abiotic resource depletion); Resource use, fossils (Abiotic resource depletion – fossil fuels) • Carbon footprint, (Fang et al., 2014; Matuštík & Kocí, 2021); Ecological footprint, (Fang et al., 2014); Water footprint (Fang et al., 2014; Matuštík & Kocí, 2021); Land footprint (Matuštík & Kocí, 2021)
Application examples & recommendations	• Integrated product management and control (OECD, 2008) • Product design (OECD, 2008) • Integrated Pollution Prevention and Control (OECD, 2008) • Government purchasing (OECD, 2008) • Applied for policy cycle (for policy formulation; supporting the implementation of information based instruments; for policy evaluation) (Owsianiak et al., 2018) • Assessment of: Energy systems- Electro mobility- Buildings and Build environment- Food and agriculture- biofuels and biomaterials- Chemicals and Chemical Products- Nanomaterial- Drinking

Area of interest	**Findings from the literature**
	water supply - Wastewater treatments - Solid waste management systems- Soil and groundwater remediation (Hauschild et al., 2018)
Strength of the method	• Most detailed environmental impact assessment (Schöggl et al., 2017) • Several international Standards, practices, tools, and software available (Murthy, 2022) • High level of detail (OECD, 2008) • LCA quantifies the environmental efficiency (impact per functional unit) and not only the burdens (Loiseau et al., 2012) • Prevents burden shifting (“life cycle thinking” approach that can be used to avoid burden shifting between two life cycle stages or two regions. In addition, the multi-criteria approach avoids the shifting of environmental burdens between environmental impact categories) (Loiseau et al., 2012; Čuček et al., 2015) • Quantitative results prevent green washing (Simonen, 2014) • Gives a more complete understanding of environmental impacts (Simonen, 2014) • Exhaustive analysis (Herva et al., 2011) • Takes different perspectives and consequences of material consumption into consideration (Herva et al., 2011)
Drawbacks & criticism of the method	• Does not provide any information about the cost/economic performance or the risk associated with the process/product. (Murthy, 2022) • Information demand too high (Schöggl et al., 2017) • Not applicable in early design phase (Schöggl et al., 2017) • High compilation effort (OECD, 2008) • Costly (money, time, and resources) (Čuček et al., 2015) • Mainly executed by the environmental specialist rather than the designer. (Kishita et al., 2010) • Time consuming (Simonen, 2014; Kishita et al., 2010) • Incomplete (local measures hard to quantify with existing method) (Simonen, 2014) • Requires judgment (on what to include or not; on how to interpret the outcome) (Simonen, 2014) • Uncertainty is high, due to forecast thinking (use case etc.) Natural disasters or assumption changes can create a very high impact (Simonen, 2014) • Quality and availability of data (uncertainty) (Čuček et al., 2015) • Base assumptions and system boundaries (Čuček et al., 2015) • Model of the process is needed (Čuček et al., 2015) • Quantification and normalization (Čuček et al., 2015) can lead to subjectivity • Health and safety issues are difficult to assess (Čuček et al., 2015) • Different studies analyzing the same products may generate very different results (Čuček et al., 2015) • In many cases there are several simplifications, because no detailed data are available (Čuček et al., 2015) • LCA only assesses potential impacts and not real impacts (Čuček et al., 2015) • Extensive databases required (Herva et al., 2011) • More difficult to interpret (Herva et al., 2011) • Complex and less intuitive (Herva et al., 2011)
Nature of the analysis	Quantitative (Schöggl et al., 2017)

Material Intensity

The methods grouped under the category of material intensity take material flows into consideration as well. In contrast to the method described above, their focus is mainly on the material input. They were developed and used as an indicator of resource utilization (Aoe & Michiyasu, 2005). The methods of Ecological Rucksack and MIPS are closely linked with each other and are often referred to as one method. This study makes a distinction between these methods, which are referred to as two individual methods belonging to the same overall concept.

3.4.4 ECOLOGICAL RUCKSACK

Ecological rucksack: It refers to the total material flow generated by a product along its life cycle extra to the product itself (Aoe & Michiyasu, 2005). This means all material resources moved from the environment for the production of the product, including hidden or invisible flows and material flows needed for energy production (Cahyandito, 2002; Aoe & Michiyasu, 2005). Hidden or also called indirect flows can be described as materials moved from the environment that, however, do not directly enter the production process of the product or trade (Daozhong et al., 2011). The ecological rucksack is referred to as: “[…] the life-cycle-wide material input minus the mass of the product itself” (Schmidt-Bleek, 2001; Spangenbergh, 2002, as cited by Herva et al. 2011, p. 1690). Overall the ecological rucksack of a product is often much heavier than the product itself (Cahyandito, 2002). The ecological rucksack is calculated as follows (Aoe & Michiyasu, 2005):

$$\text{Ecological rucksack} = \text{MI (Total Material Requirement)} - \text{Net weight (of the product)} \qquad (2)$$

Table 7 In-depth analysis of Ecological rucksack (own source)

Area of interest	Findings from the literature
Objective/ aim of the method	• Identification of resource utilization • Identification of invisible or hidden material flow. (Cahyandito, 2002)
Input data	Material inputs of all the substances involved (including direct and indirect use of material) (Daozhong et al. 2011) All materials moved from the environment (quantified); Amount of "final" material (quantified) (Cahyandito, 2002) Product mass
Output data	Ratio (Material / Rucksack): Indirect/ hidden material flow required to produce the product Identification of social hotspots (UNEP, 2012)
Indicator; Method gives indication of	• "Ecological burden indicators are widely used to study the metabolic characteristics of social - economic system, the ecological burden of human consumption and the impact on the ecology, quantitative ecological pressure" (Daozhong et al. 2011, p. 1117) • Material footprint is a newer term for "ecological rucksacks" (Giljum et al., 2013a, as cited in Čuček et al., 2015, p.173) • Resource utilization (Aoe and Michiyasu, 2005)
Application	*No concrete application examples and/or recommendations found*
Strength of the method	• It enables to measure trade-offs between environmental input categories (Burger et al., 2009) • The Ecological Rucksack provides an opportunity to identify resource utilization, including the invisible or hidden material flow. (Aoe & Michiyasu, 2005) • Database available and updated frequently (Liedtke et al., 2014)
Drawbacks/ criticism of the method	• Land use perspective is not taken into account (Burger et al., 2009) • Some people criticize that MI can only assess material flow and not the quality of flow. (Aoe & Michiyasu, 2005)
Nature of the analysis	Quantitative

3.4.5 MATERIAL INPUT PER UNIT OF SERVICE (MIPS)

Material Input per Unit of Service (MIPS): Measurement of natural resource use (material and energy intensity) along the entire life cycle of processes, products, services, technologies, and infrastructure (Liedtke et al., 2014; Cahyandito, 2002). In contrast to the ecological rucksack, the MIPS quantifies the material consumption per functional unit or service (Aoe & Michiyasu, 2005). It can be used to calculate resource utilization (meaning how productive we set ecological resources in), to measure the environmental performance of a business activity and to calculate the material footprint of an economic activity in consumption and production (Cahyandito, 2002; Liedtke et al., 2014). According to Aoe and Michiyasu, the MIPS is calculated as follows:

$$\text{MIPS} = \text{Material Input Per Service unit} = \frac{\text{MI}}{\text{S}} = \text{total material input (MI) divided by the service unit (S)} \quad (3)$$

Table 8 In-depth analysis of Material Input per Unit of Service (own source)

Area of interest	Findings from the literature
The objective/ aim of the method	• Identification of resource utilization (how productive ecological resources are set in) (Cahyandito, 2002) • To assess the efficiency (to produce better with less resource and energy input) (Liedtke et al., 2014) • Assessment of consistency to produce differently with change composition or quality of resource and energy input) (Liedtke et al., 2014). • To assess the sufficiency (producing and consuming less to enhance welfare with decreasing resource demand) (Liedtke et al., 2014). • Functions as a benchmark to: achieve a certain result with a minimum input (dematerialization) and/or to reach a maximum result with a certain input (resource productivity). (Cahyandito, 2002)
Input data	• List of all materials that are set to production process (Cahyandito, 2002) • All core and by- product produced, including waste materials and emissions. (Cahyandito, 2002) • Specification of all material inputs (quantification) into kg/ ton or kWh or MWh or MJ (Cahyandito, 2002)
Output data	MIPS value: ”The higher the value of MIPS, the worse the ecological quality” (Cahyandito, 2002, p.5)
Indicator; Method gives indication of	• Resource utilization (Aoe and Michiyasu, 2005) • Material footprint (Liedtke et al., 2014) • Water backpack (Liedtke et al., 2014) • Air backpack (Liedtke et al., 2014) • Material footprint abiotic + biotic (Liedtke et al., 2014) • Material footprint abiotic + biotic + erosion + mechanical earth movement (Liedtke et al., 2014) • Efficiency indicators (Liedtke et al., 2014): o Used/ unused resources: proportion of used and unused resources o Unused resources/profit & Used resources/profit: proportion of unused (or used) resources to profit • Consistency indicators (Liedtke et al., 2014): o Unused/product weight & MI/product weight: assessment of recycling strategies o Unused resources / production costs: Assessment of recycling strategies, closed loops & costs of unused resources • Sufficiency indicators (Liedtke et al., 2014): o Material Input (MI) individual resource use/resource target: Assessment of current resource use against resource targets o MI/time: Deceleration/slowdown in different areas of need/activity fields o MI/S: Resource input per service aiming at high service and low material input o MI/land use of activities: Land use of activities, e.g. specific inventories of products, materials, raw materials
Application examples & recommendations	• The MIPS Concept helps in the design of industrial products, in the planning of environment-friendly processes, facilities and infrastructures, as well as in the ecological assessment of services. (Cahyandito, 2002) Application examples and recommendations (Liedtke et al., 2014): • Material input of a single processes up to life cycle phase (e.g., extraction, production, use, recycling), Research and Development (R&D) of processes • MI Value chain: comparison of value chains and life cycle phases, material selection/design, R&D of technologies/products (including development, prototyping, testing, roll out), R&D of services

Area of interest	Findings from the literature
	• MI Products & services: comparison of products & service bundles • MI Critical resources: Share of critical resources in total MI, integration of material input into assessment of critical resources • MI of process costs or production costs: at process level: identification of high ecological and economic "cost drivers"; comparison of similar processes within branch; at product level: time series, knowledge base for product portfolio management • MI resource accounting: Resource cost accounting, direct material (costs), costs for processing/disposal burden/overhead materials • MI Price: Method and indicator base for calculation of "ecological appropriate prices" • MI Input per Output: Resource productivity of households, companies and sites
Strength of the method	• Material and energy expenditures are measured in the same units (Cahyandito, 2002) • Can serve as the basis for a comprehensive ecological labelling strategy (Cahyandito, 2002) • Database available and updated frequently (Liedtke et al., 2014) • MIPS is a practical solution to reduce the complexity and the uncertainty of assessments such as the LCA (Liedtke et al., 2014)
Drawbacks & criticism of the method	• Concept does not take into account the specific "surface-use" (Cahyandito, 2002) • Makes no direct reference to questions of biodiversity. (Cahyandito, 2002) • Concept does not take into account the specific environmental toxicity of material flows. (Cahyandito, 2002) • MIPS is not developed to quantify specific outputs (e.g., emissions of specific toxic substances) and assess their impacts (e.g. GHG) (Liedtke et al., 2014) • The MIPS concept has not been considered within LCA databases. (Wiesen et al., 2014). Less data available in databases than for LCA • Some people criticize that MI can only assess material flow and not the quality of flow (Aoe & Michiyasu, 2005) • Uncommon metric at corporate level (Herva et al., 2011) • Little information regarding computation (Herva et al., 2011)
Nature of the analysis	Quantitative

3.4.6 ENERGY ANALYSIS

Energy Analysis: Used to determine the energy required to produce services and goods (Nilsson, 1997). This refers to the direct and indirect energy demand along the life cycle of a product (Herva et al., 2011). It can be used to investigate energy cost reduction potentials (Nilsson, 1997). According to Chapman and Roberts, different methods (process, statistical, and input-output analyses) are available to conduct an energy analysis (Chapman and Roberts, 1983, as cited in Hovelius, 1997). Within this study, the general concept of energy analysis is considered, although the process analysis seems to be the most fitting one for the study scope. The process analysis can be "[…] used to estimate the energy requirements for production of goods and services, and to investigate the potentials to reduce energy costs" (Nilsson, 1997, p.46). Further information regarding the energy analysis can be found in Table 9.

Table 9 In-depth analysis of Energy analysis (own source)

Area of interest	Findings from the literature
The objective/ aim of the method	• Determine the energy required for the production of services and goods (Nilsson, 1997) • Investigation of the potentials to reduce energy costs. (Nilsson, 1997) • Determine energy losses (Erzen et al., 2022) • To evaluate the use of non-renewable and scarce natural resources in different production systems. (Nilsson, 1997)
Input data	• All goods and services directly required to produce the product (direct energy (fuels) as well as non-energy inputs) (Bullard et al., 1978) • Energy and non-energy inputs required to produce the non-energy inputs --> tracing back from target product through each production process (Bullard et al., 1978) • Energy inputs & energy outputs (Ojeda et al., 2020) of the system • A thermodynamic model of the system should be carried out (Hosseini et al., 2022
Output data	Energy efficiencies (Ojeda et al., 2020)
Indicator; Method gives indication of	• Resource consumption (Liao et al., 2011): 1. Direct Energy Demand (DED): Total energy of the direct inputs (primary energy resources and energy products) to the foreground production processes 2. Cumulative energy demand (CED): Total energy of the used primary resources (includes the indirect energy inputs as well) • Input renewability (Liao et al., 2011) • Physical profit (Liao et al., 2011) • System efficiency (& intensity) (Liao et al., 2011) • Net Energy Value (NEV) (Liao et al., 2011)
Application examples & recommendations	• Evaluation of energy conversion systems (Erzen et al., 2022) • Can be used as a screening indicator (Herva et al., 2011)
Strength of the method	• Interesting information on the energy use efficiency can be provided (Herva et al., 2011)
Drawbacks & criticism of the method	• Only takes energy into consideration as a measure for resource use and sustainability (Nilsson, 1997) • Energy is not an unambiguous concept in the sense that different energy forms can be totaled. (Nilsson, 1997) • The applicability may be limited by lacking data and due to the involvement of complicated processes or by-products.(Nilsson, 1997) • Difficult or even impossible to consider certain aspects (like toxicity, eutrophication, acidification and ozone depletion) (Nilsson, 1997) • Takes only the amount of energy utilized into account --> is not enough for analyzing an energy conversion system without exergy (Erzen et al., 2022) • Fails to explicate the environmental impact which can be derived from energy consumption (depletion of abiotic resources, land use, ozone depletion, global warming, toxicity, acidification, eutrophication, etc.) (Herva et al., 2011)
Nature of the analysis	Quantitative

3.4.7 EXERGY ANALYSIS

Exergy Analysis: Measurement of quantity and quality of the energy source (Hovelius, 1997, as cited in Herva et al., 2011). The concept of exergy is based on the second law of thermodynamics (Nilsson, 1997). Exergy can be understood as "[…] that part of energy that is convertible into all other forms of energy" (Beahr, as cited in Nilsson, 1997, p. 66). Another definition is: "[...] useful energy, i.e. that part of the energy that can be used as an energy source. Exergy is the maximum amount of work (mechanical energy) that can be obtained from a system in a process leading to the system reaching equilibrium with its surroundings." (Hovelius et al., 1997, p.9). The exergy analysis can be used to improve the efficiency of energy use by quantifying and locating losses of energy quality within a process (Nilsson, 1997). By identifying the causes, locations, and quantity of inefficiencies of a process, the analysis helps to determine more sustainable technologies (Rosen et al., 2008, as cited in Herva et al., 2011). Additionally, it enables the evaluation of the effectiveness of energy use (Kharrazi et al., 2014). Information regarding the remaining areas of interest can be found in Table 10.

Table 10 In-depth analysis of Exergy analysis (own source)

Area of interest	Findings from the literature
The objective/ aim of the method	• Evaluation of the effectiveness of the energy usage (Kharraziet al., 2014) • To improve process efficiency (Hau & Bakshi, 2004b), by identifying the causes, magnitudes and locations of inefficiencies (Rosen et al., 2008, as cited in Herva et al., 2011) • To quantify and locate losses of energy quality within a process (Nilsson, 1997) • To identify the lowest energy performance, irreversibility, and environmental impacts (Ojeda et al., 2020) • To evaluate the use of non-renewable and scarce natural resources in different production systems. (Nilsson, 1997) • Measurement of the optimal use of energy in processes (or buildings) (Herva et al., 2011) • “Exergy analysis is applied at different scales to identify technical improvements or protection measures which should be implemented in order to improve energy performance and to maintain resource availability.” (Loiseau et al., 2012, p. 218)
Input data	Exergy inputs, exergy outputs, exergy consumption (Ojeda et al., 2020)
Output data	Exergy efficiencies (Ojeda et al., 2020) Efficiencies associated to each process step (Ojeda and Kafarov, 2009, as cited in Ojeda et al., 2020)).
Indicator; Method gives indication of	• Exergy efficiency (Exergy return/ Exergy input) (Farajzadeh et al., 2022) ○ Resource consumption (Liao et al., 2011): ○ Direct Exergy Demand (DExD): Total exergy of the direct inputs ○ Cumulative Exergy Demand (CExD): Total exergy of the used primary resources • Input renewability (Liao et al., 2011) • Physical profit (Liao et al., 2011) • System efficiency (Liao et al., 2011) • Ecological Footprint (Fang et al., 2014) • Functions as a thermodynamically founded indicator (Herva et al., 2011) • Cumulative Exergy Consumption (CExC) (Liao et al., 2011) • Net Exergy Value (NExV) (Liao et al., 2011) • Exergy Efficiency (Energy outflow/ Exergy inflow) (Folayan et al., 2018) • Exergy Loss (Exergy inflow - Exergy outflow) (Folayan et al., 2018) • Exergetic Sustainability Index (ESI): "[…] the relationship between the input exergy and exergy losses of a system." (Folayan et al., 2018, p. 1792) • Exergy improvement potential (EIP) (Folayan et al., 2018)
Application examples & recommendations	• Has been used for a variety of processes such as milk processing, dimethyl ether production, ammonia production, and crude oil distillation (Ojeda et al., 2020) • Applied for: the environmental impact evaluation of industrial processes (Hau and Bakshi, 2004a; Zhu et al., 2005); to measure the optimal use of energy in processes (Banat and Jwaied, 2008) or in buildings (Torío et al., 2009); to measure water quality (Huang et al., 2007) or to assess the efficiency of resources use and losses of quality during recycling processes (Castro et al., 2007; Talens et al., 2008); to evaluate evaluating energy related techniques. (as cited in Herva et al., 2011) • Applied to a variety of chemical, thermo-mechanical, and other manufacturing processes (Dewulf et al., 2008), like: ○ Nonrenewable Energy Technologies, e.g. processes based on conventional coal combustion, gasification and chemical looping) (Dewulf et al., 2008)

Area of interest	Findings from the literature
	○ Renewable Energy Technologies, e.g. for solar thermal, wind, and geothermal power generation systems (like photovoltaic cells) (Dewulf et al., 2008) ○ Commodity Chemicals, processes for producing bulk and commodity chemicals and to specific types of chemical technology (Dewulf et al., 2008) ○ Heating ventilation and air conditioning processes (Dewulf et al., 2008)
Strength of the method	• Possible to find the standard exergy of many compounds in literature (Ojeda et al., 2020) • Compared to Energy analysis it is a better measure of the quality of energy, due to the representation of a systems real potential to do work (Hau & Bakshi, 2004b) • Has the potential to provide a reliable understanding of the efficiency, productivity and sustainability of energy systems, as the irreversibility of the energy system is taken into account as well. (Hosseini et al., 2022; Hau & Bakshi, 2004b)
Drawbacks & criticism of the method	• Non-energetic flows cannot directly be incorporated (e.g. labor and flow of capital investment in an economic system) (Kharrazi et al., 2013; Hau & Bakshi, 2004b) • The scope is too narrow due to the focus on the process. The performance of the remaining production chain is ignored (Hau & Bakshi, 2004b) • Difficult or even impossible to consider certain aspects (like toxicity, eutrophication, acidification and ozone depletion) (Nilsson, 1997) can lead to an incorrectly quantification of environmental impacts (Ji et al., 2009, as cited in Loiseau et al., 2012) • Conclusions can be confusing if monetary and ecological constraints of the energy conversion process are not considered (Rosen, M. 2018, as cited in Hosseini et al., 2022). • Impact categories like biodiversity or land use ore not incorporated. (Loiseau et al., 2012) • Detailed knowledge of each individual operation unit is required (lack of readily available databases) (Herva et al., 2011) • Computation based on thermodynamics usually not intuitive for non-experts (Herva et al., 2011)
Nature of the analysis	Quantitative (Hau & Bakshi, 2004b)

3.4.8 EMERGY ANALYSIS

Emergy Analysis: Method to account for the natural capital required to deliver products and services (Kharrazi et al., 2014). According to Nilsson, emergy is the abbreviation of *energy memory* or *embodied energy* (Nilsson, 1997). The underlying concept is transformity, which accounts for the required emergy per unit of service or product (Nilsson, 1997). The analysis determines the directly or indirectly used energy required to sustain ecological and industrial systems (Hau & Bakshi, 2004a). This energy is transformed into equivalents of (solar) energy (Hau & Bakshi, 2004a). “Emergy considers therefore the economic and ecological (including abiotic and biotic) aspects of a system by converting all inputs, flows, and outputs to a common unit seJ (solar equivalent Joule)” (Perez-Soba Aguilar et al., 2019, p. 6). Due to the conversion of all physical flows (materials, energy) to common units (solar emergy), a comparison of both economic and environmental products is permitted (UNEP, 2012a). Therefore, it is possible to measure all (solar) energy inputs used to create a product or service (Kharrazi et al., 2014). More information regarding the emergy analysis is provided in Table 11.

Table 11 In-depth analysis of Emergy analysis (own source)

Area of interest	Findings from the literature
The objective/ aim of the method	• To account for the natural capital required to deliver products and services (Kharrazi et al., 2014) • To determine the amount and evaluate the use of renewable and non-renewable resources (UNEP, 2012a; Nilsson, 1997) • Accounting of the contribution of ecological services and products to economic activity (Hau & Bakshi, 2004a)
Input data	• All physical flows (materials, energy) included (UNEP, 2012a) • "[…] energy systems diagrams are drawn that depict all the major types of natural resources (e.g. forests, wetlands, croplands), and economic activities (e.g. agricultural processing, manufacturing, mining)." "They include both environmental flows (e.g. rivers, solar energy, precipitation, forest harvesting) and economic flows (e.g. purchases of fuel, goods and services, and sale of natural resource products and manufactured goods)". (UNEP, 2012a, p. 12) • Data acquiring on annual flow rates and individual system components a in standard units (joules, grams) (UNEP, 2012a) • Conversion factors (Unit Emergy Values (UEV)) for the quantification of emergy in units of solar emjoules (UNEP, 2012a)
Output data	• The total emergy flow necessary for obtaining a product, incl. past and present costs to maintain that solar energy (Perez-Soba Aguilar et al., 2019) • Emergy flows expressed in monetary terms (via a simple imputation process), which can be used to aid in the communication of resource values (UNEP, 2012a) • The proportion of total use that comes from renewable sources as opposed to non-renewable sources (UNEP, 2012a) • Synthesis of all flows (in common units) (UNEP, 2012a)
Indicator; Method gives indication of	• Emergy Yield Ratio (EYR), (Wang et al., 2020) "which is the total emergy recovered by unit of emergy invested. The higher this ratio, the less the system relies on economic investments, and the greater its competitiveness" (Loiseau et al., 2012, Appendix A) • Environmental Loading Ratio (ELR), (Wang et al., 2020) "a high ELR value is symptomatic of a significant consumption of non-renewable resources in comparison with renewable resources and indicates overloaded environmental cycles" (Loiseau et al., 2012, Appendix A) • Emergy Sustainability Index (ESI), (Wang et al., 2020) "measures the potential contribution of a resource or process to the economy per unit of environmental loading" (Zhai et al., 2018 p. 235) • Emergy Investment Ratio (EIR), "a high EIR reveals the fragility of the system due to its dependence on other economic systems for its inputs" (Loiseau et al., 2012, Appendix A) • Emergy Flow Density (ED) "if this ratio is high, a significant level of emergy is used in this area, which may be indicative of a severe environmental stress and a potential lack of space (a limiting factor for future development)." (Loiseau et al., 2012, Appendix A) • Renewable Percentage (%Re) (Wang et al., 2020); Input renewability (Liao et al., 2011) • Energy Recovery Ratio (ERR) (Wang et al., 2020) • Emergy Benefit after Exchange (EBE) (Wang et al., 2020) • Net Profit (NP) (Wang et al., 2020) • (Empro): Total solar energy used for product or service (Liao et al., 2011) • System efficiency (Liao et al., 2011) • Emergy Footprint: emergy /global emergy density (Čuček et al., 2015) • Ecological Footprint (Fang et al., 2014)

Area of interest	Findings from the literature
Application examples & recommendations	• A variety of macroscopic systems, such as agricultural systems, industrial systems, urban systems (Wang et al., 2020; Perez-Soba Aguilar et al., 2019) • Food production, energy supply, ecosystem services, waste disposal Wang et al., 2020) • "electricity production systems (Brown and Ulgiati, 2002); comparison of horse and tractor traction (Rydberg and Jansén, 2002); evaluation of building materials (Pulselli et al., 2008) and their recycling options (Brown and Buranakarn, 2003); evaluation of a building (Meillaud et al., 2005); evaluation of eco-industrial park with power plant (Wang et al., 2005); production, processing and export of coffee (Cuadra and Rydberg, 2006); solar salt production process (Laganis and Debeljak, 2006); hydrogen production systems from biomass and natural gas (Feng et al., 2009)" (Herva et al., 2011, p. 1689-1690)
Strength of the method	• Enables a unification of various flows (Kharrazi et al., 2014). The common unit enables a fair comparison of all resources (Hau & Bakshi, 2004a) • Accounts for all possible inputs, which includes contributions of ecological products and services (Hau & Bakshi, 2004a) • Enables a valuation or quantification of ecosystem services and goods (Hau & Bakshi, 2004a); enables the objective valuation of non-market inputs (Hau & Bakshi, 2004a) • It is scientifically sound (Hau & Bakshi, 2004a) • Aggregation of energy and non-energy flows (like human labor, information or economic services) on a single unit (Ulgiati et al., 1994, as cited in Loiseau et al., 2012) • Enables simplifications and a comparison of energy and non-energy flows (Zhang et al., 2009, as cited in Loiseau et al., 2012) • Enables the clarification of the structure of the system under consideration as well as the environmental work provided (Nilsson, 1997) • Conversion coefficients (Unit Emergy Value (UEV)) are available for many products which eases the calculation of the emergy values (UNEP, 2012a) • More holistic assessment compared too many existing methods (like Exergy or LCA), as it takes the contribution of ecosystems to human wellbeing into account. (Bakshi, 2002, as cited in Hau & Bakshi, 2004a)
Drawbacks & criticism of the method	• May be difficult to interpret and highly dependent on the system under study (Kharrazi et al., 2014) • Fails to consider any limits to the minimization of emergy inflows and environmental stress (Kharrazi et al., 2014) • Complex methodology: has been found too difficult to compute in many cases (Kharrazi et al., 2014) • Method "[…] has been characterized as simplistic, contradictory, misleading, and inaccurate" (Hau & Bakshi, 2004a, p. 218) • "[…] ignores human preference and demand." (Hau & Bakshi, 2004a, p. 219) • "Details about the techniques for determining the emergy of various streams and in a network have been difficult to find. Consequently, emergy analysis is often misunderstood and has not been used outside a small group of researchers."(Hau and Bakshi, 2004b, p. 3769) • "[…] it is difficult or even impossible to consider, for example, toxicity, eutrophication, acidification and ozone depletion […]" (Nilsson, 1997, p. 72) • Not intuitive for enterprises (Herva et al., 2011) • Lack of readily available databases (Herva et al., 2011)
Nature of the analysis	Quantitative

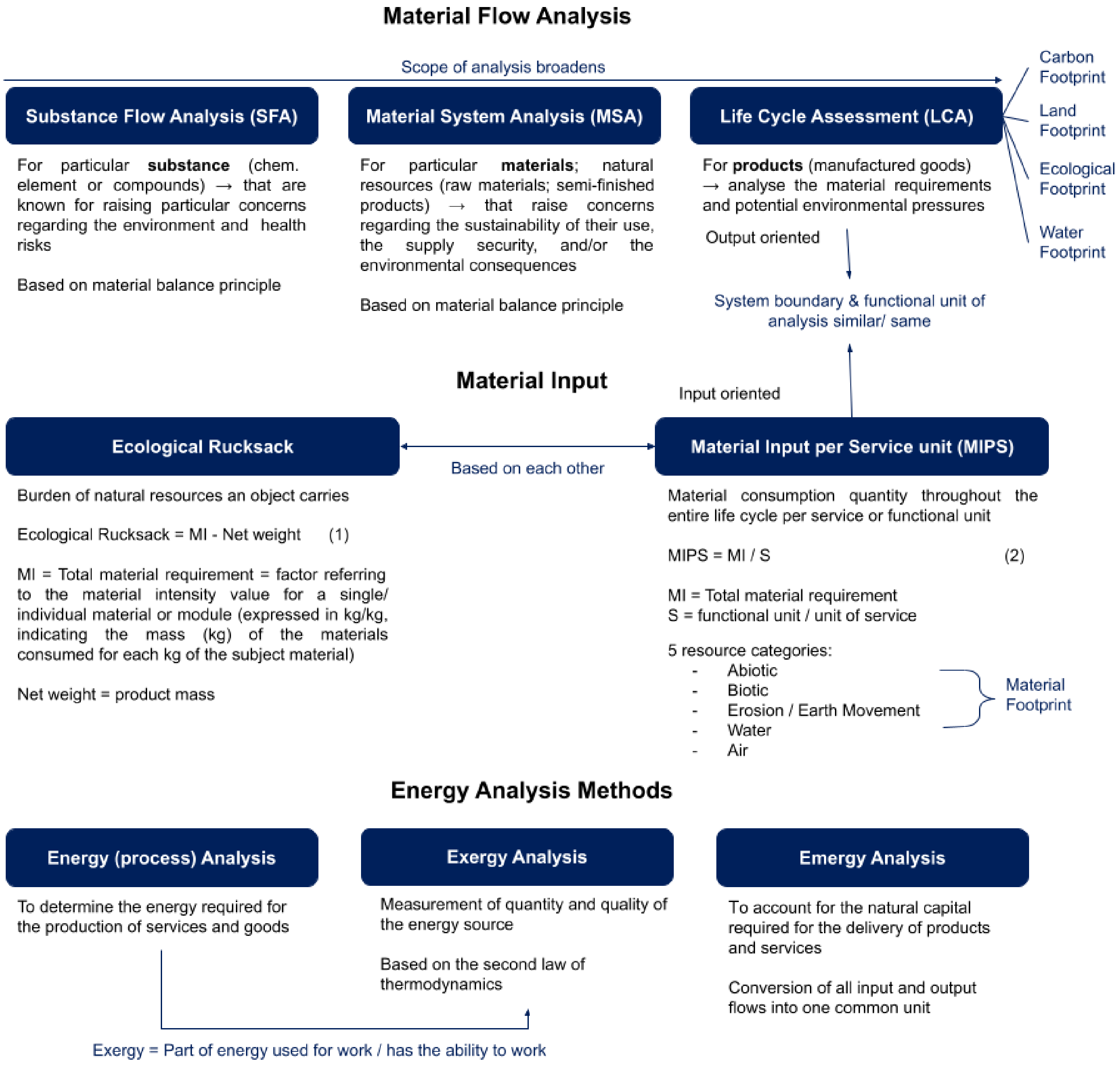
3.5 DECISION TREE/FLOW CHART

Within this chapter the collected data and methods are visualized. The visualization of data and information creates several benefits. First, the data is transferred into an easily understandable form (Deloitte, 2023). Additionally, significant values can be made clear and visible, making the data more attractive (Deloitte, 2023). To take advantage of these benefits, the in-depth analysis results are visualized in a condensed way. The aim is to ease the selection of the most appropriate environmental assessment method. It should be possible for non-experts to make this selection. Therefore, the goal is to provide enough information for founded decision-making, but in an easily and quickly understandable manner.

In the beginning, the most suitable visualization method needs to be determined. A decision tree is the first method that the researcher associates with visualization to achieve the goal of facilitating decision making. A decision tree is a sequential model which combines a sequence of tests logically and simply to classify things (Kotsiantis, 2013). Within each test, a standard attribute is compared to a set of possible values (Kotsiantis, 2013). Comparing and classifying objectives is possible, as they have different values for some attributes. By testing these values in sequential order, a classification can be achieved. Visualizing a decision tree is done in a hierarchical, tree-like structure. Due to the similarity of decision trees to flow chart diagrams, the shapes commonly used for flow charts can be utilized. However, the attributes and values need to be defined before the decision tree can be created.

As a preparation for the decision tree creation, an overview of the methods with a very short description of each is created. This should enable visualizing connections between the different methods at one glance. This overview can be seen in Figure 12. Based on the overview, the first attributes and values could be defined as follows: (**attribute**: values)

- **The scope or subject of the analysis**: A substance, a material, a product
- **The type of flows primarily considered:** Energy flows; material (resource) flows
- **The type of information which can be obtained from the study**: Quantitative, qualitative, etc.



For particular **substance** (chem. element or compounds) → that are known for raising particular concerns regarding the environment and health risks

Based on material balance principle

For particular **materials**; natural resources (raw materials; semi-finished products) → that raise concerns regarding the sustainability of their use, the supply security, and/or the environmental consequences

Based on material balance principle

For **products** (manufactured goods) → analyse the material requirements and potential environmental pressures

Burden of natural resources an object carries

Ecological Rucksack = MI - Net weight (1)

MI = Total material requirement = factor referring to the material intensity value for a single/ individual material or module (expressed in kg/kg, indicating the mass (kg) of the materials consumed for each kg of the subject material)

Net weight = product mass

Material consumption quantity throughout the entire life cycle per service or functional unit

MIPS = MI / S (2)

MI = Total material requirement
S = functional unit / unit of service

5 resource categories:
- Abiotic
- Biotic
- Erosion / Earth Movement
- Water
- Air

To determine the energy required for the production of services and goods

Measurement of quantity and quality of the energy source

Based on the second law of thermodynamics

To account for the natural capital required for the delivery of products and services

Conversion of all input and output flows into one common unit

Figure 12 Simplified overview of all selected methods (own source)

Based on the information gathered beforehand, the overview created in Figure 12, and the attributes identified, a first version of the decision tree is created. Common flowchart shapes are used to increase the understanding of the decision tree. A rounded rectangle or oval represents the start and end points. Decisions are based on a question and represented in a diamond shape. The first version of the flowchart can be found in Figure 40 in Appendix G – Decision tree version 1.

A feedback round is conducted to ensure the case company employees understand the decision tree. The first version of the decision tree is shown to one expert in the Research and Technology field of the case company. The following feedback is provided and implemented in a second version of the decision tree, which is shown in Figure 13:

- Change colors (the endpoints should be more visible than the questions)
- The attribute subject of the study should be earlier within the tree
- Definition boxes should be added at the bottom of the document

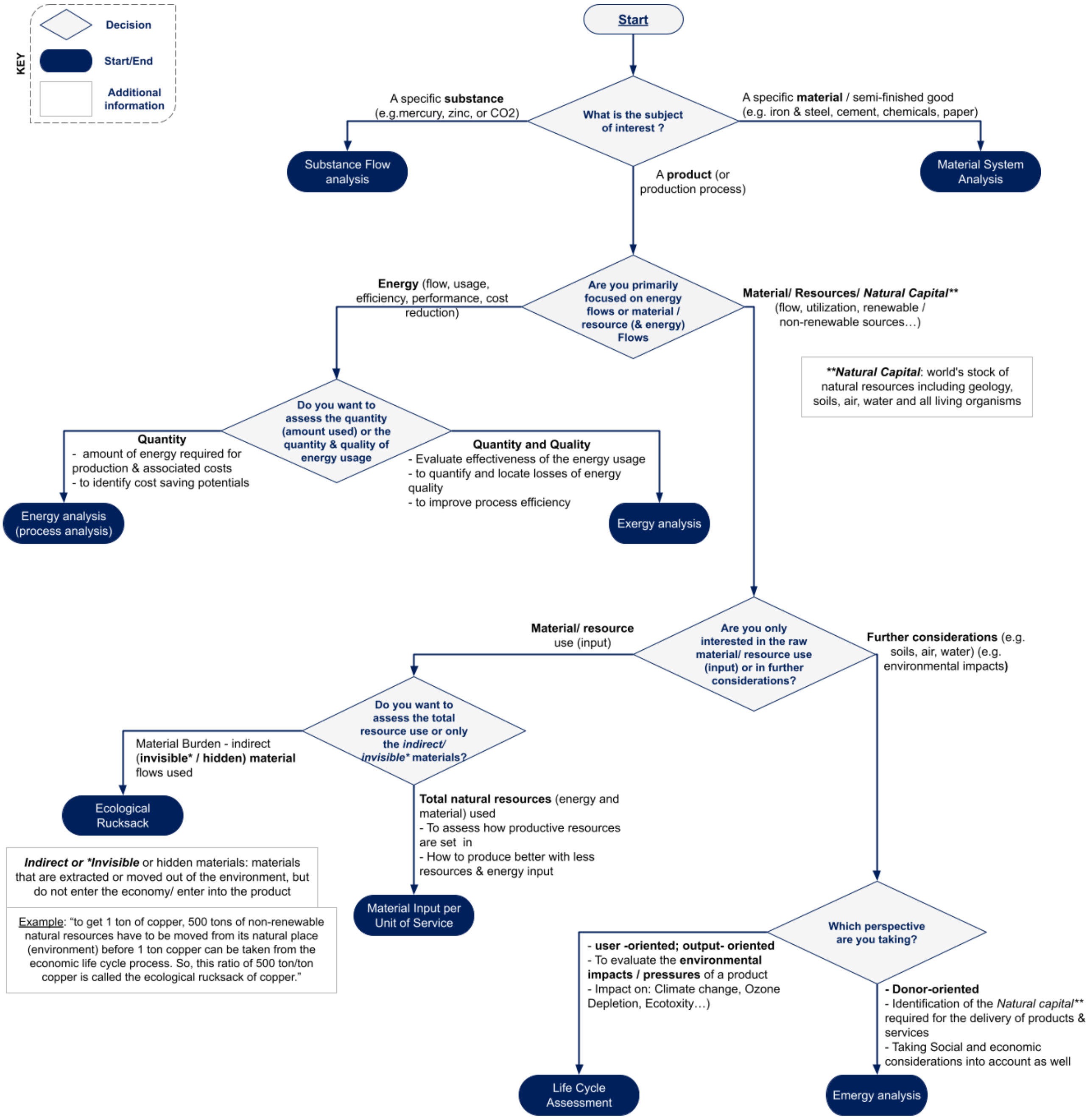


Figure 13 Decision tree for method selection (own source)

4 PHASE 3 - COMPARATIVE ANALYSIS OF METHODS

Within the chapter criteria are defined with which a qualitative comparision is developed and conducted. The criteria are selected based on the brainstorming session conducted in the phase 1 (chapter 2.1), as well as on literature. Each criterion is defined first and attributes defined. Based on the attribute a score is given from zero to three. The criterion and attributes are defined in a way, that zero always represents the least desirable option and three the most desirable option. Based on the defined criteria and points given, a total score can be calculated. Apart from the total score for all criteria, a total score for the ease of use and the completeness of the methods are developed. The total scores are used to compile a ranking of the different methods. Next to the ranking the results are presented in a visual way.

4.1 CRITERIA DEFINITION

Life cycle thinking

The first criterion concerns the boundaries of the assessment. To do so, life cycle thinking is defined as a criterion. Life cycle thinking aims for decision-making that considers the entire life cycle of a product, process, or system. This includes the material extraction from the earth, conversion of these materials into process materials, combining those to produce and assemble a product, supply, usage by the customer, and disposal at the end of life (UNEP, 2012b). Along this value chain, natural, energy, social and economic resources are used, and waste and related impacts (positive and negative) are created (UNEP, 2012b). Within each life cycle stage, there is the potential for performance improvement or resource reduction (Mazzi, 2020). The concept goes beyond the traditional industry focus, which is only concerned with the organization’s production facility (UNEP, 2012b). A way to distinguish the inclusion of life cycle stages is via the product life cycle models. Three models can be determined (see Hauschild et al. 2018):

1. Cradle-to-gate: Assessment of the life cycle from raw material extraction until the product leaves the factory (before it is transported to the consumer)
2. Cradle-to-grave: Inclusion of all life cycle stages, as explained by UNEP, 2012b (UNEP, 2012b)
3. Cradle-to-cradle: A variation of cradle-to-grave, which exchanges the disposal stage with a recycling process to enable reuse for another product.

These models and the general life cycle of a product are displayed in Figure 14.

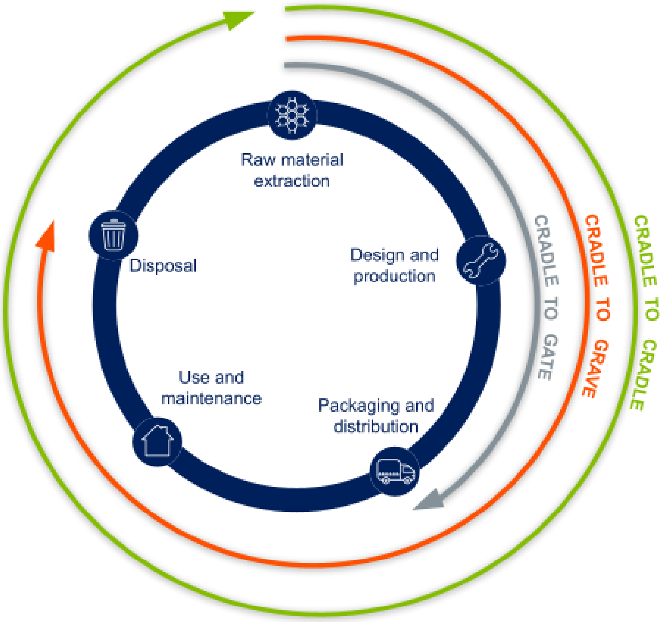


Figure 14 Product life cycle and models (adopted from UNEP, 2012b; Ecochain Technologies, 2021)

The benefit of considering the entire life cycle is the broadened perspective to identify the most significant impact reduction potential (UNEP, 2012b). It also prevents burden shifting to other life cycle stages, impact categories, regions, or social groups (UNEP, 2012b). Therefore, methods taking the entire life cycle perspective into account are preferred. The score for the life cycle thinking criterion is defined as follows:

0 - No life cycle thinking
1 - Only focused on a few life cycle stage
2 - Can take all into consideration, but highly depends on the scope, boundaries and method executer
3 - All life cycle stages (as described by UNEP, 2012b) need to be taken into account

At the beginning of each assessment the scope and boundaries of the system under study are defined. This influences the decision on which life cycle stages to include. Therefore, it is not straightforward to define the inclusion of the life cycle stages per method. Additionally, a mismatch between the method's strive to implement life cycle thinking into the assessment and the practical inclusion can be found (Loiseau et al., 2012). Ideally each method would need to be conducted for the same technology to better analyze the life cycle focus of each method. However, as this exceeds the scope of this study, the integration of the different life cycles into the method structure (e.g., via standards) is analyzed or different case studies found in the literature used.

Standardization

Within the standardization criterion, the stage of development of the method is evaluated. For this criterion, the availability of documents for achieving a common consensus on the method will be analyzed. While some methods have rules and guidance, others are already standardized. According to the international organization for standardization, the implementation of management system standards (like the environmental management ISO14000 series) increases the" […] capability to deliver consistent and improved services and products, thereby increasing value to customers and all other stakeholders" (International Organization for Standardization, n.d.). Furthermore, they lead to the specification of repeatable steps enabling performance improvement (International Organization for Standardization, n.d.). International experts also agree on standards, which achieves a consensus among them (International Organization for Standardization, n.d.). Therefore, it can be concluded that high standardization enables a structured and repeatable application of the methods and improves the comparability of the results. Furthermore, high standardization can be seen as an indication of expert acceptance.

This study defines standards as the highest type of standardization and the most desirable attribute.

As an evaluation criterion, the following is defined:

- 0 - No standardization at all
- 1 - Availability of some guidance documents (books or scientific papers)
- 2 - Availability of widely agreed upon rules or a handbook, preferably published by an official organization or the methods founder
- 3 - Defined standards are in place

Inventory flows

The scope and boundaries of each method differ and, therefore, the assessment's coverage. It is possible to distinguish the inventory flows that each method includes. According to Loiseau et al., these flows can be differentiated based on their nature (Loiseau et al., 2012). Two different types of flows are proposed:

1. The consumption of resources (inflows) (Loiseau et al., 2012)
2. Pollutant emissions (outflows) (Loiseau et al., 2012)

The two types of flows are considered as an individual criteria and individually evaluated. Overall, the inclusion of more flows (in- and outflows) is defined as more desirable. The underlying assumption is that the more flows are included, the broader the sustainability assessment. Due to the extended scope and boundaries, burden shifting should be prevented, as well as a more holistic sustainability assessment should be achieved.

The consumption of resources (inflows)

Several types of resource inputs can be accounted for by the methods. The ones mentioned most often are non-renewable (fossil) and renewable resources. Another type of resources frequently mentioned within the literature are the natural resources: land, water and air. As described above the more flows included the better. This leads to the definition of the criterion as follows:

0 - No inflows accounted
1 - One or two inflows included
2 - Three or four inflows included
3 - All five inflows included

Pollutant emissions (outflows)

According to Loiseau et al., the emissions of pollutants are defined as including soil, water and air emissions (Loiseau et al., 2012). Waste is excluded and not considered as an emission by them (Loiseau et al., 2012). The same approach is chosen for this study. The criterion is defined as follows:

0 - No outflows accounted
1 - One outflows included
2 - Two outflows considered
3 - All three outflows included

Flows exceeding the environmental pillar

During the in-depth analysis of the methods it became evident that some methods exceed the environmental pillar. Some of them take economic flows into consideration (like services or in- and export). Other methods take social flows into account (like labor). Although the scope of the study is reduced to the environmental pillar, the additionally coverage of some methods is included as well. There are several reasons for that: First, the initial goal the study was to enable a holistic assessment of technology, taking all three pillars of sustainability into account. By highlighting methods which go beyond one pillar, the potential of these method for a holistic assessment is indicated. These can be used as a starting point for further studies to achieve a holistic assessment. Second, a more holistic assessment decreases the risk of burden shifting. Hence, the inclusion of one or more flows belonging to the other pillars is preferred. For this reason the criterion is defined as follows:

0 - Only environmental pillar and flows
1 - Environmental and one additional (economic or social)
2 - Flows of all three pillars are included

Ease of use

The ease of use criterion will evaluate the ease of conducting the method. The time required to conduct the methodological assessment, the amount of data, and the availability of secondary data can be considered for this criterion. The availability of secondary data can be helpful if not all primary data is available yet. While secondary data adds uncertainty to the assessment, it can be beneficial in the early development stages. During the early development process of technology, many uncertainties are present. Decisions regarding material selection or production processes might be based on assumptions or preliminary choices. Next to the high uncertainty, collecting primary data might be time-consuming, costly, or even impossible in the early stages. Therefore, secondary data from databases or literature can provide data for a preliminary assessment, giving a tendency to compare options and help with decision-making early on. Additionally, it can reduce the time and costs of an assessment and lower the bar for conducting it early on.

As early development phases are the focus of the thesis study, the availability of secondary data is valued as something positive within this study. However, the availability of data needs to be distinguished. Secondary data can vary in quality, quantity, and in ease of accessibility. For the quality, a distinction can be made regarding the source of the information and the verification. While a high quality of secondary data is desirable to decrease uncertainty and increase accuracy, the quality evaluation of secondary data goes beyond this study and is therefore excluded. Nevertheless, it is something that should be looked into in the future. The pure amount of data or secondary data sources is considered for the quantity. The more data available, the better, as it increases the chances of finding the necessary data one is looking for. Lastly, the accessibility of the secondary data is examined. Here a differentiation is made between the availability of literature and within databases. As databases collect the data on one single spot, it is assumed to be found more straightforward and, therefore, more desirable. If no central database is available, a different method user may consider varying data for the same thing/resource (Amaral et al., 2016). Therefore, it can be assumed that the standardization and comparability of studies decreases. Overall this leads to the definition of the criterion as follows:

0 - No database available
1 - Data available within the literature
2 - Central database is available
3 - Many databases are available

A second criterion for the method's ease of use is defined, taking the amount of data needed into account. As described above and in chapter 1.1.2, the availability of data in the early development stages is low. Therefore, methods with a low data need are preferred for the assessing sustainability early on.

No comparable data on the amount of data needed for each method could be found in the literature. However, data on comparisons between individual methods could be found. Therefore, the methods will not be compared to a set of predefined scoring criteria, as with the other criteria, but be compared to each other based on the literature search results. In this way, a ranking of the methods is developed, and scores are given based on the ranking. It is assumed that an increased amount of data leads to a higher compilation effort and, thus, to a more costly and time-consuming execution. In conclusion, the higher the data need and compilation effort, the lower the score. The availability of databases is excluded within this step, as it is considered in another criterion.

Complexity/ease of concept

Lastly, the complexity of the method is evaluated. As the study aims to enable decision-making for non-experts on sustainability, it should be considered how difficult it is to understand the assessment method. To do so, the last criterion is defined to check how easy it is to understand what the method is about and its underlying concept.

Within the literature, publications can be found comparing one method with another. Additionally, literature describing the complexity of a method on its own can be found, too. However, this type of information could only be found for some of the methods involved in the study. Due to this lack of data from the literature, another approach is chosen for the complexity criterion. A pairwise comparision is conducted, which enables the comparision of two methods directly with each other on a defined criterion. Ideally, different experts are consulted to conduct the pairwise comparision, in order to achieve objective results. Afterwards, the median would be calculated and used further in the study. However, this approach is not perused here. Within the case company, only experts on Life Cycle Assessment are available. Knowledge about the remaining methods would need to be transferred to them first, before conducting the pairwise comparision. This poses the risk of information asymmetry and biases, as the experts have a higher knowledge on one of the methods. Therefore, they are likely to evaluate Life Cycle Assessment as not complex. The approach followed instead is a pairwise comparision done solely by the researcher. This creates a subjective influence on the criterion, which needs to be considered during the further steps of the study.

The result of the pairwise comparision is a ranking of the methods from least to most complex, based on the times each method is mentioned. This ranking is transferred into a score from zero to three as well, to match the remaining criteria. To do so, the number of methods considered (eight) is divided by the number of scores (four possibilities). The result is an interval of two. This interval is transferred into the criterion and scoring as follows:

0 - Highest complexity (methods with the ranking 7&8)
1 - Medium to high complexity (methods with the ranking 5&6)
2 - Low to medium complexity (methods with the ranking 3&4)
3 - Low complexity (methods with the ranking 1&2)

4.2 COMPARATIVE ANALYSIS RESULTS

A qualitative comparison of the assessment methods is conducted based on the criteria described in chapter 4.1. The scoring rests upon the author's assessment and has been made after a review of scientific literature. The results are described hereafter and summarized in Table 12. Furthermore, a visualization of the method comparison can be found in 4.3.

Table 12 Method scoring per category (own source)

Method/ Criteria	Standardization	Life cycle thinking	Resource inflows	Emissions	Additional flows	Database availability	Amount of data	Complexity
Energy	2	2	1	0	0	1	3	2
Exergy	1	2	2	0	0	1	2	0
Emergy	2	3	2	0	2	1	1	0
LCA	3	3	2	3	0	3	0	1
MSA	2	2	1	3	1	3	1	3
SFA	2	2	1	3	1	3	0	3
Ecological rucksack	2	1	1	0	0	2	1	2
MIPS	2	3	2	2	0	2	0	1

4.2.1 STANDARDIZATION

The highest standardization can be found in the Life Cycle Assessment method. An international handbook that functions as a detailed guide for LCA is available (European Commission - Joint Research Centre, 2010). Additionally, several standards (International Organization for Standardization (ISO) 14040 and 14044) are in place, which function as guidelines and a general methodological framework (Owsianiak et al., 2018).

Another method for which a standard is available is Substance Flow Analysis. The Austrian ÖNORM S 2096 defines the method and application of SFA and Material Flow Analysis for goal-oriented waste management. However, this standard can only be seen as a high degree of standardization if the SFA is applied for the specific application case (waste management). More general guidance for Substance Flow Analysis and Material System Analysis can be found in handbooks for Material Flow Analysis. An example is the book *Handbook of Material Flow Analysis - For Environmental, Resource, and Waste Engineers* (Brunner & Rechberger, 2016). Another standardization is provided by the guide *Measuring material flows and resource productivity* by the Organization for Economic Co-Operation and Development (OECD), which describes the different material flow analysis approaches and functions as a framework (see OECD, 2008, p. 4). However, it must be pointed out that this guide focuses on the national level and policy-making, not the company level, which is the scope of this study. Nevertheless, it provides guidance on the methods themselves and their indicators.

For the ecological rucksack and MIPS, there are detailed handbooks for the methods available from the method developers. The handbook from 1998 provides a comprehensive description of the underlying concept and methods. In 2002 a manual for calculating the MIPS and the Ecological Rucksack was published. It functions as an instruction guide for the analyses according to the underlying concept. Even though the methods are not officially standardized, these two publications enable a high unification.

Concerning Energy analysis, there are several handbooks (books and scientific papers) available. To mention a few: *Handbook of industrial energy analysis* (Boustead & Hancock, 1979); *Net energy analysis: Handbook for combining process and input-output analysis* (Bullard et al., 1978); *Handbook of Energy*

Engineering Calculations (Hicks, 2011), and *Handbook of Energy Data and Calculations: Including Directory of Products and Services* (Osborn, 2013). Additionally, a guideline regarding the Cumulative energy demand can be found in the Association of German Engineers (Verein Deutscher Ingenieure e.V. - VDI). It includes terms, definitions, and calculation methods. Guidelines of the VDI function as recommendations and do not need to be followed (VDI, n.d.). However, they can guide professionals and ensure that they follow good engineering practices (VDI, n.d.).

For Exergy analysis, no handbook could be found. Alternatively, several books are available that cover the concept of exergy and its applications (e.g., Exergy Energy, Environment, and Sustainable Development by Ibrahim Dincer & Marc Rosen (2012)). Lastly, for Emergy analysis, the book *Environmental Accounting: Emergy and Environmental Decision Making* (Odum, 1996) was found, which describes the theoretical principle, way of calculating, and applications of Emergy. The author H. T. Odum is often referred to as the developer of emergy analysis (see Nilsson, 1997; Wang et al., 2020) and published several papers and books concerning the method. Another publication of Odum is the *Folio 1 - Handbook of Emergy Evaluation* (Odum et al., 2000). Even though several books and handbooks are available, the methodological approach of Emergy analysis can slightly differ in individual cases (Amaral et al., 2016). Therefore, it is possible to identify room for improvement regarding the standardization of the Emergy analysis method.

4.2.2 LIFE CYCLE THINKING

While some methods (LCA, MIPS, and Emergy) are defined as taking all life cycle stages into account (see Hauschild et al., 2018; Liedtke et al., 2014; Amaral et al., 2016), others need to be evaluated in more detail, one of them is the ecological rucksack. It only considers the material input, which occurs upstream (before) and during the production state (OECD, 2008; Ritthoff et al., 2002). Therefore, the use and end-of-life phase is not considered within the Ecological rucksack. Another exemption is methods that can take the entire life cycle into account but do not necessarily do so. For Energy, Exergy, and Substance flow analysis, the life cycles included depend on the defined system and purpose. Energy and Exergy analysis can also be used to assess one life cycle step on its own. According to the VDI, the inclusion of life cycle stages within energy analysis depend on the objective of the investigation and, thus, on the person carrying out the assessment (VDI, 2012). An example of an energy analysis including all life cycle stages is the study conducted by Hassard et al. on coffee products in Japan (see Hassard et al., 2014). A counter-example is the study of Puca et al., which only take the stages from raw materials to use into account, excluding the end-of-life phase (see Puca et al., 2017).

For Exergy analysis, the scope of the study is broadened to several life cycle stages if the Cumulative exergy consumption is calculated. When accounting for the Cumulative exergy consumption, the analysis is extended beyond a single process step towards all processes from raw material acquisition to the final product (Hau & Bakshi, 2004b; Dewulf et al., 2008).

The Substance Flow analysis is described as taking the life cycle of the selected substance and its process system into account (OECD, 2008). According to van der Voet et al., this substance is followed “[…] from its (mostly economic) cradle to its (usually environmental) grave" (Van Der Voet et al., 1995, p. 94).

Studies show that the completeness of life cycle thinking depends on the system definition and can vary. An example of a study that includes all life cycle steps is the one of Ding et al., which includes the primary substance production, manufacturing, use, and waste management/recycling (see Ding et al., 2016).

The same can be said about Material System analysis. It takes the entire life cycle of the selected material and its associated process system into account (OECD, 2008). An example of this is the MSA study conducted on behalf of the European Commission in 2015 (see BIO by Deloitte , 2015). In their study, they choose a cradle-to-grave approach (Passarini et al., 2018).

4.2.3 INVENTORY FLOWS

The inventory flows considered within each method are summarized in the Table 13. Only flows that are specifically mentioned in the literature are included. If a specific type of flow is not mentions within the literature, it is assumed to not being covered by the method.

Table 13 Inventory flows in- and excluded in each method (own source)

Method	Flows included in assessment	Flows not included
Energy	• Fossil resources (Hovelius, 1997) • Renewable resources (Hovelius, 1997)	• Services (Puca et al., 2017) • Labor (Puca et al., 2017)
Exergy	• Renewable resources (bio-mass, solar, wind, hydropower) (Dewulf et al., 2008) • Fossil fuels (Dewulf et al., 2008) • Nuclear fuels (Dewulf et al., 2008) • Metal ores, minerals (Dewulf et al., 2008) • Water resources (Dewulf et al., 2008) • Atmospheric resources (Dewulf et al., 2008)	• Capital (Hau & Baksi, 2004b) • Labor (Hau & Baksi, 2004b) • Land use (Dewulf et al., 2008; Loiseau et al., 2012)
Emergy	• Renewable (e.g. solar energy, rain, wind, tide) (Herva et al., 2011) • Non-renewable (e.g. fossil fuel) local resources (Herva et al., 2011) • Input purchase from market (e.g. electricity, equipment, service) (Herva et al., 2011) • The product to be sold (Herva et al., 2011) • Waste (Herva et al., 2011) • Labor (Puca et al., 2017) • Services (Puca et al., 2017)	
Life Cycle Assessment	• Land use (Hauschild et al., 2018) • Water use (Hauschild et al., 2018) • Abiotic resource use (fossil and mineral); non-renewable resources (Hauschild et al., 2018) • Biotic resource use (e.g. fishing or wood logging); renewable resources (Hauschild et al., 2018) • Extraction or use: of minerals, crude oil, water or soil, etc. (Hauschild et al., 2018) • Waste (European Commission - Joint Research Centre, 2010) • Emissions (European Commission - Joint Research Centre, 2010) to air, water and soil (Roy et al., 2009)	• Cost/economic performance (Murthy, 2022)

Method	Flows included in assessment	Flows not included
Material System Analysis	• Economic flows (import and export) (Van Der Voet et al., 1995) • Environmental flows (material extractions and emissions) Van Der Voet et al., 1995) Depends on the scope and system definition. It can take into account: • Substances, raw materials, base materials, products, manufactures, wastes, and emissions to air or water (Nemeskeri et al., 2007) • Emissions to air, water, land (OECD, 2008)	• Ecological services (Hau & Bakshi, 2004b)
Substance Flow Analysis	• Economic flows (import and export) (Van Der Voet et al., 1995) • Environmental flows (material extractions and emissions) Van Der Voet et al., 1995) • Emissions to air, water, land (OECD, 2008)	
Ecological rucksack	Theoretically the same as MIPS (same inventory). However, when calculating the Ecological rucksack indicator only the following flows are considered : • Abiotic raw materials (Ritthoff et al., 2002) • Biotic raw materials (Ritthoff et al., 2002) • Earth movement (only erosion) (Ritthoff et al., 2002).	• Land use (Giljum et al., 2009b)
Material input per unit of service	• Abiotic raw materials: unprocessed abiotic raw materials, like ores (Ritthoff et al., 2002) • Biotic raw materials: All vegetable and animal raw materials (Ritthoff et al., 2002) • Earth movements: All earth movement (Ritthoff et al., 2002) • Water: All water taken directly from nature (Ritthoff et al., 2002) • Energy sources/carriers: Thermal and non-thermal converted sources/carriers of energy (e.g. firewood, oil, coal or gas) (Ritthoff et al., 2002) • Air: All directly extracted and altered air (Ritthoff et al., 2002) • Wastewater: All water that goes into the draining itch or into a sewage plant (Ritthoff et al., 2002) • Exhaust air: All carrier gases of solid, liquid or gas-like emissions (Ritthoff et al., 2002) • Emissions: All pollution of earth, air and water emitted (only if they are processed further (e.g. in a recycling plant, or in an exhaust air purification plant) (Ritthoff et al., 2002)	• Land use (Giljum et al., 2009b) • Specific environmental toxicity of material flows (Cahyandito, 2002)

4.2.4 EASE OF USE

Availability of databases

The availability of secondary data and databases differs between the methods. For several methods, secondary data can be obtained from literature, websites or statistics. Even though the data is available, it is not collected and stored in one central place. This is the case for Energy analysis. Secondary data can be found in government statistics (Bullard et al., 1978). However, it is more common for data to be collected directly from trade associations, manufacturers, and consultants (Bullard et al., 1978). It is similar to Exergy analysis. Data regarding the standard Exergy of chemicals or compounds can be found in the literature (Szargut et al., 1987). Although, according to Bösch et al., the data is not nearly as effortlessly available as data for LCA computation (Bösch et al., 2007). Concerning Emergy analysis, no central database is present, too (Amaral et al., 2016). Nevertheless, secondary data in the form of conversion factors for emergy quantification is available (UNEP, 2012a). Tables with collected conversion factors can be found in literature, e.g., in the Folios 1-4 from Odum et al., 2000; Odum, 2000; Brown and Bardi, 2001; Brandt-Williams, 2001.

For other methods, databases exist, but they are not publicly or freely accessible. An example is the material and process database of the *Fraunhofer Institute for Building Physics*[6].Within the database, data for Life Cycle Assessment and Material and Substance Flow analysis is collected. Another example is the European data inventory for raw materials, which can be used for Material Substance analysis (European Commission, 2023). Even though the European data inventory can only be accessed with a European Commission authentication, the results of their MSA studies are publicly available. Additional data for Substance Flow and Material Substance analysis can be obtained via the EUROSTAT economy-wide material flow accounts (for European data), SERI‘s Global Material Flow database (for global data) (Giljum et al., 2013), or from trade and production statistics (Van Der Voet et al., 1995). Accordingly, the availability of secondary data for SFA and MSA appears to depend on the scope (like national, European, global, etc.) as well as the access rights to different databases. Nonetheless, in theory, several databases are available; therefore, the highest score is given to these methods.

A central database containing more than 2000 specific material intensity factors is available for the Ecological rucksack and the MIPS approach (Giljum et al., 2013). The database is published by the institute which developed the method and is updated frequently, according to Liedtke et al. (Liedtke et al., 2014). Additional secondary data can be found in literature, for example, in a table called Material Input for Specific Raw Materials and Products published in a book by the inventor of the MIPS concept (Cahyandito, 2002).

Lastly, several centralized databases are available for the Life Cycle Assessment (Life Cycle Initiative, 2023). To mention a few: Ecoinvent; The Evah Pigments Database; Carbon Minds; Environmental Footprints; idea; Agri-footprint; bioenergiedat; worldsteel and Ökobaudat (Life Cycle Initiative, 2023).

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[6] https://www.ibp.fraunhofer.de/en/expertise/life-cycle-engineering/applied-methods/material-substance-flow-analysis.html

Amount of data

As a baseline for the comparison, the Life Cycle Assessment is chosen. According to the OECD, the compilation effort of an LCA is high (OECD, 2008). For Substance Flow Analysis, they state the same (high) (OECD, 2008). Therefore, the amount of data required and the ease of execution is assumed to be the same for LCA and SFA. Furthermore, the OECD describes that the effort for Material System Analysis is medium to high (OECD, 2008), indicating a slightly easier assessment.

Emergy analysis requires a smaller amount of data compared to Life Cycle Assessment (Amaral et al., 2016). No data concerning Energy and Exergy compared to LCA could be found. Despite this, it is possible to compare the data amount of these two methods to the one of Emergy analysis. Emergy analysis considers services and labor flows, which is not the case for Energy or Exergy analysis (Puca et al., 2017; Hau & Bakshi, 2004a; Hau & Bakshi, 2004b). As more flows are included in the Emergy analysis, it is assumed that the required data and effort are higher than for Exergy and Emergy analysis. Exergy analysis includes the valuation of the energy source's quantity and quality, while Energy analysis only accounts for the quantity (Hovelius, 1997, as cited in Herva et al., 2011). This leads to the assumption that the data amount for Exergy analysis is higher than for Energy analysis.

Lastly, no information comparing the data amount of LCA to MIPS or the Ecological rucksack could be found. The only information found regarding the comprehensive data needed for conducting a MIPS assessment is as follows: "[…] the amount of data will usually be extremely high […]" (Spangenberg, 1999, p.10). Due to this statement, it is assumed that the MIPS method demands a similar amount of data as the other methods requiring the most data (LCA & SFA). At last, the Ecological rucksack can be compared to the MIPS. The data collection and calculation of the Ecological rucksack and the MIPS are almost the same. The difference between the methods is that the MIPS goes further by taking the service unit into account and the usage and end-of-life phase (Ritthoff et al., 2002). Thus, the data amount required for calculating the Ecological rucksack is assumed to be less.

An overview of the method scoring can be found in Figure 15. Importantly, it needs to be pointed out that the comparison of the data amount of each method is mainly based on assumptions. Furthermore, it is not possible to compare each method with the other due to lacking data. A comparison of each method with each other method would be desirable. Then the method of pairwise comparison could have been used, possibly increasing the quality of the results. Due to the method used instead, the relationship between methods not directly compared to each other is entirely unknown. Consequently, the results need to be used cautiously.

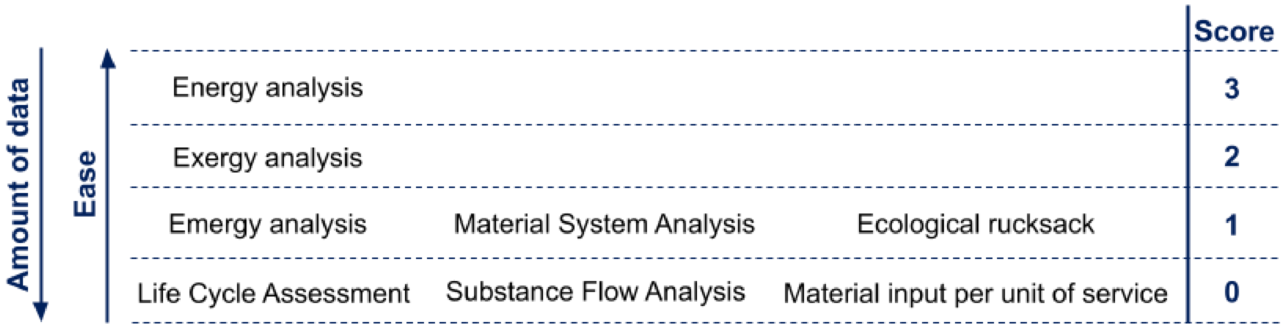


Figure 15 Method comparision based on the amount of data needed (own source)

4.2.5 COMPLEXITY

For comparing the complexity of the methods, each method is compared with one another in a direct comparison. The results of this comparison are shown in a matrix in Table 14 and explained hereafter. The first row and column in the table define the methods to be compared. In each cell, a direct comparison of the respective methods is conducted, and the winner is noted down. In this case, a win means that the researcher perceives the selected method as more complex. The method chosen most often receives the highest ranking in regards to complexity. To increase the visually, a letter (from A to H) is accounted to each method.

Table 14 Pairwise comparision of methods complexity (own source)

	Energy (A)	**Exergy (B)**	**Emergy (C)**	**LCA (D)**	**MSA (E)**	**SFA (F)**	**Ecological rucksack (G)**	**MIPS (H)**
Energy (A)		B	C	D	A	A	G	H
Exergy (B)			C	B	B	B	B	B
Emergy (C)				C	C	C	C	C
LCA (D)					D	D	D	D
MSA (E)						F	G	H
SFA (F)							G	H
Ecological rucksack (G)								H
MIPS (H)								
Times mentioned	2	6	7	5	0	1	3	4
Ranking (complexity)	**3**	**7**	**8**	**6**	**1**	**2**	**4**	**5**

The researcher perceives the methods of Energy analysis, Substance Flow Analysis, and Material System Analysis as the least complex ones. MFA and SFA include the economic concept of import and export, which is assumed that everyone is familiar with. Additionally, as the concepts of Energy, Materials, and Substance are common in other areas and day-to-day life, they are apprehended as familiar. The researcher perceives materials as the most tangible type (due to the size) of flow and most commonly occurring in other situations. Therefore, MSA is valued as the least complex method.

Methods based on thermodynamics (Exergy and Emergy) are ranked as the most complex. The researcher was unfamiliar with the concepts of Exergy or Emergy, so basic knowledge about thermodynamics must be acquired first. Loiseau et al. and Hau and Bakshi also noted the high complexity of methods based on thermodynamics (Loiseau et al., 2012; Hau & Bakshi, 2004b). Compared to Exergy analysis, Emergy analysis considers more flows and covers a broader scope. For these reasons, Emergy analysis is valued as more complex compared to all other methods.

As medium complex are the methods Ecological rucksack and MIPS ranked. The concept of hidden or indirect flows (included in both methods) is less familiar than energy, material, or substance flows for the researcher. However, the concept was easier to grasp than the methods based on thermodynamics (Exergy and Emergy analysis). Compared with each other, MIPS included more life cycle stages, more flows, and a broader scope than the ecological rucksack. Furthermore, it is necessary to define a service unit (lifetime, number of uses in a specific time frame, and maintenance) within the MIPS approach, which is not the case for the Ecological rucksack. For these reasons, the MIPS is ranked higher than the Ecological rucksack.

Lastly, the status quo method Life Cycle Assessment is ranked as having a medium to high complexity. LCA is not based on thermodynamics but on accounting flows. Therefore, it is perceived as less complex than Exergy and Emergy analysis. However, LCA contains more unfamiliar concepts (like mid- and endpoint indicators or impact categories) than the remaining methods (Energy, SFA, MSA, MIPS, and Ecological rucksack). In addition, LCA calculations are often done with the help of modelling software. As this software has never been used by the researcher before, it added a further impression of complexity. Compared to LCA's need for modelling, other methods like the MIPS or Ecological rucksack can be calculated using an excel sheet (Ritthoff et al., 2002). Thus, they can be computed without the use of complex software. A direct comparison of the complexity of MIPS and LCA can be found in the literature: "MIPS is a practical solution to reduce the complexity of the assessment as well as the uncertainties that go along with output-oriented assessments such as the ISO 14040/44 LCA" (Liedtke et al., 2014, p. 547). Lastly, criticism of LCA can be found, which claims that an environmental specialist should execute LCA as opposed to a non-expert (like a designer) (Kishita et al., 2010). Therefore, LCA is ranked with a higher complexity as MIPS.

4.3 VISUALISATION OF METHOD COMPARISION

In order to provide visual insight the results of the qualitative comparison are displayed in a spider web diagram. The diagrams are based scoring results summarized in Table 12. Each corner of the diagram represents one criterion, and the lines represent the respective scoring achieved by the method. An overview of the scoring of all methods can be found in Figure 16. Additionally, individual diagrams for each method are created to increase readability (see Figure 17 until Figure 24).

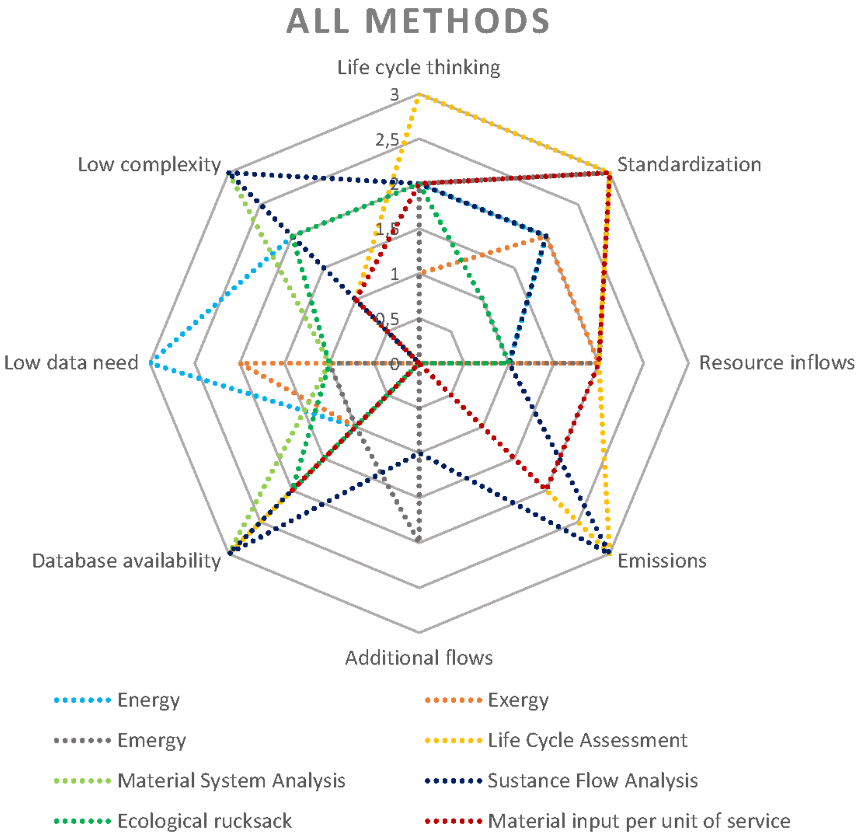
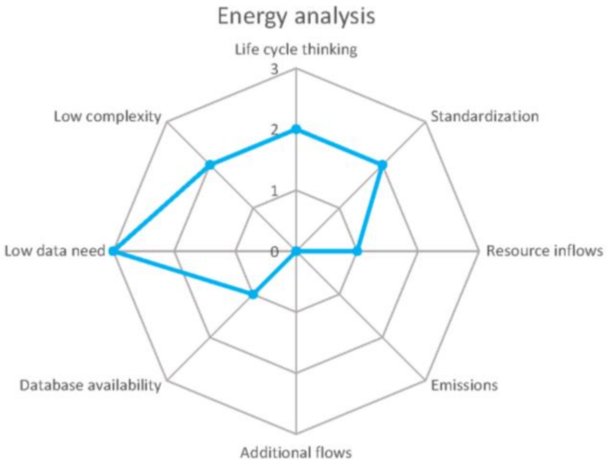


Figure 16 Spiderweb of comparision results for all methods (own source)



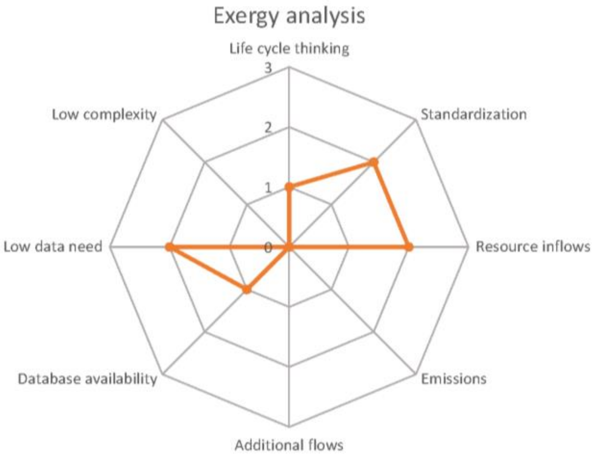


Figure 17 Spiderweb diagram of Energy analysis (own source)

Figure 18 Spiderweb diagram of Exergy analysis (own source)

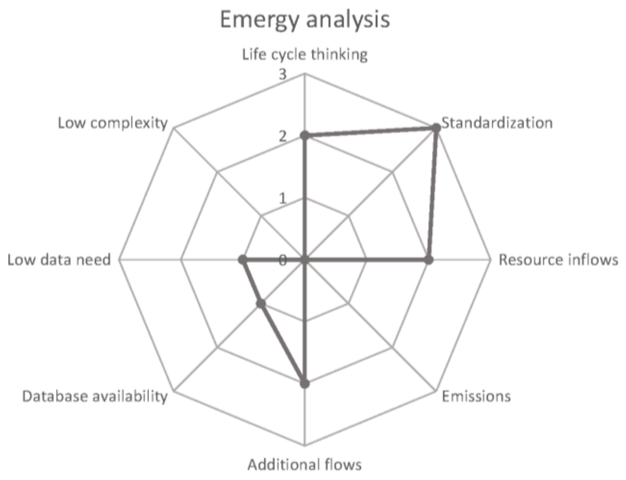


Figure 19 Spiderweb diagram of Emergy analysis (own source)

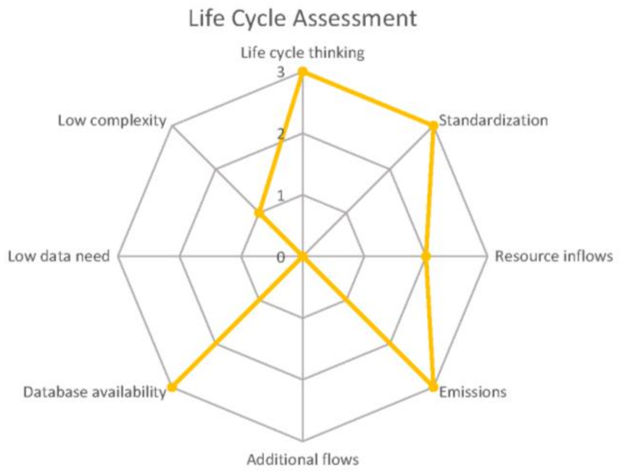


Figure 20 Spiderweb diagram of Life Cycle Assessment (own source)

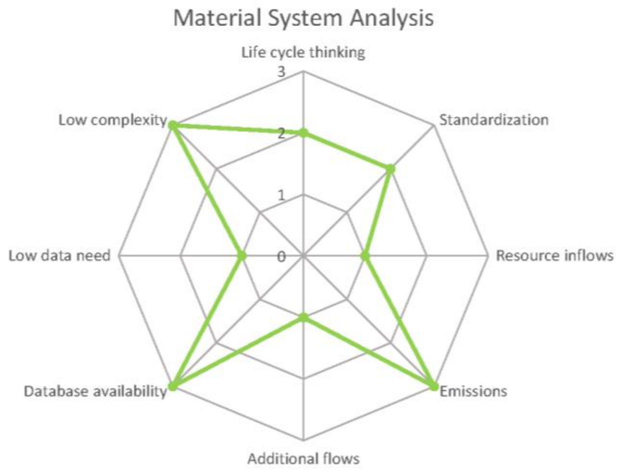


Figure 21 Spiderweb diagram of Material System Analysis (own source)

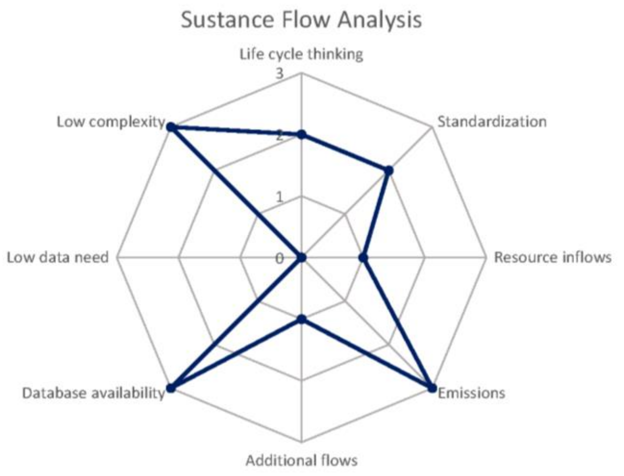


Figure 22 Spiderweb diagram of Substance Flow Analysis (own source)

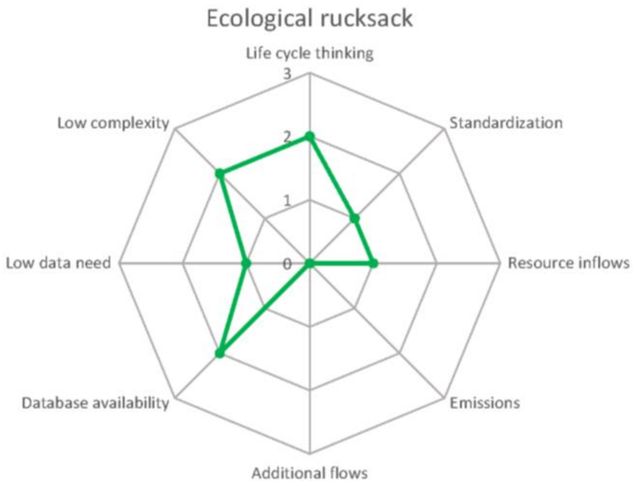


Figure 23 Spiderweb diagram of Ecological rucksack (own source)

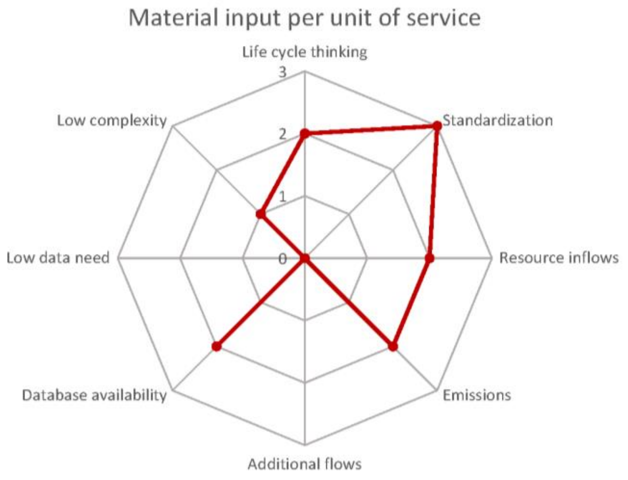


Figure 24 Spiderweb diagram of Material Input Per unit of Service (own source)

The aim is to use these individual spider webs to get a quick and comprehensive overview of the method's key characteristics. In addition, each method's strong and weak points should be recognizable at one glance. This aims to provide the decision-maker with an indication of each method's potential and to raise awareness about its weaknesses. Furthermore, the diagrams can be used to compare different methods with each other. Hence, once an undesirable or weak characteristic of a method is identified, the decision-making for a stronger method in that area should be fostered.

4.4 INTERPRETATION OF COMPARISON RESULTS

To interpret the results of the comparison, each method receives a final overall score to represent its potential for sustainability assessment (based on the defined scoring criterion). For the final score, each criterion score per method is added up. In order to account for the subjective assessment of the complexity criterion, the score is accounted for with and without the criterion. Two additional scores are developed and explained hereafter.

In order to see which method is the best for technologies in the very early development stages (based on the comparison results) an additional score is calculated. During the early development stages the amount of data available is low and uncertainty is high. However, conducting a sustainability assessment can be seen as crucial, as the influence on the technology is high. Therefore, it is likely that changes occur in the further development of the specific technology or in the worst case, the development is stopped at all. Due to this high uncertainty, it can be assumed that the time and costs invested into sustainability assessment at this point should be as low as possible.

To cope with the low data availability and to decrease the costs and time required to conduct the sustainability assessment, secondary data from databases can be used. Thus, a total score for ease of use in early development stages is calculated based on the criteria data availability and amount of data. For this the two individual scores per method are added up.

Sustainability assessments are costly and time consuming to conduct (see, e.g., Simonen, 2014; Kishita et al., 2010). Therefore, it can be assumed, that the amount of times an assessment is conducted should be as small as possible. A way of achieving this could be to include as many aspects as possible within the chosen method. Thus, methods covering as many aspects as possible are preferred. This assumption is transferred into another score. This score should display the completeness of the method. The comparison criteria selected to represent the completeness are life cycle thinking, resource inflows and emissions. Each methods score per criterion is added up to a total score for completeness.

The different scores

Next to the total score and the score without complexity, the percentage achieved per method out of the possible maximum score (23 for the score including complexity and 20 for the score excluding complexity) are displayed in Table 15. Additionally, a visualization of the scores without complexity is provided in Figure 25.

Table 15 Final score per method (own source)

Method/ Score	**Final score**	**Percentage of maximum**	**Final score without complexity**	**Percentage of maximum**
Energy	11	48%	9	45%
Exergy	8	35%	8	40%
Emergy	11	48%	11	55%
Life Cycle Assessment	15	65%	14	70%
Material System Analysis	16	70%	13	65%
Substance Flow Analysis	15	65%	12	60%
Ecological rucksack	9	39%	7	35%
Material input per unit of service	12	52%	11	55%

As a result Material Flow Analysis is scored the highest, followed by Life Cycle Assessment and Substance flow analysis. If the complexity criterion is excluded, the position of the LCA and MFA method changes (LCA is ranked the highest, followed by MSA). This is indicated by the box on in Figure 25. The same can be observed for the lowest ranked methods (see box three in Figure 25). When all criteria are included in the scoring, Exergy analysis is ranked the lowest and the Ecological Rucksack the second lowest. Once the complexity criterion is excluded, the methods switch places. Another switch of the positions can be observed for Energy and Emergy analysis (see box two in Figure 25).

Furthermore, it can be seen that no method obtains the highest or lowest score in all categories. No method achieves less than 30% or more than 70% of the possible maximum ranking. It can be concluded, that no method is the best or the worst in all areas, but each has its strengths and weaknesses.

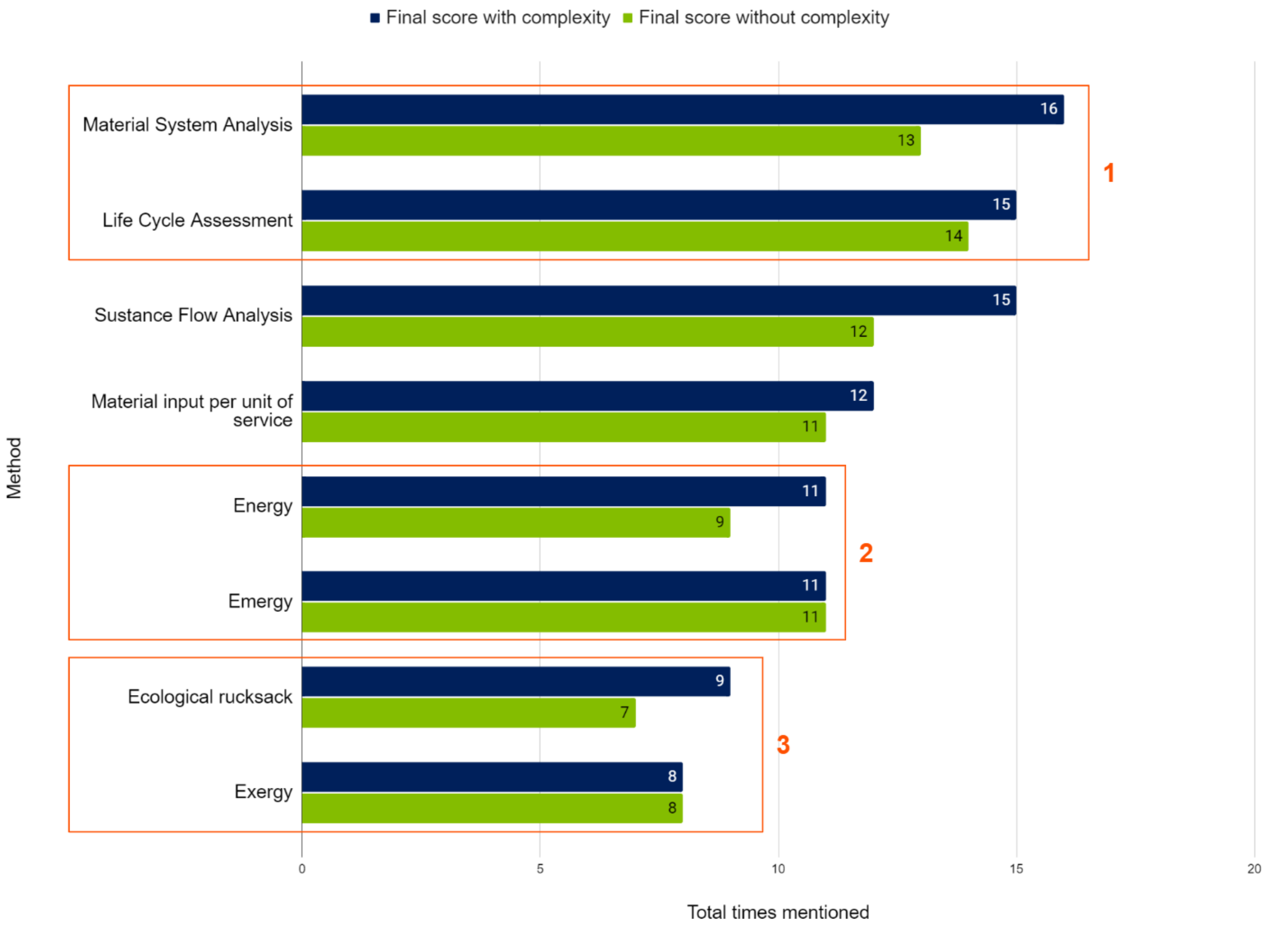


Figure 25 Comparison of final scores with and without complexity (own source)

The individual scores of the criteria database availability and amount of data, as well as the total score for ease of use are displayed in Table 16. The individual scores of the criteria life cycle thinking, resource inflows and emissions, as well as the total score for completeness are displayed in Table 17.

Table 16 Total score per method for ease of use (own source)

Method/ Score	**Score - Database availability**	**Score - Amount of data**	**Total score for ease of use**
Emergy	1	1	**2**
Material input per unit of service	2	0	**2**
Ecological rucksack	2	1	**3**
Exergy	1	2	**3**
Substance Flow analysis	3	0	**3**
Life Cycle Assessment	3	0	**3**
Energy	1	3	**4**
Material System Analysis	3	1	**4**

Table 17 Total score per method for completeness (own source)

Method/ Score	**Score - Life cycle thinking**	**Score - Resource inflows**	**Score - Emissions**	**Total score for completeness**
Ecological rucksack	1	1	0	**2**
Energy	2	1	0	**3**
Exergy	2	2	0	**4**
Emergy	3	2	0	**5**
Substance Flow Analysis	2	1	3	**6**
Material System Analysis	2	1	3	**6**
Material input per unit of service	3	2	2	**7**
Life Cycle Assessment	3	2	3	**8**

For both scores (ease of use and completeness) the highest score represents the best method. For the ease of use the highest scores are obtained by the Energy and the Material System Analysis. According to the applied method and the underlying assumptions these sustainability assessment methods are the most suitable for technologies in the early development stages.

The calculation of the total score for completeness indicates, that the Life Cycle Assessment and Material input per unit of service cover the most areas. These methods can be used to include as many aspects as possible into one assessment.

When comparing the scores for the ease of use and the completeness with each other, it can be seen, that no method is the best in both scores. To visualize the different positions of the methods within each score and to each other, the total scores are plotted against each other in Figure 26. On the horizontal axis, the score for the ease of use is shown. The further to the right a method is positioned, the higher the ease of use of conducting it in early development stages. On the vertical axis the score for the completeness is shown. The higher the method is positioned in the diagram, the greater its completeness. Methods displayed in the top right corner perform the best in both categories. These are Life Cycle Assessment and Material System Analysis. Compared to the overall score (calculated at the beginning of this chapter) the two methods preform the best there as well.

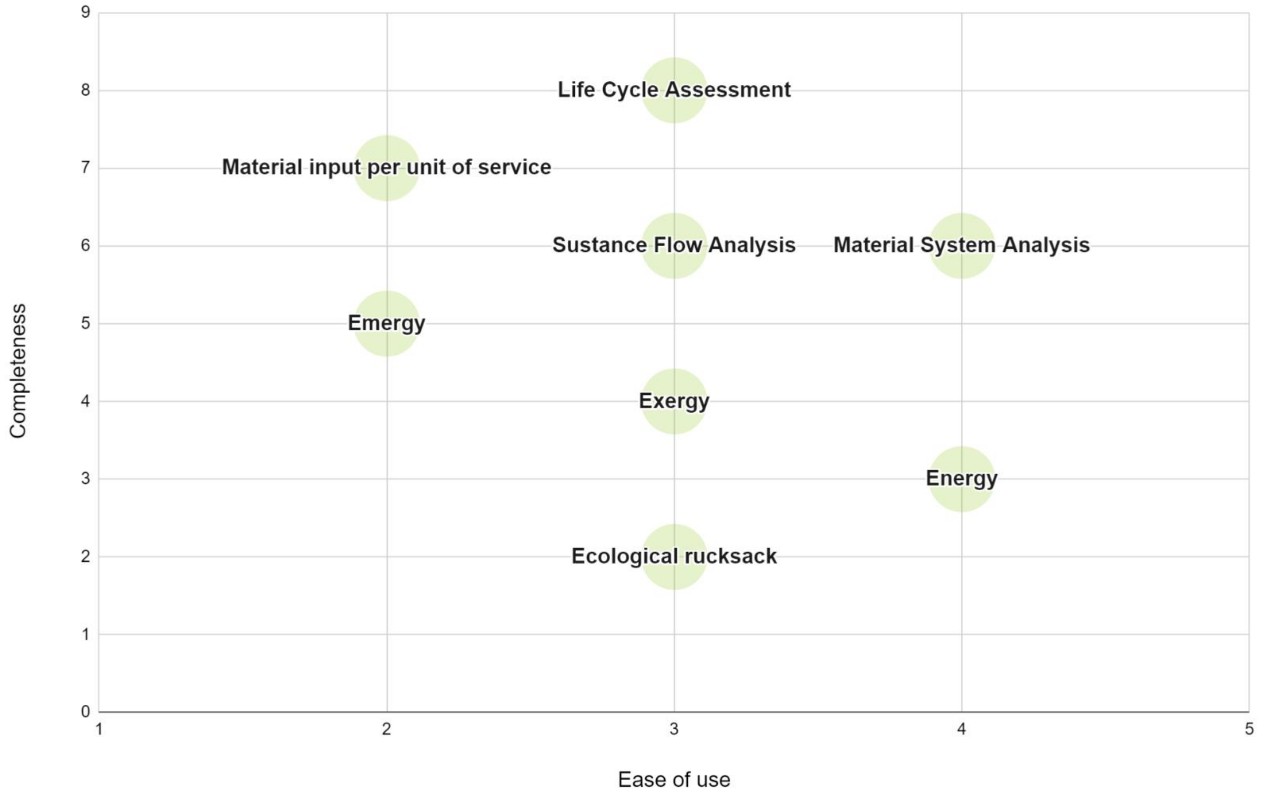


Figure 26 Score for ease of use and completeness plotted against each other (own source)

Whether or not the developed comparison, results and interpretations are accurate cannot be evaluated at this point. In order to validate the findings and the method leading to those (qualitative comparison based on literature search results), a practical application and revisiting of the scoring is proposed. As conducting all eight methods goes beyond the scope of this study, the validation is done exemplary on two method. The exemplary conduction of two methods can be found in the next chapter.

5 PHASE 4 – METHOD VALIDATION

For the validation of the qualitative comparison method and its findings, two assessment methods are applied. First, a use case is identified and the technology shortly introduced. Second, the methods which will be applied are selected. Afterwards, the execution of each analysis is presented based on the identified use case. In addition, the results of each assessment are presented shortly and interpreted. As a final step the findings of the qualitative comparison (as defined in the previous chapter 4.4) are revisited and evaluated against the gained expertise. If necessary, changes for the qualitative comparison are proposed as a last step.

Use case selection

The use case for conducting two exemplary assessments is defined in cooperation with the case company. A technology in the early development stages (between TRL 2 and TRL3) is chosen, to reflect the challenges that come with a low availability of data. According to the TRL framework (see Figure 4), the technology concept is formulated, but proof of concept not done yet. The possibility to modify the technology based on the sustainability assessment findings is perceived as high. Therefore, conduction an assessment and being able to use the findings is important for the case company.

The chosen technology belongs to the Additive Manufacturing processes (also called *three-dimensional* (3D) printing). It works based on the principle of material extrusion and is similar to *Fused Layer Modeling* (FLM) also called *Fused Deposition Modeling* (3D innovaTech Engineering Solutions, 2022). The working principle of FLM will be described shortly hereafter and is displayed in Figure 27. A thermoplastic material filament is pushed through a heated nozzle, which melts and depositions the material along a predefined path (3D innovaTech Engineering Solutions, 2022). After positioning the material, it cools down and solidifies. The extruded plastic can be placed at a precise location. Several layers of material are stacked on top of each other. The precise location and stacking of material led to the creation of a predefined geometry (3D innovaTech Engineering Solutions, 2022). For overhanging geometries a support structure needs to be printed (3D innovaTech Engineering Solutions, 2022). This support material can be removed once the part is completely produced (3D innovaTech Engineering Solutions, 2022). Post processing (such as surface smoothing or painting) is optional based on the intended use of the created part (3D innovaTech Engineering Solutions, 2022).

The technology under development at the case company functions based on the general FLM principle described above. A main difference is, that three nozzles for material extrusion are available that can be used to print different materials. Thus, a fast switch between different materials during the part production is enabled. Additionally, specific materials are under development for the use case technology. Further information is not given at this point, due to confidentiality reasons.

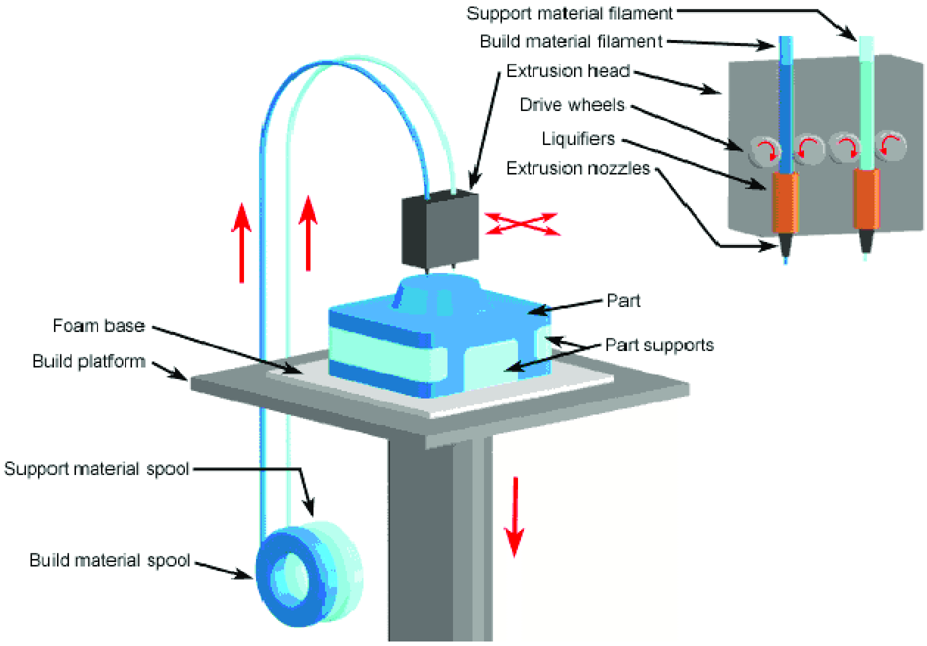


Figure 27 Basic working principle of FLM (Sreenivas Reddy, 2017)

Method selection

Two methods are selected for the partly validation of the qualitative comparison. The first method is the status quo method Life Cycle Assessment. LCA is defined as the baseline method under investigation within this study. Therefore, the practical application of LCA can be used to gain additional insight into the method and to compare the other methods to. As a second method the Material Input per Unit of Service is chosen. According to Liedtke et al., MIPS is linked to the LCA method (Liedtke et al., 2014). The definition of the system borders are similar and the service unit of the MIPS often equals the functional unit of the LCA (Liedtke et al., 2014). Thus, it is assumed, that a high comparability can be achieved, as the scope of the study and the reference units of both methods are the same. Additionally, it is possible to calculate the Ecological rucksack without any additional effort when conducting the MIPS. Therefore, it is possible to compare three of the analyzed methods by conducting two analysis. The integration of a third method should help to validate the qualitative comparison method further.

5.1 EXECUTION OF THE LIFE CYCLE ASSESSMENT

The LCA study conduct within this thesis project will be conducted following the Product Environmental Footprint (PEF) method. This method is chosen, as it is recommended by the European Commission (see European Commission, 2021). As required within the method, all 16 impact categories are accounted for. A list of the impact categories can be found in the row “Indicator” in Table 6 in chapter 0.

The Life Cycle Assessment consists of four iterative steps. An overview of the steps is shown in Figure 28, and the execution is described below. Exemplary screenshots of the Life Cycle Assessment can be found in Appendix G – LCA calculation (confidential). The aim is to provide insight into the execution of the study, and not a detailed description, therefore only examples are provided.

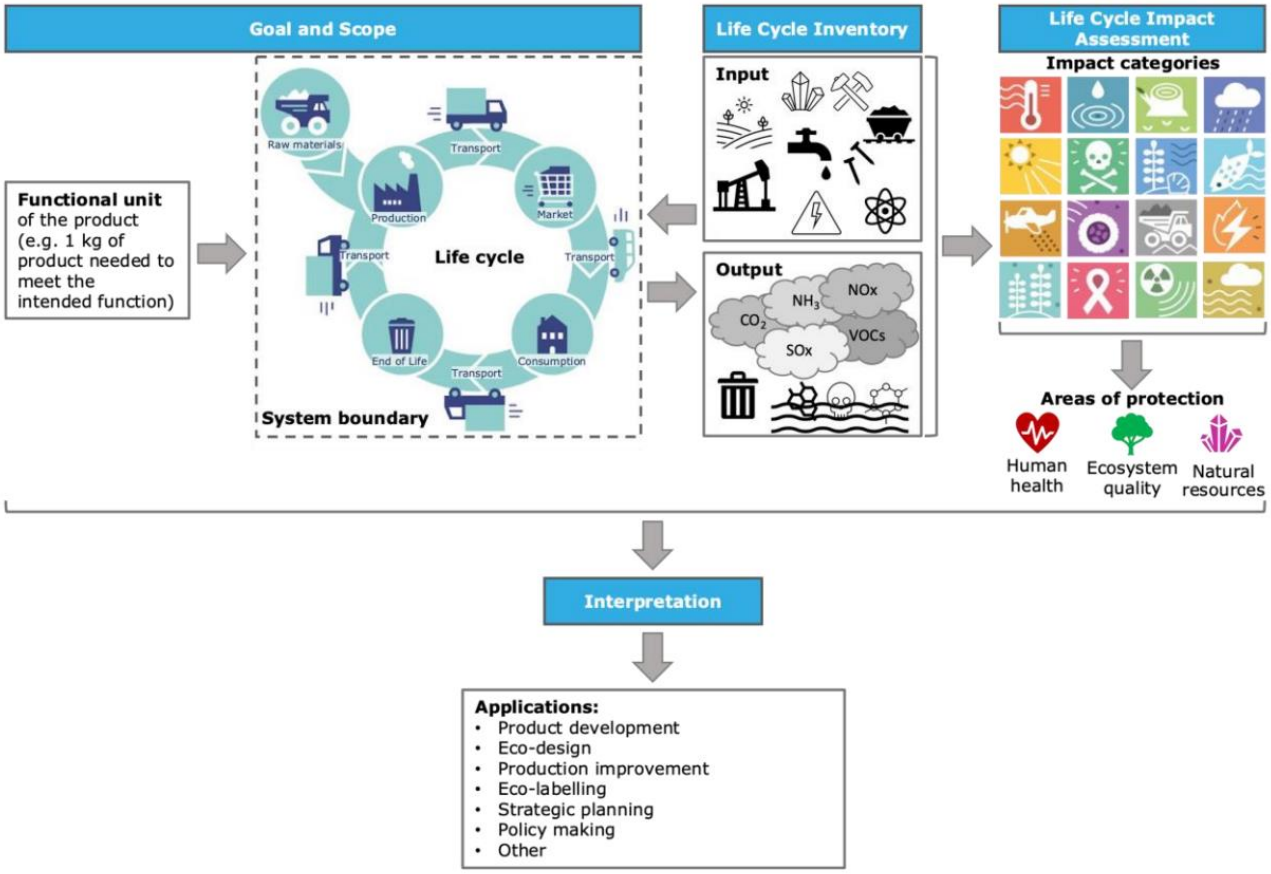


Figure 28 Generic workflow and applications of an LCA (European Commission - Joint Research Centre, 2021)

Goal and scope definition

At the beginning of the assessment, the goal and scope of the study need to be determined. This is necessary to set the frame for the study, perform quality control and evaluate the interpretation of the results (European Commission - Joint Research Centre, 2010). The goal definition ensures an alignment of the methods, aims, results, and intended application and provides a shared vision for the participants (Zampori & Pant, 2019). For this study the goal of the LCA is defined as the quantification of possible environmental impacts of manufacturing a part with the new additive manufacturing technology. It aims at identifying environmental hotspots associated with the production and to communicate those. This will help to inform about environmental impacts of the products and hotspots to stakeholders, which can help in deciding future actions to improve the environmental impacts and meet the company's sustainability goal.

In addition, the functional unit is defined, which describes the product's function and lifetime. It acts as a reference unit for the assessment (Zampori & Pant, 2019). As the technology under study can be used for the production of various products and the final use case is not determined yet. Therefore, no representative product is defined for the study. Instead a generic Life Cycle assessment approach is chosen. Thus, instead of a specific product the study is scoped for a specific product volume. This volume is defined as 1 kilogram (kg) of produced part. This generic part consists of two different materials, called raw material one and raw material two. The ratio of the materials in the final part is defined as 90% of material one and 10% of material two. Additionally, a support material is needed to manufacture the part, which is removed once the printing process is done. Thus, the support material is not included in the final 1 kg of part. Due to the generic approach no life time could be defined within the functional unit.

Furthermore, the product life cycle stages and processes included in the analysis and the environmental issues of interest are defined (Zampori & Pant, 2019). During the study the aim is to include as many environmental impacts as possible throughout the entire life cycle (cradle to cradle). However, as a generic Life Cycle Assessment approach needed to be chose (due to a missing representative product), no data for the use phase could be included. Therefore, only the following life cycle stages are considered in the assessment:

- Production of the raw materials (raw material one, raw material two, support material, and auxiliary material production)
- Manufacturing of the 1kg part using the technology under study
- Transportation (of raw materials and waste)
- End of Life and waste treatment (incineration with energy recovery)

A visualization of the process under study and the included life cycle stages can be found in Figure 29.

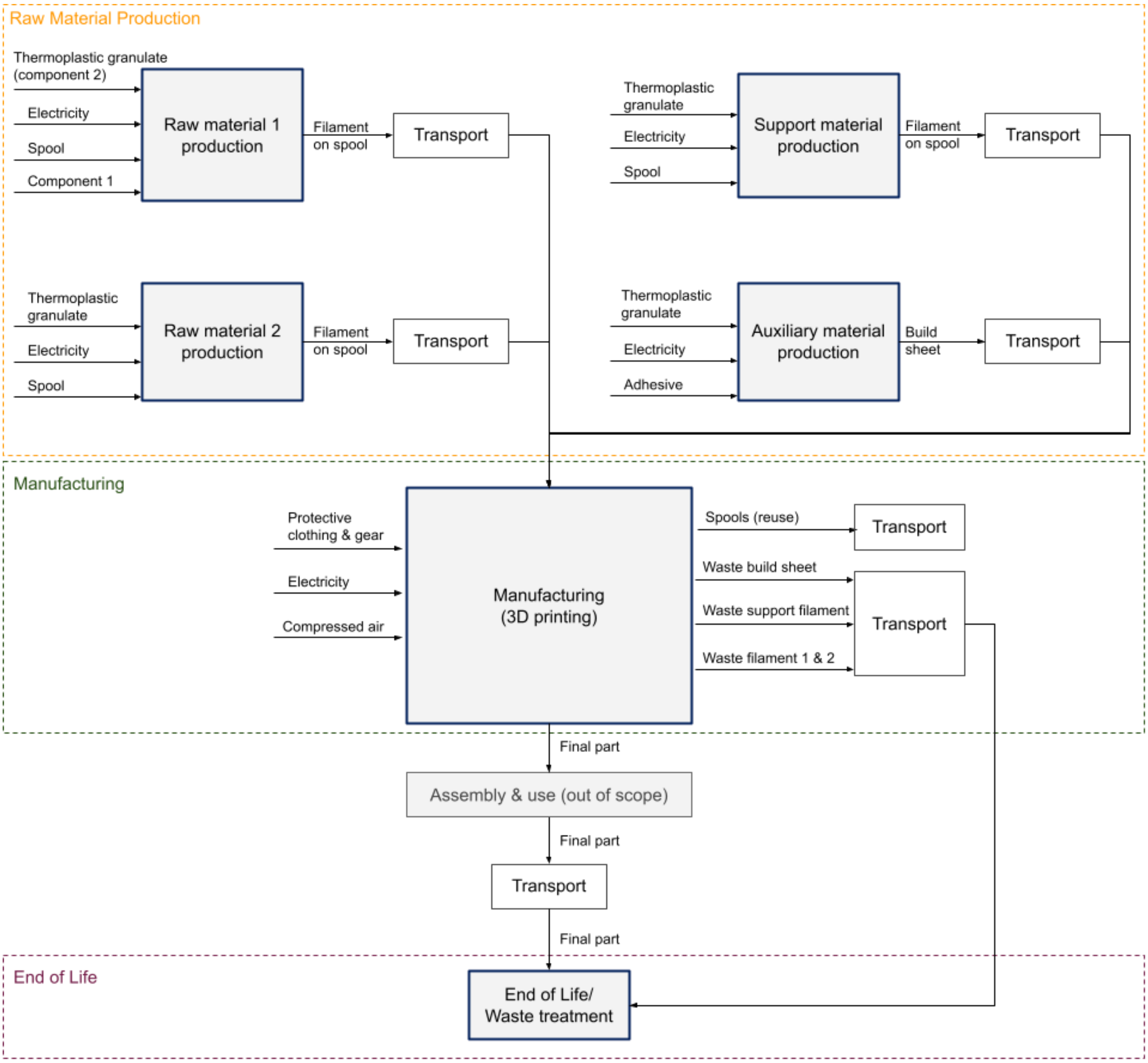


Figure 29 Life Cycle of Case Technology (own source)

Life Cycle Inventory

Within the second phase, the Life Cycle Inventory is compiled. It contains all aggregated in- and output flows (energy, materials, waste, and emissions) of the system (Zampori & Pant, 2019). The data for the different life cycle stages are determined in different ways. Part of the data is measured directly at the supplier side (at the technology prototype). Next to that, literature is used to make justified assumptions. Lastly, data from the GaBi and the Ecoinvent database[7] are used. The specific data will not be discussed further at this point, as it is subject to the confidentiality of the case company. Additional information can be found in the restricted part of the appendix.

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[7] https://ecoinvent.org/the-ecoinvent-database/

Next to collecting the data, the inventory is modelled to provide a clear overview. The material and energy flows (energy, mass and water) are modeled in the Life Cycle Assessment software GaBi. As a reference for the modelling a process flow chart (similar to Figure 29) is used. In order to ensure that the modelling is done correctly and the results can be used by the case company, the modelling is done in cooperation with a LCA expert.

Environmental Footprint Impact Assessment

Afterward, the product's environmental performance is calculated from the compiled Life Cycle Inventory. This process is called Life Cycle Impact Assessment (Zampori & Pant, 2019). First, the identified in- and output flows are classified and assigned to the relevant environmental impact category. Second, the flows are characterized, which refers to calculating the contribution amount to the respective impact category. Additionally, the contributions within each category are aggregated. Lastly, the results of the impact assessment are normalized and weighted. The normalization should help to calculate and compare the contribution of the flows to the impact categories relative to a reference unit (Zampori & Pant, 2019). Weighting is used to support interpreting and communicating the analysis results. For the weighting specific weighting factors of the case company are used. Additionally, the weighted flows are aggregated to a total PEF score.

Results and interpretation of the Life Cycle Assessment

Lastly, the analysis' findings are interpreted, serving two primary purposes: First, to derive conclusions and recommendations (European Commission - Joint Research Centre, 2010; Zampori & Pant, 2019). Second, to steer the work to improve the Life Cycle Inventory model to meet the study's goals and requirements (European Commission - Joint Research Centre, 2010; Zampori & Pant, 2019). Next to interpreting the results, it is necessary to report them, according to the PEF method (European Commission - Joint Research Centre, 2021).

For the presentation and interpretation of the result the weighted flows are used. In Figure 30 the fraction of each impact category on the total PEF score (in percentage) is presented. Here it can be seen, that the most relevant impact categories are resource use (fossil) and climate change - total.

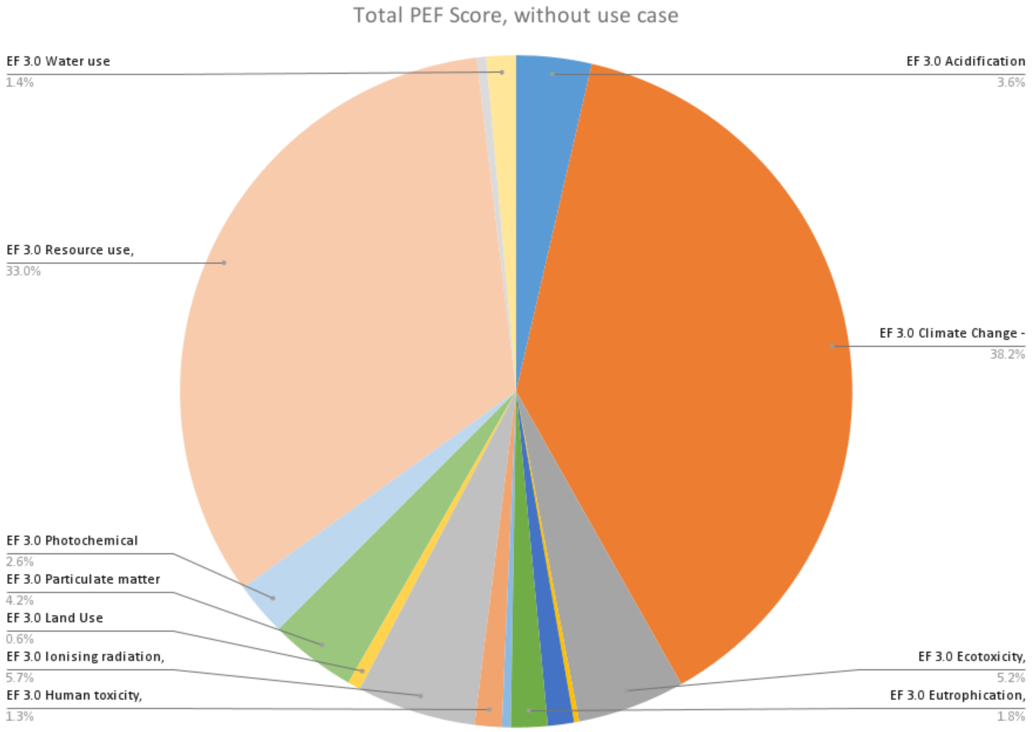

Figure 30 LCA result - total PEF score in percentage (own source)

In Figure 31 the most relevant life cycle stages are shown. The highest impact is created by the raw material production, especially the production of the raw material one and the manufacturing stage. During the manufacturing and the raw material production the electricity usage creates the biggest impact. Additionally, the production of the raw material one – component one is highly impactful.

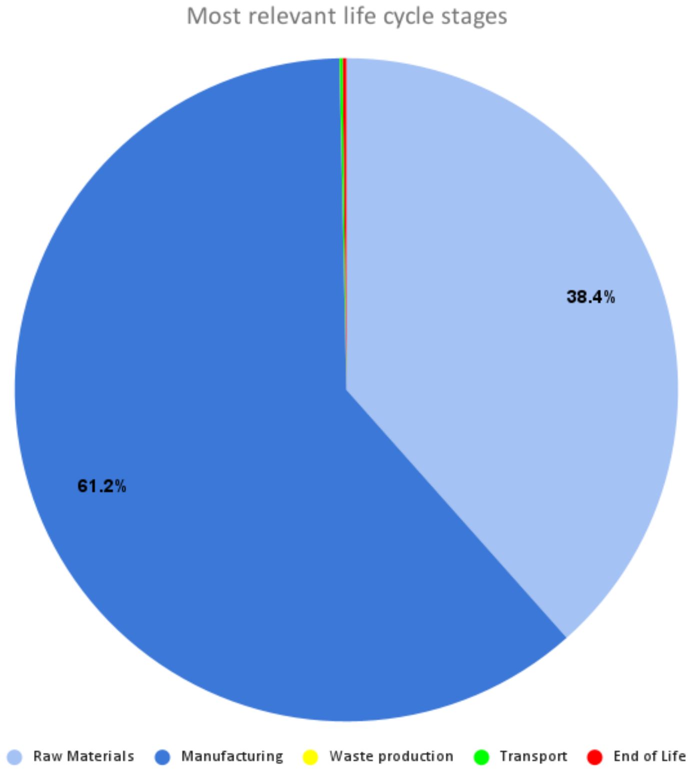

Figure 31 LCA result - most relevant life cycle stages (own source)

Lastly, the most relevant processes and their contribution to the most relevant impact categories are presented. The most relevant impact categories are Ecotoxicity Freshwater (see Figure 34), Climate Change (see Figure 35), Ionising radiation - human health (see Figure 32) and resource use fossil (see Figure 33). Overall it can be seen, that the electricity consumption during the manufacturing stage is responsible for the biggest impacts along all four most relevant impact categories: Ecotoxicity Freshwater; Climate Change; Ionising radiation, human health and Resource use fossil. Next to the manufacturing process, the production of the raw material one creates a high impact. Especially the production of the component 1 as well as the electricity usage during raw material production influence all four most relevant impact categories. Furthermore, the thermoplastic granulate (component 2 of raw material one) and the wastewater treatment of the raw material one production lead to significant impacts. These processes can be identified as the hot spots of the technology under study.

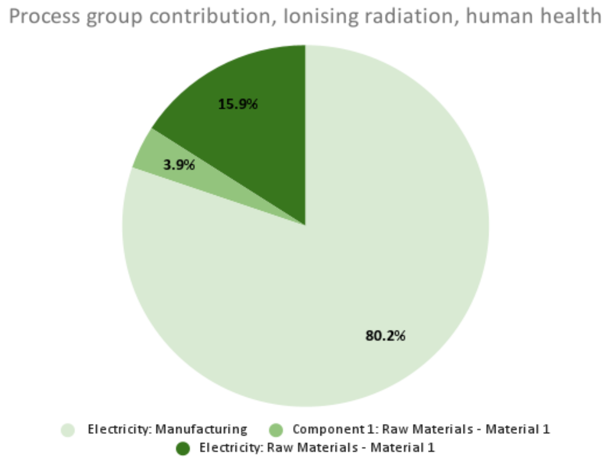

Figure 32 LCA results - Ionizing radiation (own source)

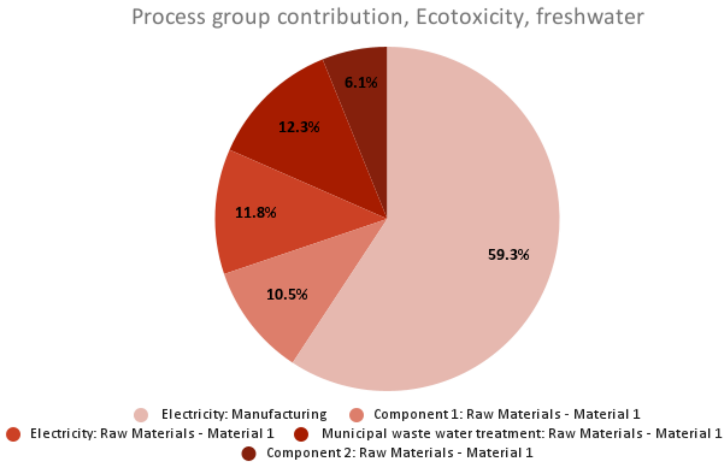

Figure 34 LCA results - Ecotoxicity (own source)

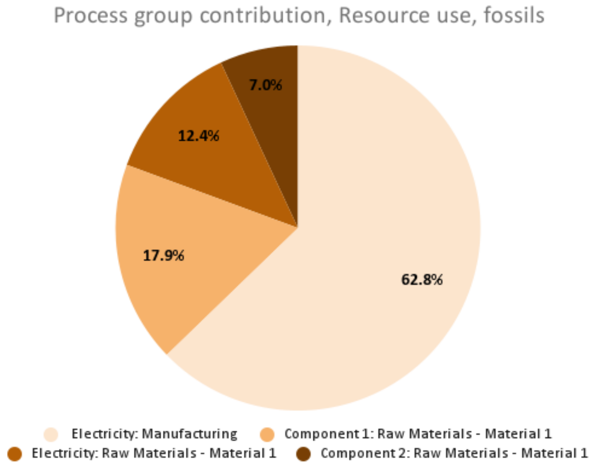

Figure 33 LCA results - Resource use (own source)

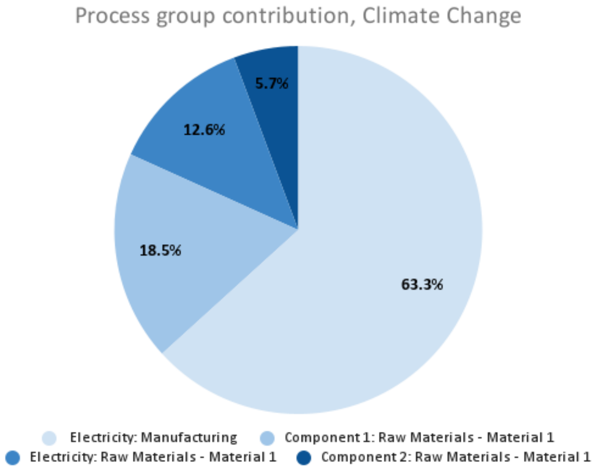

Figure 35 LCA results - Climate change (own source)

Based on the results of the LCA study several recommendations for reducing the environmental impact can be drawn:

- As the electricity usage along the life cycle creates the biggest impact on the environment, it should be looked into ways for reducing the electricity need. Alternatively or additionally the source and supply of the electricity could be investigated. To do so the usage of renewable energy sources could be looked into.
- Replacing the fossil based component 1 and thermoplastic materials with either recycled or bio-based materials could lead to a reduction of the fossil resource use impact.
- Alternatives for material recovery, reuse and recycling should be investigated further with suppliers and the industry.
- In order to reduce the impact of the tap water need and the wastewater treatment, the integration of a closed loop cooling cycle during the raw material production could be considered.

Verification and validation

While the above-described steps comply with the standards of LCA defined by ISO 14040-44, the PEF method requires an additional step. Within this step, the minimum requirements for reviewing the study and reporting results via a reviewer or review panel are defined (European Commission - Joint Research Centre, 2021). The requirements can vary and depend on the intended application (European Commission - Joint Research Centre, 2021). The verification of the LCA study, its results and the report is done by a case company internal expert. With that all five steps of the LCA are executed and the study completed.

5.2 EXECUTION OF THE MATERIAL INPUT PER SERVICE UNIT

The calculation of the MIPS proceeds in seven steps, which are explained in detail in the MIPS handbook (see Ritthoff et al., 2002), visualized in Figure 36 and shortly explained hereafter.

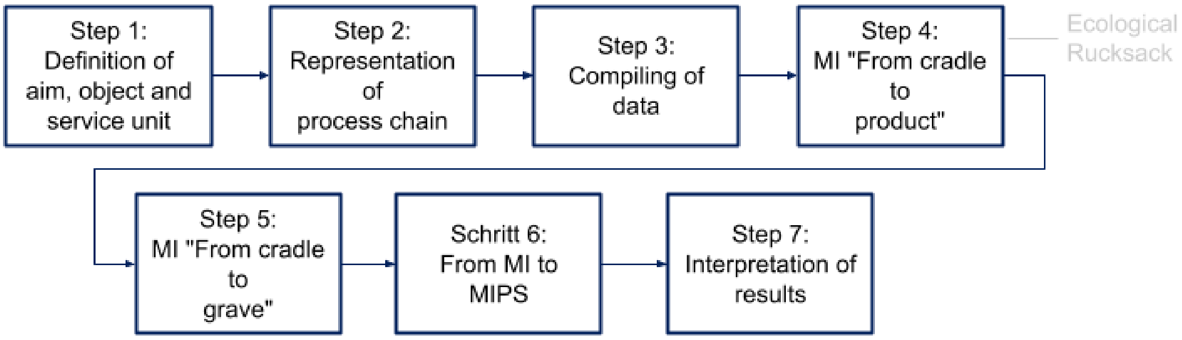

Figure 36 Generic workflow MIPS (adopted from Ritthoff et al., 2002)

At the beginning (step 1), the study’s aim, objective, and underlying service unit are defined. For this study the aim is to identify the most significant resource consumers of manufacturing a part with the new additive manufacturing technology. In addition, the potential environmental impact of the resource input should be identified.

The service unit (S) functions as the basis for the analysis, for comparison with other products, and serves as a reference unit for all numerical values. All essential aspects concerning the use of a product should be included in the service unit (Ritthoff et al., 2002). In some cases, it is not necessary to define a service unit, e.g., if the product is only an intermediary or unserviceable, if the study aims to optimize the process chain and not compare different products, or if the compared products serve the same purpose (Ritthoff et al., 2002). The service unit is defined the same as the functional unit of the Life Cycle Assessment within this study (1 kg of produced part). Due to the fact that no specific use case is identified, it is not possible to include the life time and times used into the service unit. Therefore, the use phase is excluded from the study as well. The system boundaries defined the same as the ones from the LCA.

Once the service unit is defined, the second step can be conducted. In step 2, the process chain is represented. A diagram of the product's (or service's) life cycle is made, including all necessary steps for manufacturing, use, and disposal, as well as preceding process steps. The same representation of the process chain and life cycle stages (Figure 29) is used for the LCA and the MIPS calculation.

After the overall process picture is created, data about each process step is gathered in step 3. The data collected for the LCA study (via measurements and from the literature) is used for the MIPS as well. In addition, the database provided by the methods founder is used for the calculation of the Material Input (see Wuppertal Institute for Climate, Environment and Energy, 2014). Here data on material intensity (MIT) of different products is provided. The decision to use secondary data is made for simplicity reasons. If no data for the specific material is available in the database, the data of the most similar material is used as an assumption. A datasheet (Microsoft Excel) is used to compile, document, and organize the collected data. The gathered data is organized into the following categories (Ritthoff et al., 2002):

- Natural inputs (extracted from nature): abiotic raw materials (e.g., ores in a mine); biotic raw materials; earth movements; water; air
- Pre-treated, processed inputs (raw materials treated previously): basic, working and building materials; energy sources/carriers; modules; infrastructure;
- Auxiliary and operating materials
- Outputs: main products; by-products; waste; wastewater; exhaust air; emissions (pollution of earth, air and water)

Once an overview of the energetic and material inputs is created, the calculation of the material input from cradle to product is conducted. This is done as follows: "The calculation of the Material Input (MI) is arrived at by multiplying the individual input quantities by the specific Material Intensities (MIT) of the input substances." (Ritthoff et al., 2002, p. 28).

$$\text{Material Input (MI)} = \text{ input amount} * \text{ Material Intensity (MIT)} \tag{4}$$

Instead of modelling (as done within the LCA), a calculation sheet is used for the MIPS. For each life cycle stage a calculation sheet is filled containing the materials, quantities and material intensity factors per data category. Due to confidentiality reasons it is not possible to show a filled calculation sheet. The blank calculation sheet is displayed in Table 18. An example of a filled calculation sheet can be found in Appendix I – MIPS calculation (confidential).

Table 18 Calculation sheet MIPS (Wuppertal Institute for Climate, Environment and Energy, 2000)

Calculation sheet Data refer to:												
			Abiotic Material		**Biotic Material**		**Earth movements**		**Water**		**Air**	
Name Substance/pre-product	Unit	Amount	MI-Factor kg/unit	kg/unit Main product	MI-Factor kg/unit	kg/unit Main product	MI-Factor kg/unit	kg/unit Main product	MI-Factor kg/unit	kg/unit Main product	MI-Factor kg/unit	kg/unit Main product
∑				0.00		0.00		0.00		0.00		0.00

At the end of step 4, the Material Input per product is calculated by summing up the Material Inputs per natural input category (abiotic raw material, biotic raw materials, earth movements, water, and air). Additionally, it is possible to calculate the Ecological rucksack or so called Material footprint of the product. The Total Material Requirement (TMR) is used for this calculation. The TMR consists of abiotic raw material, biotic material, and earth movement (erosion). The material input of these categories is totaled, and the net weight of the product (1kg) is deducted (see (2) and (5)). Material Inputs from water and air are not included in the calculation of the Ecological rucksack, but they are displayed separately in the form of a water and air backpack.

$$\text{Ecological Rucksack } = \text{ MI (Total Material Requirement)} - \text{ Net weight (of the product)} \tag{2}$$

$$\text{Ecological Rucksack } = 441.09\text{kg} - 1\text{kg} = 440.09\text{kg} \tag{5}$$

The calculated Ecological rucksack, water and air backpack are as follows:

MI (Total Material Requirement):	441.09 kg
Water backpack:	18887.57 kg
Air Backpack:	130.42 kg
Ecological rucksack:	440.09 kg

As an interpretation of the Ecological rucksack it can be concluded, that the production of 1 kg part, requires 440 kg additional (indirect) resources. Furthermore, 18888 kg water and 130 kg air are consumed. Based on these results it is possible to determine the most relevant life cycle stages and process steps (similar to the LCA results represented in chapter 5.1) as well as define recommendations.

Due to confidentiality reasons neither the exact or percentage contribution to the total indicators (Material footprint, water backpack, air backpack and ecological rucksack) are presented here. Only qualitative results can be stated. From the results can be concluded, that the electricity usage during manufacturing creates the highest impact on the Ecological rucksack. The second highest impact is created by the electricity usage during raw material production 1. The third most influential one is the production of the raw material 1, component one.

Compared to the results of the LCA, the most influential life cycle stages and process steps are the same. Furthermore, the same conclusions and recommendations can be drawn from the MIPS and LCA results.

Due to the fact that no life time and use cycles could be identified, it is not possible to further calculate the MIPS. However, the MIPS calculation process as described until this point equals the calculation of the Ecological rucksack. Therefore, it is still possible to compare the results of two executed methods to the ones of the qualitative comparison. In addition, as five out of seven steps of conducting a MIPS are applied, at least some of the comparison results can be checked. The remaining steps to fully calculate the MIPS are described in theory hereafter.

In the fifth step the calculation of the Material Inputs along the entire life cycle (from the cradle to the grave) is done. Here resource expenditures expected during the use and disposal stage are added to the Material Input per product (Ritthoff et al., 2002). The calculation is the same as in step 4; the material inputs per natural input category (abiotic raw material, biotic raw materials, earth movements, water, and air) are summed up.

Once the total Material Input of the product along its entire life cycle is determined, the service unit is included in step 6. To compute the Material Input Per Service unit, the Material Input per data category is derived by the number of the service unit (e.g., 100 for 100 wearing cycles of a t-shirt) (Ritthoff et al., 2002). Within this step, all five data categories are used (abiotic raw material, biotic raw materials, earth movements, water, and air). Comparability between these products can be achieved by deriving the material input with the service unit of different products (e.g., with a t-shirt with 20 wearing cycles) (Ritthoff et al., 2002). Lastly, the results of the calculations are evaluated and interpreted in step 7. Three leading indicators can be derived:

- Total Material Requirement: the sum of the categories (abiotic, biotic materials and earth movement). The indicator can be "[…] used in resource accounting of national economies."(Ritthoff et al., 2002, p. 33). It is also referred to as Material footprint by Liedtke et al. (Liedtke et al., 2014).
- Water backpack (Liedtke et al., 2014): Resource use of water
- Air backpack (Liedtke et al., 2014): Resource use of air

Comparing the results of different products makes it possible to choose a preferred alternative (Ritthoff et al., 2002). Additionally, it is possible to identify the most material-intensive process steps and life cycle stages (Ritthoff et al., 2002). Optimization strategies can be derived and defined based on the analysis results (Ritthoff et al., 2002). The calculation of the MIPS can support analyzing and finding ways to prevent and reduce resource extraction from nature and, therefore, the environmental impact (Liedtke et al., 2014). Additional applications and indications can be found in the literature (see Liedtke et al., 2014).

5.3 COMPARISION OF QUALITATIVE COMPARISION RESULTS AND USE CASE APPLICATION

The insights gained from the practical application of two methods is used to validate the findings of the comparative analysis described in chapter 4. The score received from the analysis is compared to the experiences gained from the use case application. The scores are compared for the methods LCA (Table 19), Ecological rucksack (Table 20), and partly for MIPS (Table 21). If necessary a change of the individual score is proposed. Lastly, the overall accuracy of the comparative analysis is evaluated. As a consequence, proposals to adopt the comparative analysis might become evident.

Table 19 Score validation for LCA (own source)

Criteria	**Score received**	**Experience**	**Change of score**
Standardization	3	The standards are available and helpful for conduction the analysis. Nevertheless, the definition of the study, the collection of the data and modelling the system are dependent on the study executer. Thus, although standards are available the study can still be influenced by the involved people. However, standards are the highest form of formalization possible, therefore the score given is justified.	NO
Life Cycle Thinking	3	According to the PEF method, all life cycle stages shall be included in the study. If someone purposely decides to act against this requirement (like done in this study), then the life cycle thinking is not followed by the study executer. The method in itself, however, covers all life cycle stages.	NO
Resource inflows	2	All inflows as described in theory are taken into account.	NO
Emissions	3	All type of emissions are taken into consideration.	NO
Additional flows	0	No additional flows are taken into consideration in the use case.	NO
Database availability	3	Data that could not be measured, is estimated based on literature and databases. Most of the missing data could be found either within the literature or a database. Additionally, many variants per materials could be found in the databases, so that suitable data for the study could be used (e.g. data for the same material but produced in different countries).	NO
Amount of data	0	The amount of data collected for the study is high. When conducting the method, the most time is invested into the data collection. But the data collected for the MIPS is the same.	NO
Complexity	1	Understanding the fundamentals of the LCA method was not straight forward. However, many guiding documents and examples are available within the literature that help to understand the concepts and to conduct the study. Nevertheless, it was necessary to model the LCA, which increased the complexity significantly. It was even done with the help of an expert.	NO

Table 20 Score validation for Ecological rucksack (own source)

Criteria	Score received	Experience	Change of score
Standardization	2	The handbook for MIPS calculation provides a detailed guide on how to calculate the Ecological rucksack. It was possible to follow the methodological steps, due to the detailed description.	NO
Life Cycle Thinking	1	The calculation of the Ecological rucksack only takes the cradle to gate stages into account. Additionally, it was not clear on whether to include transportation or not, based on the handbook. Even though transportation is mentioned in the handbook, it is not included in the example calculations.	NO
Resource inflows	1	Air and Water inflows are considered during the data collection (according to the handbook). However, they are reported aside from the Ecological rucksack and not necessarily used further. Due to the fact, that the data is collected anyways, the score could be changed.	MAYBE, to 2
Emissions	0	Emissions are not taken into consideration. They should be collected during the data collection, but are not relevant for the method or handled further.	NO
Additional flows	0	No additional flows were taken into account.	NO
Database availability	2	One database is available. However, the data within is limited and the data base was not updated since 2014. Much data could not be found within the database or only other versions of it (e.g. data from Finland). In addition, no data for MIT values could be found when searching for it in literature (using google and google scholar with the search terms: Material intensity; Ökologischer rucksack; Ecological rucksack, Material intensity factor). As the criterion is defined on whether or not a data base is available, the score should remain the same. However, the score should be changed, if the data base is directly compared to other methods. Alternatively, the criterion should be updated. Furthermore, if the quality of the data and database would have been taken into account, the score would need to be corrected.	NO (MAYBE to 1)
Amount of data	1	Even though the ecological rucksack indicator only takes a cradle to gate approach, the data for the entire life cycle should be collected, according to the handbook. Therefore, the data need is as high as for the LCA and MIPS assessment.	YES, to 0
Complexity	2	Calculating the Ecological Rucksack was straightforward, due to the handbook. The data collection and calculation could be done in a familiar tool (data sheet). Additionally, no use phase or service data is needed, which appears to be difficult to define and collect. Therefore, the complexity is perceived as low.	YES, to 3

Table 21 Score validation of MIPS (own source)

Criteria	Score received	Experience	Change of score
Standardization	2	The handbook for MIPS calculation provides a detailed guide on how to calculate the MIPS. It was possible to follow the methodological steps, due to the detailed description.	NO
Life Cycle Thinking	3	The MIPS approach covers the entire life cycle. However, it was not clear whether or not to include transportation, based on the handbook. Even though transportation is mentioned in the handbook, it is not included in the example calculations. Furthermore, it is only necessary to take waste and emissions into account, if they are processed further. Therefore, the disposal stage is optional and depends on the system boundary definition.	YES, to 2
Resource inflows	2	All expected inflow are considered	NO
Emissions	2	The inclusion and interpretation of the emissions depends on the system boundary definition. Therefore, an inclusion of the emissions is not always the case. But, based on the current criterion definition the score should remain the same. Alternatively, the criterion definition should be changed.	NO (MAYBE)
Additional flows	0	No additional flows were taken into account.	NO
Database availability	2	One database is available. However, the data within is limited and the data base was not updated since 2014. Much data could not be found within the database or only other versions of it (e.g. data from Finland). In addition, no data for MIT values could be found when searching for it in literature (using google and google scholar with the search terms: Material intensity; Ökologischer rucksack; Ecological rucksack, Material intensity factor). As the criterion is defined on whether or not a data base is available, the score should remain the same. However, the score should be changed, if the data base is directly compared to other methods. Alternatively, the criterion should be updated. Furthermore, if the quality of the data and database would have been taken into account, the score would need to be corrected.	NO (MAYBE to 1)
Amount of data	0	The data need is as high and the same as for LCA.	NO
Complexity	1	Cannot be assessed do to missing definition of the service unit.	/

No score is proposed to be changed based on the experiences of conduction the LCA in practice. Therefore, the scoring given for the LCA method during the comparison analysis appears to be accurate. Two scores need to be changed after conducting the Ecological rucksack method in practice. The score for the amount of data and for the complexity need to be adopted. Furthermore, for two scores is not clear whether or not they should be changed or not. Based on the defined criteria they do not need to be changed, however, from the gained experience a change should be done. Here the conclusion can be drawn, that the defined criteria needs to be revisited and adopted. The respective criterion are for the resource inflows and the database availability.

Based on the experiences of the practical application, the score for the life cycle thinking of the MIPS needs to be changed. Furthermore, the definition of two criteria should be revisited (emissions and database availability). For these criteria, a score change is not necessary according to the defined scoring criteria. However, after conducting the assessment (or parts of it), the score given for these criteria does not appear to represent a real-life situation. Here the conclusion can be drawn that the defined criteria need to be revisited and adopted.

Overall, it can be concluded that the qualitative comparison developed in this study provides a way to assess and rank the method. Furthermore, it can function as a baseline for comparing methods with each other. However, there is room for improvement. The qualitative comparison is purely based on results from the literature and subjective assessment. Compared to a practical application, it becomes clear that the theoretical assessment is not accurate for all defined methods and criteria. While it works well for Life Cycle Assessment, mismatches are identified for the Ecological rucksack and MIPS. Here the theoretical knowledge provided in the literature does not match the practical experiences. This could be the case due to unclear literature or a misunderstanding of the researcher. Hence, evaluating the method's potential only on theoretical and secondary data is not entirely accurate. Experiences from a practical application should be considered to increase the findings' accuracy and validity.

Additionally, the criteria for the comparative analysis are not defined clearly enough in some cases. The criteria database availability, resource inflows, and life cycle thinking should to be revisited and defined further. Some criteria can be influenced by the assessment executor (like life cycle thinking or flows). Therefore, the scoring is not always straightforward or black and white. A way of including these varying characteristics needs to be defined.

Lastly, further validation of the qualitative comparison method, the defined criteria, and the results should be done. As only the results for the methods LCA, MIPS, and Ecological rucksack could be reviewed, it is not possible to validate the entire qualitative comparison. All methods would need to be executed, and the experiences compared to the theoretical based scoring. Furthermore, within this thesis study, only one use case representing one specific type of technology is applied. Different use cases should be used in the future to validate the entire method and increase the generalizability of the findings. Ideally, these other technologies are in different development stages as the use case technology. Only if several applications with different types of technologies at varying development stages are performed the qualitative comparison can be more thoroughly verified.

6 CONCLUSIONS

The last chapter of the thesis is divided into three parts. First, the results are summarized and conclusion drawn from them. This includes a revisit of the research question and whether or not it could be answered. In addition, the practical and academic relevance is assessed. Second, the findings and the methodological approach are discussed and limitations pointed out. Lastly, recommendations for the future are given.

6.1 SUMMARY AND CONCLUSIONS

Sustainability is a crucial topic in the day to day life as well as in industries. With the help of new technologies, the negative impacts on sustainability can be decreased. During the development of these technologies, the concept of sustainability should be included at all times. This can be done with the help of sustainability assessment methods. However, companies (like the case company of this study) often only adopt one or a few sustainability assessment methods into their product development process. These methods might not necessarily be suitable for the technology under investigation. Furthermore, guidance on when to use which method is missing. The aim of this thesis study is to fill this gap.

Main research question

What decision support can be used to select a sustainability assessment method for technology development in the aviation industry?

Resulting of the analysis, it can be concluded that there is not one sustainability assessment method that is best in all criteria and application cases. Therefore, it is impossible to define one best method in all cases. Choosing the proper method depends on the scope (substance, product, or material) and the intended outcome. Thus, relying solely or predominantly on the Life Cycle Assessment cannot be recommended. Alternative methods, like the ones included in this study, should be adopted and applied within the case company.

Within the thesis study, two main components for selecting the most suitable sustainability assessment methods are developed. A flowchart for choosing the most suitable method base on the intended objectives and a ranking of the methods. Two different types of ranking are developed. On the one hand, a spiderweb diagram that raises awareness and enables a comparison between methods. On the other hand, four rankings that enable comparison based on a number. The spiderweb and the ranking can be used to assess whether or not the choosen method has drawbacks. Additionally, they can guide the selection of an alternative method if the drawbacks are not acceptable. By following the main components (first, the selection via the flowchart diagram, then the comparison via the spiderweb and /or the ranking), a user should be able to select the most suitable sustainability method or decide on which alternative to take.

Phase 1: Identification of methods and tools

Which sustainability assessment methods are suitable for an assessment during technology development?

Based on the literature study, 56 sustainability assessment methods could be identified. These sustainability assessment methods varied from each other in several ways (like the sustainability pillar assessed). In order to decrease the number of methods and make sure they fit the scope of the study (technology development within the aviation industry), criteria for down-selection are identified. These criteria cover the following aspects:

- The method is widely accepted as a sustainability assessment method
- An analysis or assessment of the sustainability of the technology is enabled
- The scope of the method fits the study need (new technologies/ the development of new products)
- The method assesses the environmental pillar

Based on the criteria, a down selection to four suitable methods / method groups could be made. Energy/Exergy/Emergy Analysis, Life Cycle Assessment, Material Intensity methods, and Material Flow methods.

Phase 2: Analysis and decision support design

How can a decision support for the selection of a suitable assessment method be designed?

Based on literature search results and identified relevant knowledge, a shared understanding of the methods could be provided. The requirements for the knowledge collection on each method is done based on a brainstorming approach. As relevant for the study are the following type of information identified: The objective/ aim of the method; Input data required; Output data required; Indicator/ the indication derived from the method; Application examples & recommendations; Strength of the method; Drawbacks & criticism of the method and Nature of the analysis. After justifying why this type of information is relevant, the data was compiled for each method. The collected information and knowledge of the individual methods led to the design of a guidance for non-experts. Here a decision tree is designed, which supports the selection of a method based on the scope or subject of the analysis (a substance, a material, a product); the type of flows primarily considered (Energy flows; material (resource) flows) and the type of data (quantitative and qualitative).

Phase 3: Development of a ranking

How can a ranking of the methods to each other be developed?

In order to rank the method a qualitative comparison is developed. To do so, criteria for the comparison are defined. These criteria build the foundation of the ranking and the qualitative comparison. The defined criteria are standardization, life cycle thinking, inventory flows (in- and outflows), coverage of other sustainability pillars, the availability of databases, the amount of data needed, and complexity. For each criterion, a score from zero to three can be achieved (except for the sustainability pillar, here a two is the maximum achievable score). While a zero always represents the least desirable option, a three defines the most desirable option. Each method is evaluated against the defined criteria and receives the according score.

The obtained scores are used to develop two different representations. On the one hand, a visual representation of the individual scores in the form of spiderweb diagrams. With the help of these spiderweb diagrams, a method can be compared to another method at one glance. Additionally, awareness of the strength and weaknesses are provided (high and low scores). On the other hand, the scores of the different criteria are added up, and a ranking based on numbers is provided. Here four types of ranking are developed to account for different types and objectives of sustainability assessment studies.

- An overall ranking including all criteria. Material Flow Analysis is ranked the highest, followed by Life Cycle Assessment and Substance Flow Analysis.
- An overall ranking including all criteria except complexity. Complexity is taken out of this ranking, as it is based mainly on subjective evaluation. If the complexity criterion is excluded, LCA is ranked the highest, followed by MSA.
- A ranking based on ease of use. It shows which method is especially suitable for early development stages. Energy Analysis and Material System Analysis obtain the highest ranks.
- A ranking based on completeness, indicating which assessment method covers the most topics at once. Life Cycle Assessment and Material Input per Unit of Service receive the highest rankings and thus cover the most areas.

Based on the ranking, conclusions can be drawn for the status quo method Life Cycle Assessment. The status quo method LCA is ranked the second best when complexity is considered. Without complexity, it even becomes the best-ranked method. Furthermore, the Life Cycle Assessment method considers the most environmentally relevant flows. However, the data need and complexity of LCA are high; therefore, it is not recommended to be used in very early design stages. It can be concluded that Life Cycle Assessment is a suitable method for sustainability assessment. However, for technologies in the early development stages, it is not the best.

Phase 4: Validation of the developed ranking method

What influence does the practical application have on the developed method of qualitative comparison?

Based on the practical application of the two methods, the developed qualitative comparison could partly be validated. It can be concluded that the qualitative comparison developed in this study provides a way to rank methods. However, improvement needs to be done. The qualitative comparison is purely based on findings from the literature and subjective assessment. When compared to a practical application, it becomes clear that the theoretical assessment is only accurate for some of the methods and defined criteria. While it works well for Life Cycle Assessment, mismatches are identified for the Ecological rucksack and MIPS. Hence, ranking the methods only on theoretical and secondary data is only partially accurate. In conclusion, an unignorable influence of the practical application on the developed qualitative comparision and ranking method can be seen.

6.1.1 ACADEMIC RELEVANCE

In this thesis project, different ways of providing decision support for selecting a suitable sustainability assessment method are developed. In the beginning, a literature review is conducted to identify an academic knowledge gap, which is defined as follows:

- No harmonized method or framework for choosing a sustainability assessment method seems to exist or is being agreed on.
- No clear guidance on which sustainability assessment method to use during the development of new technology in the aviation industry could be found within this literature review.

Two types of literature can be frequently found. The first type is a general description of various sustainability assessment methods. In comparison, the second type is the application of one or two methods on one specific use case. Literature taking several sustainability assessment methods for various use cases in a specific industry into account is rarely found. This project contributes to this type of literature by identifying and selecting a range of methods for a specific industry. Apart from this, literature comparing methods with each other mainly focus on two or very few methods. Although it is possible to identify literature comparing several methods, the comparison is mainly based on secondary data without further validation. In contrast, an approach to validate the comparison results is developed and shown within the thesis. This contributes to the existing body of literature and might make future research more robust.

Finally, guidance on selecting a suitable sustainability assessment method is developed. This guidance consists of two parts, a visual decision tree and a comparison/ ranking in the form of spiderweb diagrams and numbers. While other literature entailing spiderweb diagrams can be found in the literature, the transfer of these findings into a ranking can be found rarely. Additionally, visual guidance with the help of a flowchart/ decision tree is seldom encountered. Furthermore, the suggested methods contribute to developing a harmonized method or framework for choosing sustainability assessment methods. The project findings can be used to base further research on and contribute to filling the identified knowledge gap.

6.1.2 PRACTICAL AND SOCIETAL RELEVANCE

This thesis project is carried out in cooperation with Airbus Operations GmbH. An exchange with the case company Airbus revealed a practical knowledge gap. It is described as a missing clear recommendation on methods and tools and the most appropriate application timing during the innovation process. Thus, it is also essential to look at the practical relevance of the thesis project.

First of all, the literature review done in the project's first phase provides an overview of available sustainability assessment tools, methods, and concepts. The down selection of methods with the help of selection criteria supplies a narrower and as more suitable evaluated list of methods. This can provide the case company, the industry and other stakeholders an idea about which methods to investigate for adoption in the future. Secondly, a short description of the characteristics of each method is provided. The concise summary can function as a starting point for investigating other methods for the case company and other companies. Thirdly, the development of the decision tree for method selection showcases a possible way of designing a practical and visual decision guide for the method selection based on the type of technology and intended assessment focus. Additionally, it shows the case company that the selection of the assessment method has an impact on the assessment results. Fourthly, by comparing the different methods, awareness is raised that there is not one method that fits best in all scenarios. Therefore, it is not advisable for the case company to only focus on Life Cycle Assessment. The outcome of this study can therefore be seen as two different assets for the case company:

1. A guide on how to develop a practical guide for method selection
2. A recommendation to adopt further sustainability assessment methods within the technology development process

Concerning the societal relevance of the thesis project, it can be said that the outcome fosters an increase of sustainability considerations in technology development. By presenting different sustainability assessment methods and a way of including them in the development process, an increase in sustainability assessment and awareness can be expected. Selecting a suitable assessment method for the respective technology might lead to the development of more sustainable technologies. As a result, negative impacts on our environment are expected to decrease. The method developed in this project could also be transferred and help to identify and select sustainability assessment methods for the economic and social pillar. This might help to develop holistically sustainable technologies and decrease their impacts.

6.2 DISCUSSION AND LIMITATIONS

The most frequently used method within this study is the literature study. The literature identified with this method depends on the defined search terms as well as the chosen search engine. Therefore, it is possible to overlook important information if the search terms are defined incorrectly, too narrow, or if only a specific search engine and database used. An example of this is the identification of methods that are included in the study. A high chance exists that methods are overlooked or not found in the beginning due to the defined search terms, used search engines, and selected literature. These excluded methods might have led to different results and recommendations.

Another limitation arising from the literature study is the amount of possible information available and the information considered within the study. Only a certain amount of literature could be studied during the literature study. The literature taken into consideration was mainly the ones proposed as most relevant by the search engines. Therefore, a dependency on search engine algorithms can be identified.

Most of the data used within the thesis study are secondary data from the literature. Primary data is obtained only during the exemplary application and validation of the methods of LCA and Ecological rucksack (and MIPS). Therefore, the findings and conclusions depend on other people's results. The methods used and the conclusions drawn in the studies of other researchers might not precisely fit the study's scope, not be transparent, or are influenced by personal opinions. In addition, other researchers might be biased and overemphasize a method positively or negatively. This could especially be the case in literature, which is written by the method developer or his/her colleagues. In general, high uncertainty is added to the study and the findings due to the use of secondary data.

Additionally, an asymmetry of data and literature availability can be identified. Some methods, like the Life Cycle Assessment, are integrated in many companies and are included in several studies. Therefore, the amount of literature and knowledge accessible for LCA is higher than for a method that is not as frequently and widely used.

During the validation of the comparative analysis, several flaws could be identified. First, the comparative analysis is only based on secondary data (see above). Furthermore, the developed ranking is influenced by the researcher. This becomes especially evident during the evaluation of the complexity criteria. Since no expert was available at the case company, the complexity evaluation is on subjective evaluation. Consequently, the results should be used cautiously.

Compared to a practical application, it becomes clear that the theoretical assessment is inaccurate for some defined methods and criteria. The theoretical knowledge provided in the literature and the assumptions made by the researcher do not match the practical experiences. This could be caused by unclear literature or a misunderstanding by the researcher. However, evaluating the method's potential only on theoretical and secondary data is only partially accurate.

Additionally, the comparative analysis criteria are not clear enough in some cases. Here a revisit and update of the criteria are needed. An example is the quality of databases as opposed to only taking the quantity into account. When considered, the MIPS and Ecological rucksack score would change for the criterion *database availability*. This could also result in a change of the ranking.

Lastly, the validation of the method is only performed partly, with the help of two/ three methods. Only the findings for the methods LCA, MIPS, and Ecological rucksack could be reviewed. Thus, it is not possible to validate the entire qualitative comparison method. Furthermore, only one use case representing one specific type of technology is used. Overall it can be concluded, that the ranking derived by the qualitative comparision is not accurate, influenced by subjective decisions and not generalizable.

Limitations can also be found regarding the selection and conduction of phase 4 –validation. The life cycle phase needed to be excluded from the use case due to the generalizability of the technology and the not yet defined product. Therefore, it is impossible to consider the entire life cycle, which would be needed to evaluate the life cycle thinking criterion. It was also impossible to conduct the entire MIPS study, as the use phase is essential for the calculation. Overall a different use case should have been chosen, and the selection of the use case done more carefully.

Furthermore, many assumptions are made during the data collection and application of the LCA and MIPS/Ecological rucksack data. The reason for this is the low data availability due to the early development stage. Even though the assumptions increase the uncertainty included in the findings of the LCA, MIPS, or Ecological rucksack, the impact on the results of the thesis study is expected to be low. The assessment of technologies within early development stages and the way of dealing with the low data availability are part of the research gap identified.

Finally, no test of the developed components is done. Neither by the researcher nor by a potential user. Therefore, it could be the case that the use of the flowchart and the rankings (spiderweb and number ranking) is not as practically applicable as the researcher expects it to be. Furthermore, it might lead to the proposal of a not suitable method. Thus, a practical application of the method by a potential user (non-expert) is recommended for the future.

In addition, it is necessary to discuss the possible impacts of the findings on the case company. The recommendation for the case company is to adopt additional methods next to the LCA. This could lead to an increased effort for the case company. Competences and skills need to be developed and made available for each method. An employee might need to acquire knowledge about several sustainability assessment methods, which could be time consuming and complex. Furthermore, it might be necessary to buy software or datasets for the execution. Lastly, the within this thesis developed decision support needs to be integrated into existing business practices. A possible way could be the integration into the TRL process. To do so the TRL process would need to be updated and additional criteria for the method selection defined. This creates an additional effort for the case company.

However, the adoption of additional methods, that might be more suitable for the individual technology under development, could lead to an increased use of sustainability assessment method. The willingness of employees to conduct an assessment could increase. This could result in more assessments and an increased focus on sustainability (the environment) during technology development. Thus, more sustainable technologies might be developed. This could benefit Airbus' sustainability strategy (as described in chapter 1.1.3) and contribute to the following (SDG) goals:

- Foster innovation to reduce the environmental impact (goal 9)
- To minimize the environmental footprint (goal 12)
- Improve the environmental performance of the products (goal 13)

6.3 RECOMMENDATIONS

Recommendations for further work and improvement of the study can be proposed.
As an improvement of the study and chosen research methods, the involvement of further experts can be suggested. The researcher and one expert conduct the criteria definition and underlying brainstorming. The same is the case for feedback on the decision tree. The involvement of further experts might increase the objectivity of the methods and the results.

Experts should also be consulted for the evaluation of the method's complexity. Even though these experts might not be available within the case company, they might be available outside of it. The consultation of experts outside the company for the complexity criteria is recommended.

Recommendations for the validation phase can be found as well. The application of all methods (and not only a few) for the same technology should be made in the future. Further use cases should be identified, and all methods applied to those. Ideally, these additional use cases represent technologies in different development stages.

Another recommendation is to include further criteria in the qualitative assessment. For example, the quality of databases or guidance documents can be presented. Moreover, the meaningfulness of the sustainability assessment should be added. In the currently defined criteria, no information regarding what precisely or sustainability is assessed with the method is included. This could be a piece of valuable information for the user. In addition, a weighting of the individual criteria and scores could be added, to put an emphasis on specific aspects of a method.

Further work should be invested into looking at hybrid approaches. Within hybrid approaches, different sustainability assessment methods are combined. This could lead to the elimination of individual studies' drawbacks (e.g., LCA). Examples of those are:

- "Emergy accounting can be used to expand LCA's focus in order to properly account for contribution of flows that are not associated to significant matter and for energy carriers (such as labor, culture, and information) responsible for system/ process sustainable dynamics." (Ameral et al., 2016, p. 886)

- "The combination of exergy-based methods and LCA is attractive because exergy can provide a common ground for ecological and industrial processes, in which all types of material and energy streams can be fairly assessed, or valued." (Hau & Bakshi, 2004b, p. 3769)

The components and scientific methods used and developed within this thesis study could be applied to the other two sustainability pillars. Doing so could create a similar decision-making guide for the economic and social pillars. Once all three decision supports are defined, a holistic approach can be achieved, or the findings can be combined into one decision support.

The methods identified as going beyond the environmental pillar (Emergy, Material System Analysis, and Substance Flow Analysis) could be a starting point for a more holistic sustainability assessment. These methods should be investigated further by the case company.

In the future, a checklist could be selected or developed for the case company and the integration into the decision support. A checklist might be helpful to raise awareness and conduct a sustainability assessment at the earliest development stages.

Lastly, the case company should adopt more environmental assessment methods, as Life Cycle Assessment is only sometimes the best method to choose.

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APPENDIX A – LITERATURE STUDY

As described in chapter 1.2.1, a literature study was conducted to identify the current knowledge base and knowledge gap. Resulting of the literature study with the first search string (displayed in Table 22 and called search 1 in Figure 37), 104 search results were generated. Twenty-six of those were not accessible. After identifying the accessible literature findings, the abstracts of the literature were scanned. Many literature search results focus on airline services, airport operations, or assessing existing technologies. Thus, they did not fit into the scope of this study and were not analyzed further. The promising articles were looked at in more detail and the full text was analyzed. The first search string led to the identification of eight suitable studies.

Table 22 Scopus search string 1 (own source)

Connector	Search area	Search term
	Title, Abstract, Keywords	sustainable AND product AND development
AND	Title, Abstract, Keywords	aviation OR aircraft OR airplane
AND	Title, Abstract, Keywords	method OR tool

After the first literature search, another review was performed. For this, the search string within Scopus was modified. The overall scope got broadened, but also areas out of scope were excluded (like drones, airline services, etc.). Furthermore, the search results got reduced by only considering English and open-access findings. A detailed overview of the search string can be found in Table 23. Fifteen literature findings were identified by both search strings, probably due to the similarity of the search strings. These duplicates were excluded from the further assessment of the second results. After scanning the abstracts and the full text of relevant studies, five literature findings got identified as suitable for inclusion in the study. An overview of the identified literature search results can be found in Figure 37.

Table 23 Scopus search string 2 (own source)

Connector	Search area	Search term
	Title, Abstract, Keywords	sustainable AND product AND development OR innovation
AND	Title, Abstract, Keywords	aviation OR aircraft OR airplane OR aerospace
AND	Title, Abstract, Keywords	method OR tool OR assessment
AND NOT	Title, Abstract, Keywords	airport OR airline OR drone* OR unmanned OR remote*
AND	Title, Abstract, Keywords	manufacturing OR production

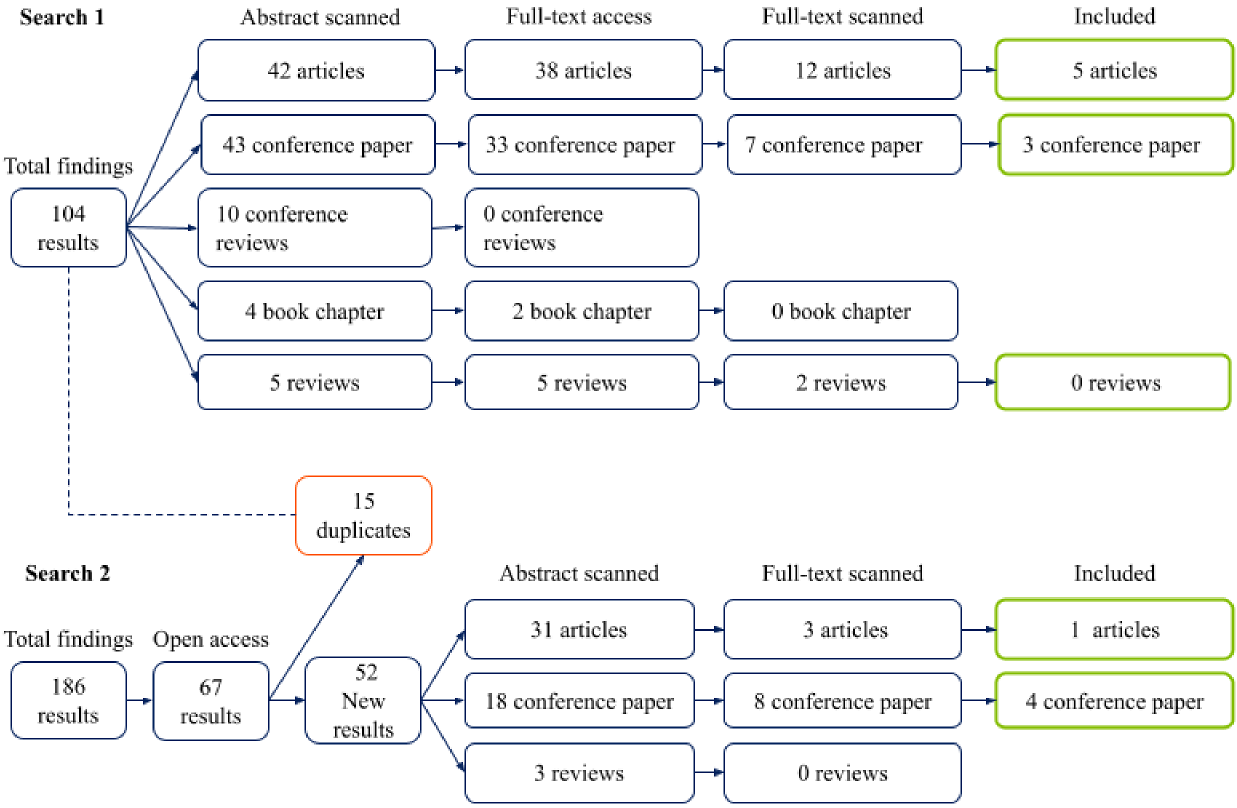

Figure 37 Literature research results (own source)

APPENDIX B – OCCURRENCE PER METHOD WITHOUT HALLSTEDT

Within Figure 5 the occurrence of a method within the analyzed literature, excluding the one Hallstedt is involved in, is visualized. This figure shows that the life cycle methodologies are mentioned most often within the literature.

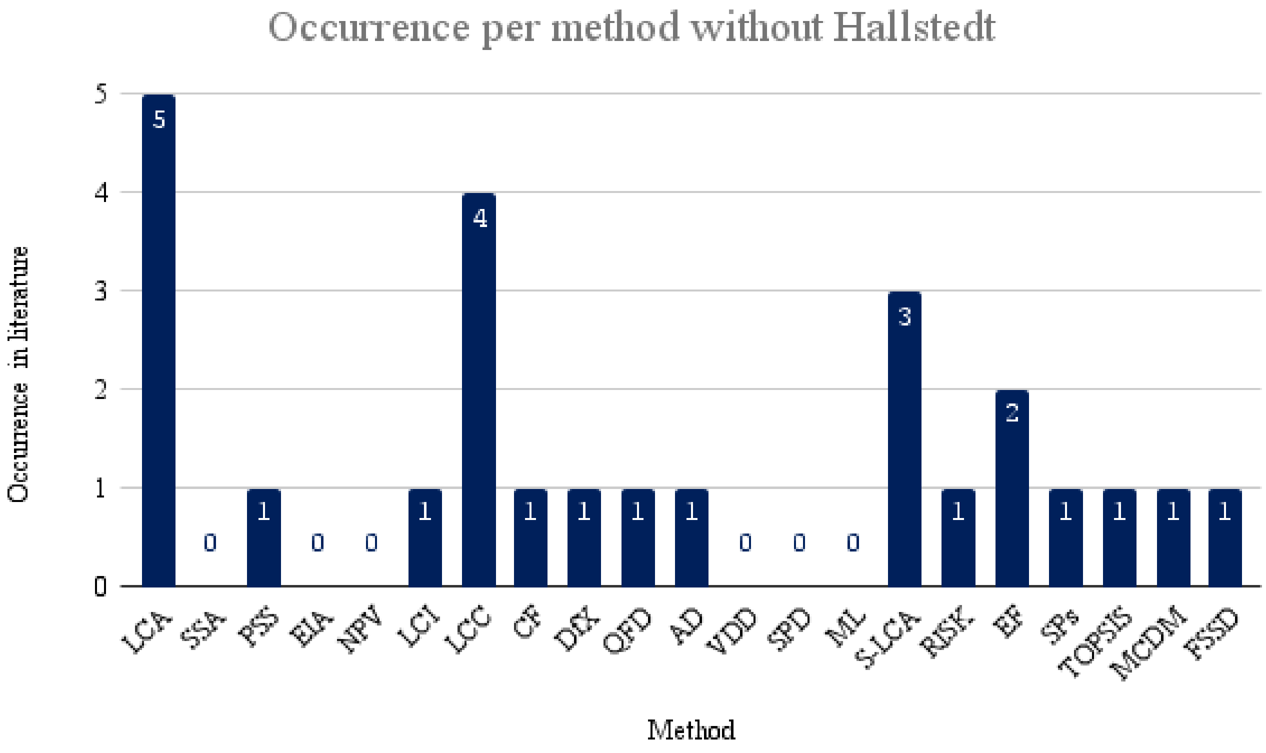

Figure 38 Occurrence per method in studied literature without Hallstedt (own source)

APPENDIX C – DESCRIPTION OF METHODS IDENTIFIED IN THE LITERATURE

Table 24 Name and description of identified methods (own source)

Method name (Method Abbreviation)	Short description	Reference
ABC-Analysis (ABCA)	ABC analysis enables the classification of items into groups based on one criterion. It is widely used within inventory management. The traditional ABC analysis allows the separation of stock-keeping items into three groups: A – very important, B – important, and C – least important. The efforts spent dealing with each item are based on the classified importance.	Chu et al., 2008
Agent-Based Modelling (ABM)	Agent-based modeling (ABM) can be used to simulate dynamics within geographic systems. It allows the disaggregation of systems into individual components, which can potentially have their properties and rule sets.	Crooks & Heppenstall, 2012Crooks
Axiomatic Design	Axiomatic design principles form systematic scientific bases for designers to solve design problems and integrate customer needs. It is especially applied during product, product systems, and software design processes	Kulak et al., 2010
Checklists (CL)	A series of questions that should help designers address sustainability issues during the design process systematically	Woodhouse et al., 2018
Conceptual modelling or Causal modelling or Soft-systems modelling or Mental modelling (CM)	Analysis of quantitative relationships. It can be used to visualize and determine possibilities for change within a system.	Ness et al, 2007
Cost-Benefit Analysis (CBA)	A method to weight the costs and the benefits of a proposal, project, or policy. Assessment of the attractiveness of private or public investment proposals or projects by weighting the costs against the expected benefits.	Hoogmartens et al., 2014, Ness et al, 2007 ; Andersson et al., 2016
Cost-Benefit Matrices (CBM)	Integration of difficult to quantify (intangibles) issues into the cost-benefit analysis (mainly social impacts). Developed for decision-making in the public sector	Ziller & Phibbs, 2003
Customer Immersion (CI)	Describes the process through which consumers interact with a product, gaining access to a holistic experience	Arnould et al., 2002; Pine and Gilmore, 1998; Schmitt, 1999, as cited in Addis & Sala, 2007
Design of X/ design for Excellence (DfX)	Set of design guidelines. Each design guideline addresses a specific issue that affects or was caused by the characteristics of	Moreira et al., 2015

Method name (Method Abbreviation)	Short description	Reference
	a product. Overall, DfX considers all design goals and interconnected constraints in the early design phases	
Diffusion Assessment and Growth-Curves Models for New Technologies (DAGCM)	Diffusion assessment: A process for communication through certain channels over time and among social system members. Growth curves: A modeling approach. Used e.g., To model energy resources, energy demand, fuel substitution, and energy technology development within an energy system analysis	Rao & Kishore, 2010; Davidsson et al., 2014
Driving Force-Pressure-State-Impact-Response Reporting (DPSIR)	A conceptual framework to analyze the cause–effect relationships between the environment and society. Furthermore, it supports decisions in response to environmental issues.	Spanò et al., 2017
Dynamic integrated Driving Force State Impact Response Model (DIDFSIRM)	No information found	
Ecological Risk Assessment (ERA)	A process to evaluate the likeliness of an environmental impact caused by exposure to stressors, like: chemicals, land change, disease, invasive species and climate change.	Murthy, 2022
Energy/Exergy/Emergy Analysis (EEEA)	"Emergy analysis can provide a common scale for measuring and comparing different substances, energy types, environmental impacts and economic indicators" "Energy, exergy and emergy analysis is critical to determine both thermodynamic efficiency and resource utilization performance of a desalination process which also serves as a sustainability indicator"	Gude et al., 2017
Environmental Footprint (incl. carbon, water, energy, etc. footprints) (EF)	It aims to visualize the impact (like resources use and waste production) created by human activities on the planet's resources and their production. They are oriented on resource use and emissions.	Andersson et al., 2016; Vanham et al.,2019
Environmental Impact Assessment (EIA)	Evaluation of potential environmental impacts of projects aiming to reduce the negative effects. "[…] a simplified, qualitative, life-cycle assessment and eco-design tool, aiming at identifying and assessing significant environmental impacts generated by the product's life cycle, from the resource extraction phase to the end of life, early in the product development process."	Sadler, 1999, as cited in Ness et al., 2007; Hallstedt & Isaksson, 2013
Environmental Risk Assessment (ERA)	"Environmental risk assessment (ERA) is a tool for evaluating the environmental impacts of chemicals that are released into the environment and can be used in risk management. The potential	Andersson et al., 2016; European Commission, 2003

Method name (Method Abbreviation)	Short description	Reference
	pathways of released chemicals are modelled, and the resulting doses to ecosystems or individual species are assessed". "[…] attempts to address the concern for the potential impact of individual substances on the environment by examining both exposures resulting from discharges and/or releases of chemicals and the effects of such emissions on the structure and function of the ecosystem."	
Experience Curves for Future Performance Assessment (ECFPA)	"The experience curve approach is an empirical concept that models production costs of technologies as a power–law function of cumulative experience, i.e., cumulative production. Cost dynamics are thereby quantified by learning rates, which indicate the rate of cost decline with each doubling of cumulative production. For several decades, experience curves have been widely used for strategic planning in manufacturing. Since the 1990s, experience curves are increasingly applied to establish efficient energy technology policies and to forecast technology diffusion and technological change in energy and greenhouse gas (GHG) emission models".	Weiss et al., 2010
Framework for Strategic Sustainable Development (FSSD)	Name to various sustainability assessment methods, tools, and concepts. It enables clarification of their respective strengths and aids the coordinated use of them.	Broman & Robèrt, 2017
Full Life Cycle Assessment (LCA)	Method to analyze and quantify potential environmental impacts of product systems throughout their entire life cycle, from raw material extraction until the end of life.	European Commission - Joint Research Centre, 2021; Ness et al, 2007
Hedonic Pricing Method (HPM)	An economic method for isolating the impacts of individual attributes of a good or a service on the price of that good or service.	Czembrowski & Kronenberg, 2016
Life Cycle Costing (LCC)	Economic approach to analyze the total costs related to an activity, product or process discounted over its lifetime.	Gluch and Baumann, 2004, as cited in Ness et al, 2007; Ciroth et al., 2011
Life Cycle Index (LInX)	"LInX is an indexing system that incorporates the life cycle attributes of process and products in decision-making. " It can be seen as an attempt to enable a simplified assessment by bringing Multi criteria assessment and Life Cycle Assessment together.	Khan et al., 2004; Bailey et al., 2010
Life Cycle Sustainability Assessment (LCSA)	Life Cycle Sustainability Assessment (LCSA) was developed to deal with all three pillars of sustainability. Apart from the LCA,	Ciroth et al., 2011

Method name (Method Abbreviation)	Short description	Reference
	it consists of a Life Cycle Costing (LCC) and a Social Life Cycle Assessment (sLCA). Combining all three analyses should enable a holistic and balanced assessment of the product system life cycle. It should help to make a trade-off between the three sustainability pillars, different products, and other life cycle pillars.	
Market Assessment (conventional) (MAUM)	Assessments of customer wishes, market size, and probability of success.	Deszca et al., 1999
Material Criticality assessment	Method to characterize and analyze the criticality of alloys in a three-step process, aiming to support product design teams in selecting what material alloy to use. A proactive and systematic approach to taking critical materials and the potential long-term problems arising from them into account.	Hallstedt & Isaksson, 2017
Material Flow Analysis and Substance Flow Analysis (MFA/ SFA)	MFA is an analytical accounting tool that provides information about amounts and kinds of physical flows through socioeconomic systems When substances are addressed within the assessment, it is called the substance flow analysis (SFA). The method is used to define flows, stocks, and sinks of materials within a particular system.	Fischer-Kowalski et al., 2011; Andersson et al., 2016
Mathematical Programming	Model widely used in operational research and management science. Involves a set of mathematical relationships.	Williams, 2013
Morphological Matrix	A method of thinking. It enables the selection of the best (design) concepts/solution by combining the various function actuators in a systematic way.	Fargnoli et al., 2006; Ölvander et al., 2009
Multi-Attribute Utility Methods (MAUM/MAUT)	"[…] a set of procedures to guide decision-making process that integrates multiple outcomes from a choice into a single number that represents the usefulness of that choice.". Part of multi criteria decision making methods.	Shaik & Abdul-Kader, 2011; Pohekar & Ramachandran, 2004
Multi-Criteria Decision Making/ Analysis (MCDM/ MCDA)	Tool to identify goals and objectives, trade-offs between them and indicate the optimal policy. A structured method for decision support in complex multi-criteria situation.	Ness et al, 2007; Andersson et al., 2016
Multi-Objective Decision Methods (MODM)	MODM is also referred as: Multi-Criteria Decision Analysis (MCDA); Multi-Dimensions Decision-Making (MDDM); Multi-Attributes Decision-Making (MADM).	Brauers et al., 2008
Net Present Value (NPV)	Economic valuation technique. "It consists in discounting all future cash flows (both in- and out-flow) resulting from the innovation project with a given discount rate and then summing them together"	Žižlavský, 2014

Method name (Method Abbreviation)	Short description	Reference
Outranking Methods (OM)	"[…] OMs build a preference relation, usually called an outranking relation, among alternatives evaluated on several attributes. In most OMs the outranking relation is built through a series of pairwise comparisons of the alternatives (this implies that these methods deal with finite sets of the alternatives […]".Part of multi criteria decision making methods.	Bouyssou, 2009; Pohekar & Ramachandran, 2004
Pugh Matrix	A method for evaluation and elimination. Evaluation tool to compare design concepts based on selected criteria. Enables a pairwise comparison of design alternatives and a reference design.	Guler & Petrisor, 2021
(Product) material intensity (Ecological Rucksack, MIPS) (PMI)	Analytical accounting tool considering all material and substance flows related to a product or service	Ness et al, 2007
Product Service Systems (PSS)	Consideration of alternative socio-technical systems that can provide the fundamental end-use function that an existing product offers. Aims to increase the profitability and competitiveness and of a company as well as to reduce product consumption through alternative product use scenarios.	Roy, 2000; Beuren et al., 2013
Quality Function Deployment (QFD)	"[…] an over-all concept that provides a means of translating customer requirements into the appropriate technical requirements for each stage of product development and production (i.e., marketing strategies, planning, product design and engineering, prototype evaluation, production process development, production, sales)''	Sullivan, 1986b, as cited in Chan & Wu, 2002
Simplified Checklists (sCL)	Assumption: Similar to Checklists	
Social Life Cycle Assessment (sLCA)	Decision support method for the social impacts related to product life cycles	Wu et al., 2014
Stakeholder analysis	Method aiming to understand an evaluate stakeholders from an organizational perspective or to examine their relevance for a project/policy. Areas of relevance are the past, present and future position of a stakeholder and their characteristics like interest, influence, position, interrelations and networks.	Brugha & Varvasovszky, 2000
Strategic Environmental Assessment (SEA)	Evaluation of potential environmental impacts of strategic decisions. Environmental assessment process for plans, programs and policies.	Partidario, 1999, as cited in Ness et al., 2007; Lee & Walsh, 1992
Strategic Sustainability Assessment (SSA)	"The Strategic Sustainability Assessment (SSA), which covers all the three pillars of sustainability (social, environmental and	Hallstedt et al., 2015

Method name (Method Abbreviation)	**Short description**	**Reference**
	economical) aims to reveal the hotspot complexity and to clarify its short- and long-term sustainability consequences. SSA is based on guiding questions that are founded on backcasting from sustainability principles and a product life cycle"	
Streamlining Life Cycle Costing (StLCC)	Assumption: Similar to Streamlined LCA: “The simplification (or streamlining) of the LCA can be made by reducing the scope of the study or by reducing data needs through the substitution of surrogates for data that may not be readily available to the practitioner”	Casamayor & Su, 2009
Streamlining Social Life Cycle Assessment (StsLCA)	Assumption: Similar to Streamlined LCA: “The simplification (or streamlining) of the LCA can be made by reducing the scope of the study or by reducing data needs through the substitution of surrogates for data that may not be readily available to the practitioner”	Casamayor & Su, 2009
Streamlining /Matrix LCA (StLCA)	Can be seen as an ad hoc version of a full LCA. Simplification of a full LCA by reduction of the scope or data needs. The selection of the appropriate boundaries and environmental categories is done by specialists. The method is less quantifiable and thorough than a regular LCA.	Santos et al., 2019; Casamayor & Su, 2009
Sustainability Life Cycle Assessment Matrix		
Sustainable Principles	No direct definition found. In general principles linked to the context of sustainability and sustainable development	
System Dynamics (SD)	Creation of computer models of complex problem situations and experimenting with those to studying the model’s behavior over time.	Ness et al, 2007
Theme-Based and Accounting Indicator Frameworks (TBAIF)	Framework to organize indicators by grouping them into different issues or themes related to sustainability development. Widely established, especially in official national indicator sets.	United Nations, 2007
Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)	Technique for multi-criteria decision making. Suitable for decision making based on people's experience. Possible to determine critical sensory attributes related to rejection or preference. Part of multi criteria decision making methods.	Ramón-Canul et al., 2021; Pohekar & Ramachandran, 2004
Uncertainty Assessment	Assessment of systems regarding their natural variability and/or a prediction inability due to lack of knowledge.	Kann and Weyant, 2000; Vose, 2000, as cited in Ness et al, 2007

Method name (Method Abbreviation)	Short description	Reference
Value Assessment Matrix	Method to help identifying considerations needed to model and simulate the value aspects.	Hallstedt et al., 2013
Value-Driven Design (VDD)	Method using the concept of value to generate and select early design concepts. It aims to complement traditional systems engineering (SE) processes.	Isaksson et al., 2013
Vulnerability Analysis	Evaluation of the vulnerability of coupled human-environment systems. Used to determine a system's capability to encounter change and the degree to which a system component, subsystem or system is likely to experience harm.	Turner et al., 2003 ; Ness et al, 2007
Waste Reduction (WAR)-Algorithm (WAR-A)	A method/tool aiming to aid the evaluation of the environmental friendliness of a (chemical) process. It can be used to retrofit a current process or during the design of a future process.	Young & Cabezas, 1999

APPENDIX D – NUMBER OF LITERATURE SEARCH RESULTS PER METHOD

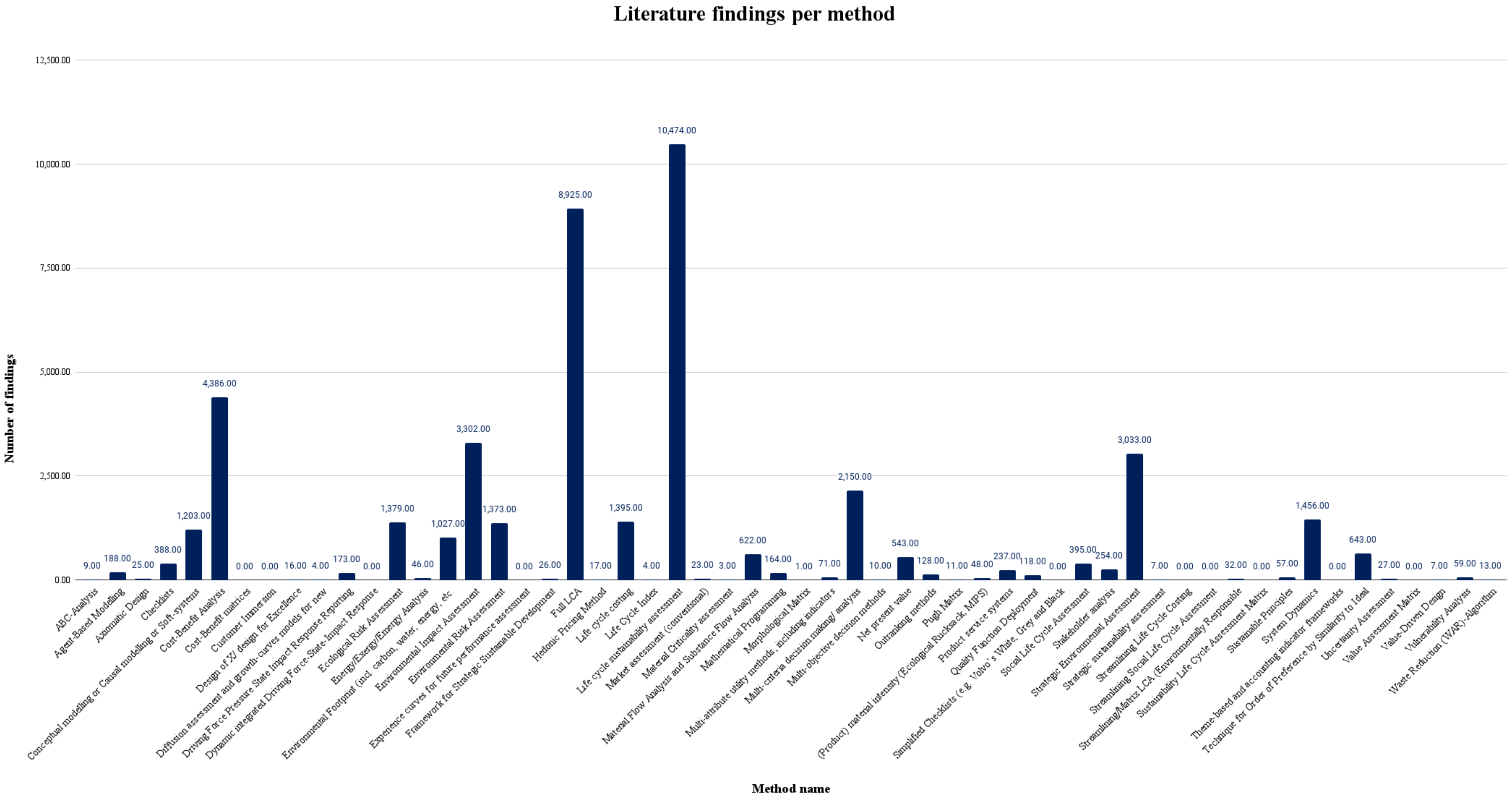

Figure 39 Number of literature search results per method detailed (own source)

APPENDIX E – METHOD SELECTION WITH REFERENCES

Table 25 Methods and selection criteria with references (own source)

Method (abbreviation)	Number of findings	Assessment method?	Scope of method	Sustainability pillar
ABC-Analysis (ABCA)	9	Yes, based on method name		
Agent-Based Modelling (ABM)	188	No, based on method name - model		
Axiomatic Design	25	No, Axiomatic design principles (Kulak et al., 2010)	Product (Kulak et al., 2010)	
Checklists (CL)	388	Yes, "[...] checklists have been developed for both assessment and design which include the early stages of product development" (Pigosso et al., 2016, as cited in Woodhouse et al., 2018)	Product (Pigosso et al., 2016, as cited in Woodhouse et al., 2018)	Environment, Economic, Social (Woodhouse et al., 2018)
Conceptual modelling or Causal modelling or Soft-systems modelling or Mental modelling (CM)	1203	Partly, enables an analysis of quantitative relationships but categorized as a model (Ness et a. 2007)	Policies or Projects (Ness et a. 2007)	
Cost-Benefit Analysis (CBA)	4386	Yes, based on method name	Policies or Projects (Ness et al., 2007) Proposal, project or policy (Andersson et al., 2016)	Economic (inclusion of environmental & social considerations possible) (Hoogmartens et al., 2014)
Cost-Benefit matrices (CBM)	0	Yes, as the methods enables an integration of difficult to quantify issues into cost-benefit analysis. (Ziller & Phibbs, 2003) Assumption: same as cost benefit assessment		
Customer Immersion (CI)	0	No information found		
Design of X/ design for Excellence (DfX)	16	No, set of design guidelines (Moreira et al., 2015)		
Diffusion assessment and growth-curves models for new technologies (DAGCM)	4	Yes, based on method name		
Driving Force Pressure State Impact Response Reporting (DPSIR)	173	Partly, enables analyzing cause–effect relationships cause–effect relationships between the environment and society (Spanò et a. 2017), but it is a framework	System (Gari et al., 2015)	Environment (partly social aspects) (Gari et al., 2015)
Dynamic integrated Driving Force State Impact Response Model (DIDFSIRM)	0	No information found		
Ecological Risk Assessment (ERA)	1379	Yes, based on method name	Policies or Projects (Ness et a. 2007)	Environment (Murthy, 2022)

Method (abbreviation)	Number of findings	Assessment method?	Scope of method	Sustainability pillar
Energy/Exergy/Emergy Analysis (EEEA)	46	Yes, based on method name	Product (Ness et al., 2007)	Environment (& economic) (Finnveden & Moberg, 2005)
Environmental Footprint (incl. carbon, water, energy, etc. footprints) (EF)	1027	Yes, "[...] footprints that can be used for the assessment of environmental sustainability" (Vanham et al., 2019, p.2)	Product and Service (Andersson et al., 2016)	Environment (Huang et al., 2015)
Environmental Impact Assessment (EIA)	3302	Yes, based on method name	Policies or Projects (Ness et al., 2007) Projects and Plans (Andersson et al., 2016)	Environment (Ness et al., 2007)
Environmental Risk Assessment (ERA)	1373	Yes, based on method name	Policies or Projects (Ness et al., 2007) Substances (Andersson et al., 2016)	Environment (European Commission, 2003)
Experience curves for future performance assessment (ECFPA)	0	Yes, based on method name		
Framework for Strategic Sustainable Development (FSSD)	26	No, "Framework which aims to provide a structure [...]" (Broman & Robert, 2017)	Strategies, Product, Services (Broman & Robèrt, 2017)	
Full Life Cycle Assessment (LCA)	8925	Yes, based on method name	Product (Ness et al., 2007) Product or Service (Andersson et al., 2016)	Environment (Finnveden & Moberg, 2005)
Hedonic Pricing Method (HPM)	17	Yes, "The Hedonic Pricing Method is one of the principal assessment methods for evaluating services and resources not normally exchanged on the market" (Rosato et al., 2017)	Product or Service (Czembrowski & Kronenberg, 2016)	Mainly Economic (Czembrowski & Kronenberg, 2016)
Life Cycle Costing (LCC)	1395	Yes, economic approach to analyze the total costs (Ness et al., 2007)	Product (Ness et al., 2007) Product or Service (Andersson et al., 2016)	Economic (but an inclusion of environmental & social considerations is possible) (Ciroth et al., 2011)
Life Cycle Index (LInX)	4	Partly, indexing system used for decision making, but it incorporates life cycle assessment (Khan et al., 2004).		
Life Cycle Sustainability Assessment (LCSA)	10474	Yes, based on method name	Assumption: Same as Life Cycle Assessment	Environment, Economic, Social (Ciroth et al., 2011)
Market assessment (conventional) (MAUM)	23	Yes, based on method name	Product (Deszca et al., 1999)	
Material Criticality assessment	3	Yes, based on method name		

Method (abbreviation)	Number of findings	Assessment method?	Scope of method	Sustainability pillar
Material Flow Analysis and Substance Flow Analysis (MFA/SFA)	622	Yes, based on method name	Product (Ness et al., 2007)	Environment (Finnveden & Moberg, 2005)
Mathematical Programming	164	No, model (Williams, 2013)	Product (Ameli et al., 2017)	
Morphological Matrix	1	No, method of thinking (Ölvander et al., 2009)		
Multi-attribute utility methods (MAUM / MAUT)	71	Yes, assumption: belongs to multi criteria decision making	Assumption: same as multi criteria decision making	
Multi-criteria decision making/ analysis (MCDM/MCA)	2150	Yes, based on method name	Policies or Projects (Ness et al., 2007)	
Multi-objective decision methods (MODM)	10	Yes, contains multi criteria decision analysis (Brauers et al., 2008). Assumption: Same as MCDA	Assumption: same as multi criteria decision making	
Net Present Value (NPV)	543	Yes, investment profitability assessment (Gaspars-Wieloch, 2019)	Project (Žižlavský, 2014)	Economic (Žižlavský, 2014)
Outranking Methods (OM)	128	Yes, belongs to multi criteria decision analysis (Wang et al., 2009) Assumption: Same as MCDA	Assumption: same as multi criteria decision making	
Pugh Matrix	11	No, Method for evaluation (Guler & Petrisor, 2021)		
(Product) material intensity (Ecological Rucksack, MIPS) (PMI)	48	Yes, Analytical accounting tool (Ness et al., 2007)	Product (Ness et al., 2007)	Assumption: same as material flow analysis materials Environment (Finnveden & Moberg, 2005)
Product service systems	237	No, concept (Roy, 2000)		
Quality Function Deployment (QFD)	118	No, "[...] an over-all concept [...]" (Chan & Wu, 2002)		
Simplified Checklists (sCL)	0	Yes, Assumption: Same as checklists	Yes, Assumption: Same as checklists	
Social Life Cycle Assessment (sLCA)	395	Yes, based on method name	Assumption: Same as Life Cycle Assessment	Social (Ciroth et al., 2011)
Stakeholder Analysis	254	Yes, based on method name	Policies or Projects (Brugha & Varvasovszky, 2000)	
Strategic Environmental Assessment (SEA)	3033	Yes, based on method name & "[...] environmental assessment process for policies, plans and programmes [...]" (Lee & Walsh, 1992)	Policies, Plans and Programs (Lee & Walsh, 1992)	Environment (Ness et al., 2007)

Method (abbreviation)	Number of findings	Assessment method?	Scope of method	Sustainability pillar
Strategic Sustainability Assessment (SSA)	7	Yes, based on method name		Environment, Economic, Social (Hallstedt et al., 2015)
Streamlining Life Cycle Costing (StLCC)	0	Yes, Assumption: same as Life Cycle Costing	Assumption: Same as Life Cycle Assessment	
Streamlining Social Life Cycle Assessment (StsLCA)	0	Yes, based on method name	Assumption: Same as Life Cycle Assessment	
Streamlining/Matrix LCA (StLCA)	32	Yes, based on method name	Assumption: Same as Life Cycle Assessment	Assumption: Same as Life Cycle Assessment - Environment
Sustainability Life Cycle Assessment Matrix	0	No information found	Assumption: Same as Life Cycle Assessment	
Sustainable Principles (SP)	57	No, based on name - principles		
System Dynamics (SD)	1456	No, Computer models (Ness et al., 2007)	Policies or Projects (Ness et al., 2007)	
Theme-based and accounting indicator frameworks (TBAIF)	0	No, based on name - framework		
Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)	643	Yes, belongs to multi criteria decision making (Wang et al., 2009)	Product or Production Process (Ramón-Canul et al., 2021)	
Uncertainty Assessment	27	Yes, based on method name	Policies or Projects (Ness et al., 2007)	
Value Assessment Matrix	0	Yes, based on method name		
Value-Driven Design (VDD)	7	No, design process (Isaksson et al., 2013)		
Vulnerability Analysis	59	Yes, based on method name	Policies or Projects (Ness et al., 2007)	Environment (Turner et al., 2003)
Waste Reduction (WAR)-Algorithm	13	No, evaluation method for the environmental friendliness of a (chemical) process (Young & Cabezas, 1999)	Process (Young & Cabezas, 1999)	Environment (Young & Cabezas, 1999)

APPENDIX F – IN DEPTH ANALYSIS OF CHECKLIST METHOD

Table 26 In-depth analysis of checklists (own source)

Area of interest	Findings from the literature
The objective/ aim of the method	• Gain insight into aspects to be considered in regards to sustainability performance (Woodhouse et al., 2018) • Raise awareness of the factors that are important from a sustainability perspective (Woodhouse et al., 2018) • Identification of the specific environmental weak points (Kishita et al., 2010)
Input data	*Dependent on the respective method*
Output data	*Dependent on the respective method*
Indicator	*Dependent on the respective method*
Application	*Dependent on the respective method*
Strength of the method	• No quantitative data needed, thus application within early development stages possible (Woodhouse et al., 2018) (Schöggl et al., 2017) • No methodological knowledge, experts or trainings needed for application (Woodhouse et al., 2018; Schöggl et al., 2017) • Depended on the concrete method, an integration of all three sustainability pillars is possible (Woodhouse et al., 2018) • Allows to cover some less obvious aspects resulting in a good overview of sustainability issues (Woodhouse et al., 2018) • Can be adjusted towards a specific company and industry setting (Woodhouse et al., 2018) • No modelling needed, thus modeling issues can prevented (Woodhouse et al., 2018) • Does not hinder creativity (like complex methods do) (Schöggl et al., 2017) • “Ecodesign checklists are an effective method in terms of cost and time savings in order to identify the specific environmental weak points of a product” (Kishita et al., 2010, p.2)
Drawbacks & criticism of the method	• No direct result or answer is given at the end (Woodhouse et al., 2018) • No direct support regarding decision-making or trade-off making (Woodhouse et al., 2018) • “In most ecodesign checklists, specifically in eco-label checklists, the designer is unable to understand the environmental performance of a product in each individual requirement of a checklist quantitatively and objectively since requirements are evaluated as yes or no. This […] does not significantly clarify how the designer should improve products concretely” (Kishita et al., 2010) • “Ecodesign checklists do not prioritize their requirements objectively. Also, the relationships between requirements and environmental impact, e.g., CO2 emissions and hazardous substances, are unclear. Therefore, designers cannot easily comprehend critical points for design improvements” (Kishita et al., 2010, p.2) • Sometimes only yes and no answers possible - No middle ground can be indicated (Woodhouse et al. 2018)
Nature of the analysis	Qualitative or quantitative (Byggeth & Hochschorner, 2006)

APPENDIX G – DECISION TREE VERSION 1

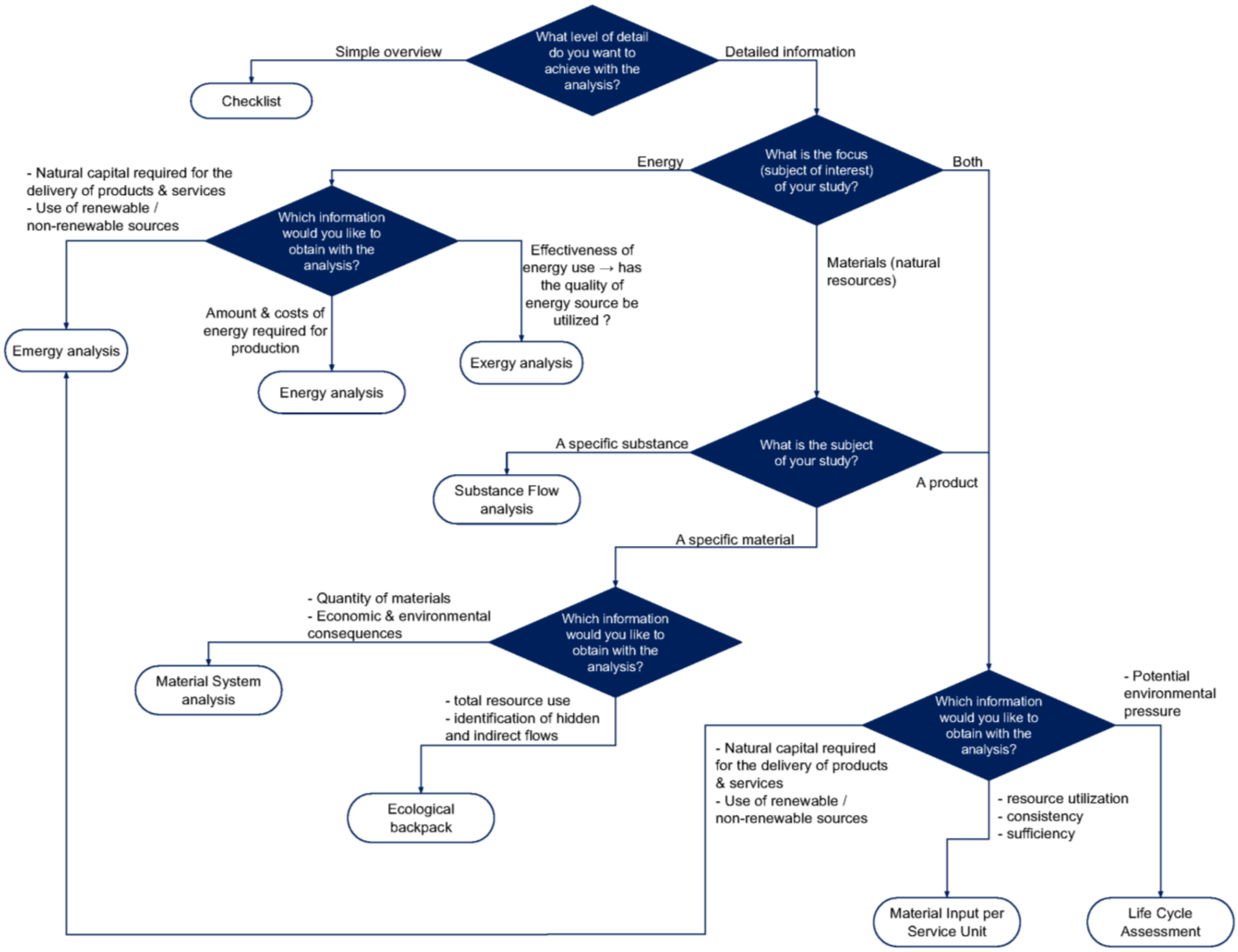

Figure 40 Decision tree version one (own source)