ENVIRONMENTAL IMPACT ASSESSMENT WITH LCA

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Every activity can be correlated with environmental impacts. But designing effective measures to reduce them requires an evaluation of the impacts first. To date, life cycle assessment (LCA) is the only standardised and most comprehensive method for assessing environmental impacts. Slovenian companies do not use the LCA method to the same extent as their competitors abroad and therefore cannot take advantage of the benefits that LCA can offer. LCA is a job for engineers and can only be carried out by trained professionals with a broad knowledge of materials, technologies, energy, appropriate software and access to databases. However, an LCA cannot be carried out without the client's input and notification of the intended use of the results. The purpose of this material is therefore to understand what an LCA is, how an LCA project should be designed so that contractors can prepare a suitable tender for the LCA service and then carry out the assessment. In order to avoid misleading expectations of potential clients, some examples of the results of LCA studies will be presented to show the reader will thus learn what data and in what form the client has to provide and how it will be used to create responsible business.

Keywords:
environmental impact assessment,
LCA,
Environmental Life Cycle,
environmental data,
environmental indicators

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1 Introduction to LCA

Business operations today are intertwined with global connections. Manufacturing processes are becoming increasingly technologically diverse, and supply chains are geographically dispersed. As a result, companies want to understand the potential environmental impacts of sourcing materials, production and assembly, usage, and, ultimately, disposal of products. This global expansion, along with the increasing awareness of sustainability and responsibility towards environmental, economic, and social dimensions, has prompted environmental managers and decision-makers to adopt a broader, more holistic view of products and services, considering them 'from cradle to grave.' The need for a tool that helps users gather data and information for accurate and consistent measurement of resource consumption and the environmental impacts of their activities has never been more pressing. It is crucial for people to realize that decisions should not lead to the improvement of one part of the industrial system at the expense of another. In the decision-making process, it is key to recognize and avoid unintended consequences. This need gave rise to Life Cycle Assessment (LCA) (Curran, 2012).

Companies can approach the realization of environmental and sustainability goals in various ways. In recent years, the most common environmental goals include: reducing carbon footprints and water consumption, increasing the share of energy from renewable sources, establishing circular flows, and others. These goals are usually very ambitious, which raises the legitimate question of whether companies and national governments will be successful in achieving them (PRe, 2016).

Tools to support business decisions are also diverse. Some tools, such as the concept of 'cradle to cradle' or circular economy, are successful because they offer an appealing narrative that users can easily relate to the activities in companies. Other tools, such as life cycle environmental analysis, can convince us with a large number of environmental indicators.

Environmental and sustainability goals in companies are most often set by management (e.g., regarding energy, water, and climate change), after which individual business units and departments begin implementing measures to achieve these goals within a specific timeframe. However, these goals are often not aligned with the operational capabilities at the implementation level, where the improvements are supposed to be achieved. As a result, individual business units undertake measures to reduce greenhouse gas emissions without knowing the current state of emissions, nor are they aware of which measures in their plant/unit can contribute the most to improvements, or where it would be appropriate to prioritize actions and what their contribution will be to achieving the overall goals. Such an approach often proves inadequate and does not yield the desired results. Successful companies typically first review the characteristics of individual business units or products, using LCA to determine indicator values and identify critical points in business processes or the supply chain. They then assess which goals are important for each department, unit, or product and attempt to achieve them through actions at the previously identified critical points. To achieve their goals, they continuously plan measures for updates and improvements that are implemented at the critical points (PRe, 2016).

The combined use of LCA and sustainability or the circular economy enables product developers to effectively measure environmental performance, compare circular strategies, and ensure a positive environmental balance from new products designed based on circular flows. Furthermore, LCA requires many of the same data as, for example, the calculation of the material circularity indicator in the circular economy. Therefore, these measurements complement each other with relatively little effort. The material circularity indicator can also be calculated using the same software as LCA. It is important to note that the material circularity indicator focuses on the flow of material between the production and use of the product, explicitly encouraging the use of recycled or reused materials and extending the product's lifespan. In contrast, LCA focuses on determining environmental impacts at the level of the entire life cycle (PRe, 2017). As the LCA method is increasingly used in practice, we will now present it in more detail.

The use of LCA in Slovenia is not as widespread as abroad. LCA analysis is a task for engineers and can only be carried out by qualified professionals with a broad understanding of materials, technologies, energy, with appropriate software and access to databases. However, LCA analysis cannot be conducted without data from the client and communication regarding the intended use of the results. Therefore, the purpose of this material is to improve the understanding of what LCA actually is, how an LCA project should be structured so that contractors can prepare an appropriate proposal for conducting the environmental impact assessment using the LCA method, and later carry out the assessment. To avoid misconceptions among potential clients, some examples of results from conducted LCA studies are presented. The reader will thus understand which data and in what format the client must prepare it, and how they will be used. The provided content will be useful for all those who will encounter the need to evaluate environmental impacts and demonstrate environmentally responsible practices.

2 Understanding and usability of LCA analysis results

2.1 General information about the LCA method

To implement an effective environmental policy, every company (regardless of its activity) needs relevant environmental data. The data that companies acquire, for example, for establishing an environmental management system (ISO 14001, EMAS), is often insufficient for the comprehensive development of more environmentally friendly products and services or for understanding the impacts along supply chains. In this case, only data on emission values from technological processes or energy consumption during product use are not enough to actually optimize products environmentally. For this purpose, other additional data, obtained based on different methodologies, are now required and used. We can expect that in the future, the demand for credible and increasingly comprehensive environmental data for products and services will continue to grow (in the areas of communication, ISO standards, product development, etc.)

For this purpose, life cycle assessment (LCA) of products has become widely established worldwide. However, when introducing this concept, we need tools that can quantitatively determine such comprehensive impacts. One such tool is the LCA method, which has become one of the most important tools for assessing the environmental impacts of products globally. Through LCA, we evaluate all the environmental impacts caused by a product throughout its life cycle, with the aim of environmentally optimizing the product. It is a collection of all inputs, outputs, and potential environmental impacts of a specific production system throughout its entire life cycle (ISO, 2006a).

LCA is the only internationally standardized environmental assessment method (ISO 1997, 1998, 2000a, b). ISO standard 14040 defines LCA as a technique for evaluating environmental aspects and potential impacts associated with a product. It is conducted using the following steps:

– preparation of a list of relevant inputs and outputs of the system (inflows and outflows);
– assessing the potential environmental impacts associated with these inputs and outputs;
– interpreting the results of the inventory and environmental impacts in relation to the study's objectives.

The goal of LCA is to identify and quantitatively define all environmental impacts associated with a product. LCA achieves this with a 'cradle-to-grave' approach, considering all impacts related to the product throughout its life cycle, i.e., from raw material extraction ('cradle') through production, use, and disposal ('grave'). In this way, LCA highlights the aspects of the product that have the greatest environmental impact. Manufacturers can then focus their efforts on these aspects in order to reduce the product's environmental footprint (EEA, 1998).

The environmental life cycle of a product generally includes the following stages: extraction and preparation of raw materials, production, distribution and transport, consumption or use, and disposal of products. The consideration of the environmental cycle of a product always includes the acquisition of the energy required for the extraction of raw materials, their processing, production, transport, distribution, use, etc., which also begins with the acquisition of the necessary energy sources. Therefore, using the LCA method, companies not only obtain data on the impacts in individual phases of life cycles but also data on environmental impacts that cannot be determined using other methods (Denac, Radonjič, 2023).

According to the methodology outlined in the ISO 14040 standard, the LCA method consists of 4 steps or structural elements: (i) definition of the goal and boundary, (ii) data inventory, (iii) assessment of environmental impacts and (iv) interpretation of results.

2.2 Application of environmental life cycle assessment

In recent decades, we have witnessed the increasing use of LCA to support decision-making regarding environmental protection. Much effort has been made to integrate the life cycle concept into society and to facilitate its use at all levels – from the regulatory and governmental level, through industry and production, to citizens and consumers. The spread of LCA has been facilitated by numerous initiatives to support and harmonize the use of this tool at a global level (e.g. the international standard ISO 14040, the global partnership known as the Life Cycle Initiative (LCI), the establishment of the European LCA Platform and others), which have also been followed by initiatives to support the use of LCA at a national level. Recently, LCA services have been reflected in environmental product declarations (EPDs) and greenhouse gas emissions monitoring. Universities, research institutions and private companies often work closely together in commercial projects or doctoral theses for industry (Hauschild et al., 2018). The immense popularity of the life cycle concept has led to its use in a variety of assessment approaches, including those focused on a single environmental aspect. Increased concern about climate change is reflected in individuals and organizations making significant efforts to measure the release and impact of greenhouse gases. For example, the term LCA is often used in writing about carbon monitoring, even though the results only address climate change and not other equally or even more important impacts. The precise meaning of the methodology is often misunderstood, resulting in carbon footprint and LCA being used interchangeably, which is incorrect. By narrowing the assessment to a single environmental category, the results will not reflect the necessary breadth that only LCA provides (Curran, 2012).

The usefulness of the LCA method for decision-makers at the national level

The use of LCA and life cycle approaches can support policy design, policy implementation and regulation, and can also be used for policy evaluation. The European Commission has identified LCA as one of the reference models for assessing the impacts of policies in the EU in the Better Regulation Guidelines (EC, 2015b). This indicates a potential increased use of LCA for assessing existing policy frameworks (e.g., compliance assessment or verification) and for assessing future possible policy options.

The applicability of the LCA method in business and industry

The use of LCA in companies can be classified into five main groups according to purpose: (i) decision support in product and process development, (ii) marketing purposes (e.g., environmental labeling), (iii) development and selection of indicators used in monitoring the environmental performance of products or production facilities, (iv) selection of suppliers or subcontractors, and (v) strategic planning (Hauschild et al., 2018).

We note that the use of LCA within an industry can serve more than one purpose well, and often the same results can be used for different purposes within a company (e.g., product development is often combined with marketing). As a company gains more experience using LCA, one analysis can trigger another (e.g. insight into the environmental impacts of a product can lead to decisions about choosing other suppliers or changing strategies). It is also noted that although LCA was developed as a tool to be used at the product level, there is increasing interest in using LCA at the corporate level to reflect the performance of a company or individual plants throughout their entire life cycle. This is especially important for large companies (Hauschild et al., 2018). (For more information, see Bradač Hojnik et al., 2020; Bradač Hojnik et al., 2020).

There are several reasons for performing an LCA. These may include the following:

- Financial benefits. LCA examines the life cycle of a product and identifies where the main environmental impacts occur. Often these environmental impacts can be reduced by increasing the efficiency of the use of input materials and energy. Increasing the efficiency of resource use will reduce the amount of input streams used and waste generated, thereby reducing costs. Costs are also associated with environmental charges due to the environmental damage caused.
- Product and design. LCA can be used as an aid in decision-making about the design or redesign of a product or process. LCA can be used to compare the environmental impacts of different design alternatives and to assess whether any alternative has potentially significant environmental advantages or disadvantages.
- Marketing. Large companies have often used LCA as a marketing tool. Manufacturers exploit the environmental friendliness of their products as a means of increasing sales. LCA can be used as a basis for advertising claims that a product has a lower environmental impact than other similar products. However, the use of LCA for this purpose has sometimes been controversial (EEA, 1998).
- In the past, the initiator of LCA was usually the marketing department, which wanted to present the environmental benefits of products. However, the

marketing department most often found that the results of LCA were very difficult to use in marketing communications. Later, the role of initiator was taken over by other departments, usually the R&D department or the environmental protection department, which led to frequent difficulties in implementing LCA due to lack of clarity regarding purpose and use. Today, sustainable business operations are slowly changing from current activities to activities that are integrated into the company's current operations, with LCA being used to monitor and measure environmental impacts. The Sloan survey showed that in 2012 already, approximately 70% of managers ensured that achieving sustainable business operations was their goal, which was regularly included in the content of work meetings in companies. This report shows that sustainability is becoming a tool for creating value and not a tool for reducing costs. The focus is shifting from cost-cutting activities and strategies to better products with larger market shares (Goedkoop et al. 2013, 6).

- Many large companies now care not only about their own environmental performance, but also about the performance of their suppliers and vendors throughout the supply chain. In other words, they care about the environmental performance of all companies involved in the entire life cycle of their products. By encouraging companies to improve their environmental performance, large companies can reduce the environmental impacts of their products throughout their life cycle (EEA, 1998).
- This means that suppliers to a large company will have to demonstrate good environmental management and provide their customers with information that will enable them to carry out an LCA for their products. The ability to demonstrate good environmental management and provide adequate information for an LCA will undoubtedly put the company in a good position to continue doing business with existing customers, whereas if the company does not do this, customers might switch suppliers (EEA, 1998).

2.3 Some features of the current LCA methodology

The fundamental feature of LCA is the consideration of environmental impacts that occur throughout the entire life cycle of a product, from raw material extraction, production, use and disposal. However, considering the entire life cycle for individual environmental issues can be carried out in different ways. This issue has been the main driving force of all methodological discussions in recent decades (Werner 2005, 29).

LCA environmental assessment methods are constantly evolving, and LCA results may only be valid for decision support for a limited time, until new environmental impact calculation models are developed or updates to the databases used are published. For this reason, environmental impact assessments should be carried out continuously.

The main characteristics of LCA compared to other decision-making tools are the following:

LCA is a tool for modeling the environmental aspects of business operations;

- LCA is used as a tool in the decision-support process, but it does not encompass the entire decision-making process;
- LCA is designed to support decision-making at the micro-level, where the subject of analysis is products, including services and processes or production facilities;
- LCA evaluates changes caused by specific human activities or average human activities and cannot describe the state of the environment or social responses to environmental pressures;
- LCA assesses environmental interventions and the resulting damage by assuming/considering consistent (global) data with average meteorological and environmental conditions;
- LCA is based on monitoring input and output flows;
- LCA, in both the modeling phase and the environmental impact assessment phase, reflects only the current time component; therefore, continuous implementation of analyses with data updates in mathematical models is necessary (Werner, 2005, p. 31).

As already mentioned, LCA is the only internationally standardized method for assessing environmental impacts. The first LCA studies were conducted as early as the 1970s and 1980s. The historical development of LCA is summarized in Klöpffer (2006), with special emphasis on the role of the SETAC (Society of Environmental Toxicology and Chemistry) in this process. International standards were revised and updated in 2006 (ISO 2006a, b; Finkbeiner et al., 2006). These updated standards replaced the old series that had been in use prior to October 2006. LCA is an active research field, where further methodological development can be expected. The leading standards for LCA are ISO 14040 and ISO 14044. ISO 14040 addresses the principles and framework for LCA, while ISO 14044 defines the requirements and guidelines for conducting an LCA study (Goedkoop et al., 2013, p. 7). In addition to the standards, it is also necessary to follow the guidelines from the ILCD (International Reference Life Cycle Data System) manuals when conducting LCA analyses. ISO standards are defined rather loosely, which makes it difficult to assess whether an LCA study has been conducted in accordance with the standard. Unlike ISO 14001, it is not possible to obtain official accreditation for LCA that would confirm whether an LCA study, LCA methodology, or the use of LCA software has been carried out in compliance with the ISO standard (Goedkoop et al., 2013, p. 7). For example, ISO 14044 does not permit weighting between environmental impact categories if the results are intended for public comparisons between products. However, weighting is explicitly allowed for other applications, which is why some software tools, such as SimaPro, support the use of weighting. This means that it is the responsibility of the LCA practitioner to apply weighting appropriately. Similar issues arise with rules for the allocation of environmental impacts, system boundaries, and so on (Goedkoop et al., 2013, p. 7).

The most important consequence of striving to comply with the ISO standard is the need for careful documentation of the study's goal, scope, and interpretation issues. The practitioner may carry out an LCA study in several different ways, as long as they thoroughly document what was done. Another consequence of adhering to the standards is that you may also need validation or a peer review of the conducted LCA study by independent experts (Goedkoop et al., 2013, p. 7).

It is up to the LCA practitioner, in agreement with the client, whether to adhere to these standards or to (intentionally) deviate from them. However, in the case of deviation, it will be more difficult to convince other stakeholders of the reliability of the results (Goedkoop et al., 2013, p. 7). In addition to the LCA approach, which analyzes multiple environmental impact categories, there have recently been approaches developed that focus on just one environmental category. A typical example is the calculation of a carbon footprint or water footprint. These approaches also follow the life cycle perspective, but they focus solely on one impact category and therefore do not provide a complete picture. In response to society's growing need for transparency regarding greenhouse gas emissions associated with products, several methods and standards for determining carbon footprint have been developed or are still under development (Goedkoop et al., 2013, p. 7).

2.4 LCA guidelines at European level

At the European level, the International Reference Life Cycle Data System (ILCD) provides a common basis for consistent, reliable, and quality-assured life cycle data and studies. Such data and studies support coherent sustainable consumption and production instruments, such as environmental labeling, eco-design, carbon footprinting, and green public procurement. The ILCD Handbook was published in 2010. This handbook is based on the ISO 14040 and ISO 14044 standards but it provides much more detailed technical guidelines. The ILCD Handbook spans more than 400 pages, whereas ISO 14040 and ISO 14044 together comprise around 60 pages. The ILCD Handbook includes detailed descriptions and requirements to reduce the flexibility of interpretation and to support consistency and quality assurance in LCA results. Additionally, several ILCD handbooks have been published, each addressing specific steps in the implementation of LCA studies in detail.

Between June 2011 and February 2012, the Directorate-General for the Environment (DG Environment) and the Joint Research Centre – Institute for Environment and Sustainability (JRC-IES) developed and tested a harmonized methodology for calculating the environmental footprint of products and organizations, known as the draft Product Environmental Footprint (PEF) and the draft Organization Environmental Footprint (OEF) methods. These two methods were based on the ISO 14040 and ISO 14044 standards and the ILCD handbook, but they are stricter and more concise. In parallel, the Product Environmental Footprint Category Rules (PEFCR) and Organization Environmental Footprint Category Rules (OEFCR) are being developed. PEFCR/OEFCR are based on the ISO 14025 standard for environmental product labeling and complement the general methodological guidelines for environmental footprinting with additional specifications at the product level. PEFCR/OEFCR will enhance the repeatability and consistency of environmental footprint studies. Over time, these two methods could become part of future European policies on sustainable consumption and production (EC 2021, 18). This will significantly increase the demand for knowledge in the field of LCA among all stakeholders.

3 LCA methodological structure

The methodological structure of LCA is defined by the environmental standards of the ISO 14040 series. The ISO/SIST EN ISO 14040 standard defines LCA as "the collection and evaluation of input and output data and potential environmental impacts of a production system throughout its life cycle" (ISO 14040, Chapter 3.9). The introduction of the ISO 14040 standard (ISO, 2006a) states that "LCA addresses environmental aspects and potential impacts (e.g., resource consumption and environmental consequences of emissions) throughout the product's life cycle; from material extraction to production, use, and disposal (i.e., cradle to grave)" (Klöpffer and Renner, 2008). Environmental impact assessments can, of course, be conducted within different boundaries: (i) 'cradle to gate' (from resource extraction to the end of the production process of a given product), (ii) 'gate to gate' (only the production process of a given product), (iii) 'cradle to cradle' (from resource extraction to the reuse of the product or its components).

The LCA methodology is somewhat complex and requires in-depth knowledge from the practitioner, so it will not be explained in detail here. As shown in Figure 1, the LCA analysis is carried out in four steps: (i) definition of the goal and scope, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation of results.

Definition of Goal and Scope. In the first step of the LCA study, the initial framework for conducting the research is established. At this stage, it must be clearly stated who the results of the LCA study are intended for and why they will be used. The subject of the research must be precisely defined, and the functional unit and reference flow should be specified. Considering the environmental life cycle, the system boundaries are also defined, the method of allocating environmental impacts is determined, the set of environmental categories is specified, along with the corresponding calculation methods, data requirements, the type of critical review, and the format of the report (Werner, 2005).

Inventory analysis (Life Cycle Inventory analysis) involves the collection of data and recalculation procedures to quantitatively assess the environmental impacts that occur throughout the environmental life cycle of a product. These inputs and outputs must include resource consumption and emissions to air, water, and soil that can be linked to the system under study. The collection of all environmental interventions throughout its life cycle is also called the Life Cycle Inventory (LCI)

(Werner, 2005). Inventory analysis is a complex and in-depth process, during which data on materials and energy used are collected, constituting the most demanding and time-consuming step of the entire LCA analysis. The inventory analysis is usually carried out by consultants or several internal working groups with knowledge and experience in each phase of the life cycle. If the necessary information in various forms or databases is already available within the company, it can be compiled/assembled to complete the inventory analysis (IMA, 1996). A portion of the inventory data is always obtained from business partners involved in the supply chain.

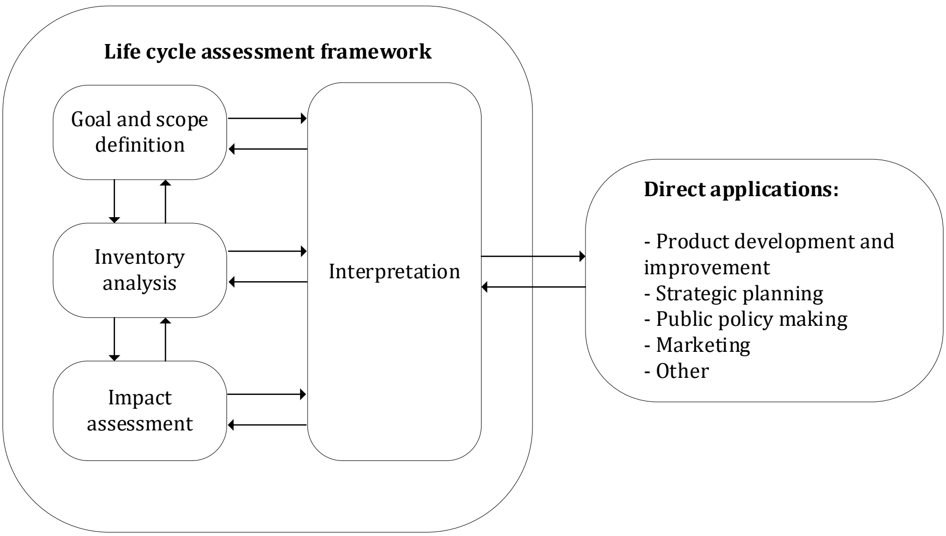

Figure 1: Methodological Structure of LCA
Source: (ISO, 2006a).

An LCA study cannot be conducted without the use of specialized databases. One of the most prominent is the Ecoinvent database, which is the most comprehensive, extensive, and probably the most widely used database in the world. Currently, the database includes over 4,000 products and 19,000 processes, available for three different system models, and the data is updated and supplemented at least once a year (PRe, 2023). Due to the very high dynamics of data availability and validity, the client should verify which databases will be used for calculations before each LCA analysis (Hauschild et al., 2018).

The Life Cycle Impact Assessment (LCIA) evaluates the inputs and outputs of substances based on their environmental impacts. The assessment consists of several steps: classification (sorting inventory data into impact categories), characterization (weighting classified inventory data within individual impact categories), and valuation (combining environmental categories through normalization and summation) (Werner, 2005). In the environmental impact assessment, the selection of the calculation method and the impact categories is crucial, and these are determined based on the definition of the study's goal and scope. It is also important to consider the desired level of integration of the results (i.e., which results to display and how detailed the breakdown should be). There are more than 40 different qualitative methods for conducting LCA. The eco-indicator concept appears to be the most successful in practical use within LCIA, as it also allows for the comparison of environmental impacts across different environmental categories (Zbicinski et al., 2006). This method has been upgraded several times and is currently used as the ReCiPe 2016 method, the most widely applied method for assessing environmental impacts on a global scale. The environmental assessment results are presented through 18 indicators of environmental categories (midpoint approach) and 3 indicators of the resulting environmental damage (endpoint approach) (PRe, 2020).

The international standards ISO 14040 and ISO 14044 (ISO, 2006a; ISO 2016b) distinguish between mandatory and optional steps within the LCIA. The mandatory steps are:

- selection of environmental categories, their indicators, and characterization models (during the modeling process, the LCA practitioner does this by choosing one of the existing LCIA methods);
- classification: linking inventory data to environmental categories based on known potential impacts;
- characterization: calculating the values of environmental indicators by converting the contributions of inventory flows to specific environmental categories.

The results of characterization do not provide information about the relative impacts of environmental categories in relation to each other. They also do not provide information about which environmental category has a greater impact compared to all environmental impacts in a specific geographic area.

The optional steps of LCIA according to the requirements of ISO 14040 and ISO 14044 standards are:

- Normalization: Expressing LCIA results relative to the reference system data. Normalization allows us to assess the contribution of a specific environmental category to the overall impact in a given geographic area, or the contribution per capita in a particular region. Normalization can be a useful step in LCA analysis if we want to compare environmental impacts across different geographic areas;
- Weighting: Determining priorities or weights for individual environmental categories;
- Aggregation: Combining various environmental impact indicators into groups of environmental damages.

It should be emphasized that ISO 14044 states regarding weighting of environmental impacts: "Weighting shall not be used in LCA studies intended to be used in comparative assertions intended to be disclosed to the public" (ISO, 2006b). The described environmental impact assessment (LCIA) is specific to the LCA methodology and requires a thorough understanding of the models and the differences between all existing LCIA methodologies (Hauschild et al., 2018).

Interpretation of results involves explaining the findings from the inventory analysis and environmental impact assessment. The research findings and recommendations are also documented based on the goal and scope of the study. LCA analyses can also include various simplifications, assumptions, and value judgments about processes, meaning that LCA studies may yield different results, even though they appear to examine the same product. Differences can arise due to several factors: the differently defined goals, the use of different functional units, different system boundary settings, and varying assumptions made during data modeling. It is crucial to minimize the scope of simplifications and ensure that, during the reporting phase, the assumptions and values used are clearly specified. This way, the reader of the study can assess and decide on the acceptability of the simplifications and either accept the study results or reject them entirely as unsuitable (Curran, 2015).

4 Case studies

As an example of appropriately defining the problem and providing the necessary data for conducting an LCA study, the contribution of Ardente et al. (Ardente et al., 2006) is cited. The article presents the results of a simplified LCA study on the production of grapes and the processes of transforming them into high-quality bottled wines in Southern Italy. The results of the study were used to support decision-making within the framework of the Environmental Management System (EMS) and to obtain Type III environmental labels (EPD). The following steps were performed in the study:

- company analysis and definition of the functional unit;
- conducting the LCA study of the product, which included: (i) description and analysis of production processes, (ii) analysis of input and output flows, (iii) development of an eco-profile for the functional unit, and (iv) detailed analysis of environmental impacts;
- preparation of an environmental improvement program.

Company analysis and selection of the functional unit

The product under study is bottled red wine produced by a company located in Sicily. The production of red wine is the main activity of the company and accounts for 95% of its revenue. The company offers six types of high-quality, premium wines on the market. The company cultivates 77% of the grapes required for processing on 138 hectares of land, while the remaining 23%, grown on 43 hectares, is purchased from local producers. The average distance between the company's vineyards and the processing facility is 2.1 km, and the processing plant covers an area of 0.25 km^2. The company could be described as a typical smaller Italian winery, producing 950 m^3 of wine annually. The selected functional unit for the study was a 0.75litre bottle of red wine.

Conducting the LCA study of the product

When performing LCA for food products, certain specific challenges arise. It is quite evident that the production of agricultural goods is highly dependent on weather conditions, which means that some environmental impacts can vary significantly from year to year. The present study refers to the 2003 vintage, which represents an average year of production. Similar to most agricultural activities, winemaking impacts the environment through the use of pesticides and synthetic fertilizers. However, there is a lack of sufficient environmental information related to these products (Weidema et al., 1995). Furthermore, wine production involves several processing stages, which can vary between producers depending on the desired quality of the wine. As a result, LCA outcomes for different wineries are generally not directly comparable. The LCA study was conducted in accordance with the requirements of the international standard ISO 14040. The life cycle included the following phases: grape cultivation and transport to the processing facility, wine production and storage, bottling and packaging, as well as transport of the final products. The impacts from waste disposal were excluded from the assessment.

The analysis of the processes was limited to the input and output flows of materials and energy. Inventory data were obtained through direct measurements. Indirect environmental burdens related to material production, energy sourcing, and the transport of raw materials and final products were estimated. The materials included in the analysis are organic and synthetic fertilizers, sulfur and plant protection products, sodium carbonate, perlite, and bottling materials. The energy sources used include fuel for operating agricultural machinery, electricity consumed during viticulture processes, liquefied petroleum gas used for steam and hot water production as well as for building heating, and diesel fuel used for transportation. The collected data were logically grouped into specific categories.

<u>(i) Description and analysis of the production process.</u> Wine production consists of two main phases: the agricultural phase (grape cultivation) and the industrial phase (processing grapes into wine). The processes are presented in detail in the authors' contribution and will therefore not be repeated here. The studied system must also be presented graphically, with system boundaries clearly marked, including the phases that were not included in the LCA. The system boundaries for the analyzed case are shown in Figure 2.

<u>(ii) Analysis of input and output flows.</u> The next step in the LCA study is the collection of input and output data related to the consumption of raw materials, substances, energy sources, emissions, and waste. The most challenging aspect is the estimation of mass flows associated with the production of raw materials, which cause indirect environmental impacts (Ardente et al., 2005a, 2005b). The high

accuracy of the study requires a large number of data points, which extends the time of execution and thus increases costs. Therefore, some authors suggest simplifying the LCA to assist small organizations, which often lack the necessary resources and competencies (Luciani et al., 2003). However, it is not easy to specify what the "simplified" LCA should include. The main simplification could be related to exclusion rules, which allow for less precision in defining system boundaries and data quality (e.g., excluding materials whose quantities are below a certain percentage of the total mass used or using data that are not fully representative or up-to-date). All these "simplifications" require agreement between the client and the LCA practitioner.

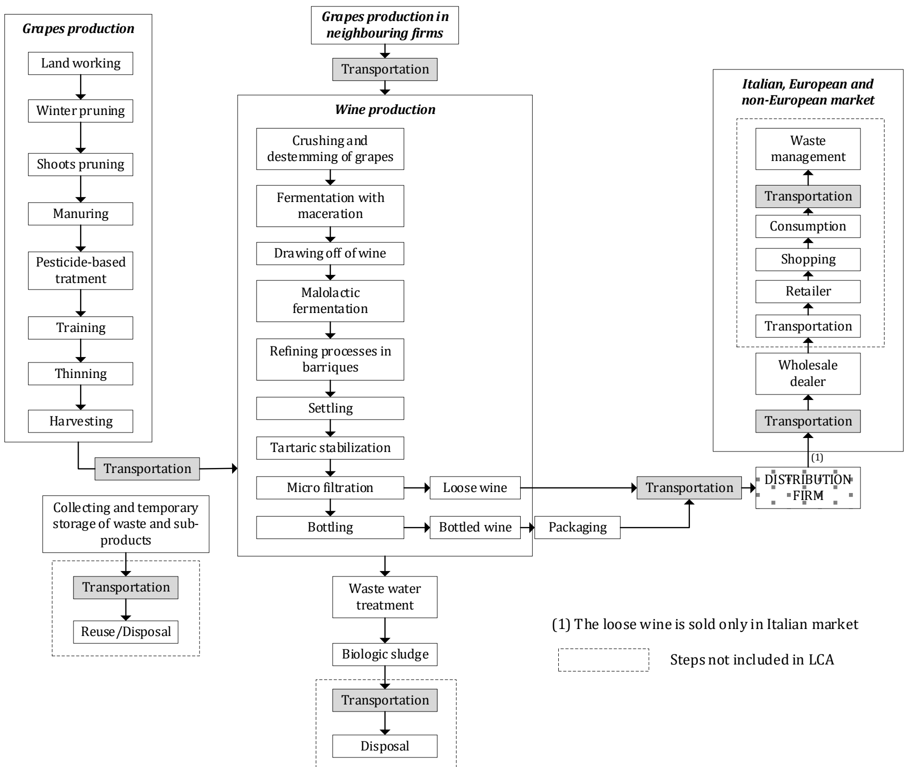

Figure 2: Bottled wine life cycle diagram

Source: Adapted from (Ardente et al., 2006)

Table 1 shows the input and output mass flows in the main stages of the processes, while Table 2 shows the energy flows. All quantities in Table 2 should be considered as primary, defined as: "energy embodied in natural resources (e.g., coal, crude oil, sunlight, uranium) that has not undergone any anthropogenic conversion or transformation" (Boustead, 2001). Secondary sources can be converted into primary quantities using specific conversion factors.

(iii) Eco-profile for the functional unit. In the next step, it is necessary to calculate the consumption of materials, energy, and emissions per functional unit. The analysis included the assessment of direct impacts (those directly related to the activities of the organization, i.e., emissions from greenhouses or agricultural machinery) and indirect impacts (i.e., impacts associated with input materials). The calculations for the functional unit can be performed by the client or the study contractor, as agreed. More information about the study and results is available in Ardente et al. (Ardente et al., 2006).

Table 1: Analysis of input and output flows for wine vintage 2003

Main inputs			Main outputs	
Raw materials			Products	
Grapes	1.269.400 kg		Bottled wine	377.000
Agriculture products			Loose wine	575.050
Compost	181.339 kg		Sub-products	
Potassium sulfate	54.402 kg		Marc	230.782
Urea	36.268 kg		Grape stems	57.123 kg
Fertilizer (phosphorous	36.268 kg		Lees	29.445 kg
Sulfur	23.175 kg		Agriculture wastes	
Fertilizer (nitrogen based)	15.232 kg		Exhausted oils	400 kg
Pesticides	3.919 kg		Packaging of chemicals	260 kg
Additives			Others	234 kg
Perlite	1.269 kg		Process wastes	
Potassium meta-bisulfite	222 kg		Plastics	10.000 kg
Albumin	286 kg		Carton	5.000 kg
Yeast	97 kg		Glass	3.765 kg
Bottling and packaging			Sludges	864 kg
Glass	262.750 kg		Special wastes (oils, packaging,	844 kg
Carton	19.167 kg		Undifferentiated wastes	118 kg
Wood crating	6.730 kg		Wastewaters	
Closures	2.257 kg		Wastewaters	1.728 m^3
Labels	903 kg			
Pallets	900 kg			
Water consumption				
Irrigation	98.104 m^3			
Process consumption	2.160 m^3			
Total	100.264 m^3			
Other				
Soda	2.500 kg			
Cleaning products	377 kg			
Peracetic acid	20 kg			
Laboratory chemicals	8 kg			

Source: Adapted from (Ardente et al., 2006)

(iv) Detailed analysis of environmental impacts. As mentioned earlier, the organization within the EMS should focus on the impacts that are considered the most significant to establish an effective improvement program. In relation to the case study of wine production and packaging, three indicators were analyzed in detail: energy consumption, carbon dioxide emissions, and water consumption.

The environmental impact indicators are determined by selecting the calculation method, which is defined by the client and the study executor. Tables 3 (a) – 3 (c) present examples of environmental categories included in the calculation methods Eco-indicator 99, ReCiPe 2008, and ReCiPe 2016. The results of the environmental assessment calculations differ in terms of the number of environmental categories, their definitions, units of measurement, and the final result. More information on this can be found in the furniture manual (Denac, Radonjič, 2022).

Table 2: Total energy consumed (in GJ)

Diesel	
Agriculture machines	2.870
Transports	66
Transports (input products)	346
Transport (output products)	1.013
Total	4.295
Electricity	
Agriculture (irrigation)	84
Process	5.814
Bottling	275
Total	6.173
LPG	
Hot water production	121
Steam production	33
Plant heating	88
Total	242

Source: Adapted from (Ardente et al., 2006)

In the following case study, we will present the difference in the presentation of LCA study results when they are provided solely in the format required by the international standard ISO 14040 versus other formats enabled by professional software. The presented formats are based on the use of the software SimaPro Analyst 9.3.0.2. Different result presentation formats require different configurations of the environmental life cycle model and therefore must be agreed upon already in the project planning phase. Such discussions require the client to have prior knowledge of the LCA concept.

Table 3: Environmental categories considered within the framework of different LCA assessment methods: (a) Eco-indicator 99, (b) ReCiPe 2008, (c) ReCiPe 2016

(a) Eco-indicator 99			(b) ReCiPe 2008 Midpoint			(c) ReCiPe 2016 Midpoint	
Environmental categories	**Units**		**Environmental categories**	**Units**		**Environmental categories**	**Units**
Carcinogens	DALY		Climate change	kg CO2 eq		Global warming	kg CO2 eq
Respiratory organics	DALY		Ozone depletion	kg CFC-11 eq		Stratospheric ozone depletion	kg CFC-11 eq
Respiratory inorganics	DALY		Terrestrial acidification	kg SO2 eq		Ionizing radiation	kBq Co-60 eq
Climate change	DALY		Freshwater eutrophication	kg P eq		Ozone formation, Human health	kg NOx eq
Radiation	DALY		Marine eutrophication	kg N eq		Fine particulate matter formation	kg PM2.5 eq
Ozone layer	DALY		Human toxicity	kg 1,4-DB eq		Ozone formation, Terrestrial ecosystems	kg NOx eq
Ecotoxicity	PAF*m2yr		Photochemical oxidant formation	kg NMVOC		Terrestrial acidification	kg SO2 eq
Acidification/Eutrophication	PDF*m2 yr		Particulate matter formation	kg PM10 eq		Freshwater eutrophication	kg P eq
Land use	PDF*m2 yr		Terrestrial ecotoxicity	kg 1,4-DB eq		Marine eutrophication	kg N eq
Minerals	MJ surplus		Freshwater ecotoxicity	kg 1,4-DB eq		Terrestrial ecotoxicity	kg 1,4-DCB
Fossil fuels	MJ surplus		Marine ecotoxicity	kg 1,4-DB eq		Freshwater ecotoxicity	kg 1,4-DCB
			Ionizing radiation	kBq U235 eq		Marine ecotoxicity	kg 1,4-DCB
11 environmental categories			Agricultural land occupation	m2a		Human carcinogenic toxicity	kg 1,4-DCB
			Urban land occupation	m2a		Human non-carcinogenic toxicity	kg 1,4-DCB
			Natural land transformation	m2		Land use	m2a crop eq
			Water depletion	m3		Mineral resource scarcity	kg Cu eq
			Metal depletion	kg Fe eq		Fossil resource scarcity	kg oil eq
			Fossil depletion	kg oil eq		Water consumption	m3
			18 environmental categories			18 environmental categories	

Source: (PRe, 2020)

As part of the environmental suitability assessment of solutions in the field of electromobility, two different vehicle configurations are compared – a vehicle with an electric drive combined with an internal combustion engine, and a vehicle with an internal combustion engine equipped with a conventional mechanical transmission (Dobnik, 2023).

Goal and Scope Definition. The objective of this study is to conduct an LCA (Life Cycle Assessment) to support the results obtained from the simulation of powertrain systems. The LCA results provide deeper insight into environmental impacts, especially when raw material usage and fuel consumption of each system are taken into account. The LCA study incorporates estimated data on the components that make up either the mechanical transmission or the electric drive of the freight vehicle. Additionally, fuel consumption data obtained from prior simulations will be considered. The LCA study covers the entire life cycle, within the boundaries from cradle (raw material extraction) to grave (recycling or disposal of components).

Inventory Analysis. At this stage of the analysis, precise data on the individual powertrain components–such as the mass of components and the materials they are made from–are not yet available. Therefore, we will assume a typical distribution of component masses and materials commonly used in the production of such parts (Tables 4 and 5). The baseline mass distribution of individual components is based on a 3D model of a comparable transmission, the GAZ A32R22-1700010. At the end, each powertrain was assigned the corresponding fuel consumption, taking into account the expected service life (10 years) and total driving distance (1,000,000 km) at an average speed of 90 km/h. This results in 313,800 liters or 265,161 kg of diesel fuel (D-2) for the conventional mechanical drivetrain, and 213,900 liters or 180,745 kg of D-2 for the electric drivetrain.

The weight of the Eaton Fuller T-955ALL transmission, which was selected for the driving simulation, is 293 kg. For the electric drivetrain analysis, the competing electric motor ZF CeTrax was used, with a weight of 285 kg. It is assumed that this is the total weight of both the generator and the electric motor, as they have similar characteristics and each contributes approximately half of the total mass.

Table 4: Weight distribution of individual components of a mechanical transmission

Mechanical transmission component	Materials	Mass fraction (%)	Mass (kg)
Housing	Grey cast iron (EN-GJL-350)	50	146,5
Gears, axles, bearings	Steel SCr420	30	87,9
Non-load-bearing parts	Aluminium Si11Cu2	10	29,3
Non-load-bearing parts	Bronze CuSn12	10	29,3

Source: (Dobnik, 2023)

Table 5: Weight distribution of individual electric motor components

Electric motor component	Materials	Mass fraction (%)	Mass (kg)
Housing	Aluminium Si11Cu2	39	111,15
Stator winding	Copper Cu	10	28,5
Rotor and stator core	Steel S235 JR	43	122,55
MAgnets	Neodymium NdFeB	8	22,8

Source: (Dobnik, 2023)

The study utilized material and processing data from the Ecoinvent 3.6 database, which is described in more detail in the Master's thesis. For waste management modeling, average data for France were used. The environmental life cycle model is presented in Figure 3.

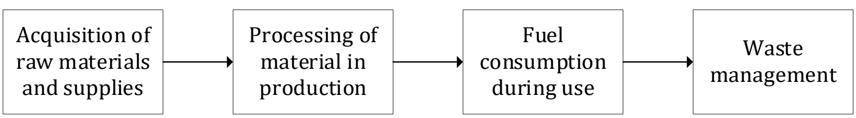

Figure 3: Environmental life cycle model of a mechanical transmission
Source: (Dobnik, 2023)

Environmental Impact Assessment. The environmental life cycle modeling was carried out using SimaPro Analyst 9.3.0.2 software, applying the ReCiPe 2016 (H) method. Using the midpoint approach, results were obtained for 18 environmental impact indicators, which are a mandatory part of the characterization phase in an LCA study report. The endpoint approach provided values for 22 environmental indicators, which were further aggregated into three damage categories: human health, ecosystems, and resources. Using weighting, the total environmental impacts were calculated and expressed in ecopoints, which allow for comparison of environmental impacts across different impact categories. A process diagram was also created to highlight the most influential processes. While such a presentation of results is not mandatory according to ISO 14040, it provides key insights for environmental optimization of processes and products. Below, we present a selection of results for the conventional powertrain with a mechanical transmission. The figures indicate which outputs are required under ISO 14040 and which go beyond the standard's requirements. The results are shown for demonstration purposes and will not be discussed in detail. They are presented in their original form as generated by the SimaPro Analyst 9.3.0.2 software, since real-world LCA reports will also provide results in the same format.

In the characterization phase, the results of the LCA study are presented using environmental impact indicators, which depend on the method applied. As shown in Table 6, the ReCiPe 2016 method provides assessment results through 18 environmental impact categories. The results within each category are expressed in equivalent amounts of selected reference substances; however, this does not imply that the selected reference substances are the most impactful within their respective categories. The results can be analyzed either in aggregated form or broken down, depending on the objectives of the analysis (e.g. most impactful processes, materials used, or life cycle stages). Based on the characterization results alone, it is not possible to determine which environmental category is the most burdensome. According to ISO 14040, characterization results are a mandatory element in every LCA assessment report.

For the environmental optimization of products, it is therefore necessary to use additional tools and result presentation methods that are not required by ISO 14040. One example of a more detailed analysis includes normalization and weighting of results, which provide insights into the overall environmental damage caused. The results are expressed in ecopoints (Pt), which are additive and allow for direct comparison. Figure 4 and Table 7 present the weighted results both graphically and in tabular form, broken down by individual life cycle stages: production, use, and end-of-life treatment. Higher bars in Figure 4 or higher values in Table 7 indicate greater environmental impact, while the contributions of individual environmental categories in Figure 4 can be interpreted using the accompanying legend.

Table 6: LCA characterization results for the life cycle of a conventional gearbox drive. Assessment performed according to ReCiPe 2016 Midpoint (H) (mandatory step according to ISO 14040)

Se	Impact category	Unit	Total	Gearbox production	Machine operation, diesel, >= 74.57 kW,	Waste (waste scenario) {FR}|
☑	Global warming	kg CO2 eq	1,03E6	9,57E3	1,02E6	32,4
☑	Stratospheric ozone depletion	kg CFC11 eq	0,372	0,00318	0,368	3,2E-5
☑	Ionizing radiation	kBq Co-60 eq	5,79E3	720	5,07E3	0,116
☑	Ozone formation, Human health	kg NOx eq	5,38E3	23,5	5,35E3	0,0368
☑	Fine particulate matter formation	kg PM2.5 eq	1,04E3	22,9	1,02E3	0,00816
☑	Ozone formation, Terrestrial ecosystems	kg NOx eq	5,59E3	25,1	5,56E3	0,0376
☑	Terrestrial acidification	kg SO2 eq	2,57E3	39,4	2,53E3	0,0199
☑	Freshwater eutrophication	kg P eq	40,6	5,39	35,2	0,00598
☑	Marine eutrophication	kg N eq	23,3	0,752	22,5	0,000728
☑	Terrestrial ecotoxicity	kg 1,4-DCB	1,31E6	1,66E5	1,15E6	20
☑	Freshwater ecotoxicity	kg 1,4-DCB	6,42E3	1,58E3	4,76E3	75,3
☑	Marine ecotoxicity	kg 1,4-DCB	9,65E3	2,06E3	7,5E3	91,9
☑	Human carcinogenic toxicity	kg 1,4-DCB	4,42E4	4,53E3	3,97E4	4,24
☑	Human non-carcinogenic toxicity	kg 1,4-DCB	1,42E5	2,56E4	1,16E5	337
☑	Land use	m2a crop eq	7,25E3	231	7,02E3	0,0423
☑	Mineral resource scarcity	kg Cu eq	2,02E3	364	1,65E3	0,02
☑	Fossil resource scarcity	kg oil eq	3,36E5	2,45E3	3,33E5	1,15
☑	Water consumption	m3	1,15E3	57,1	1,1E3	0,0981

Source: (SimaPro)

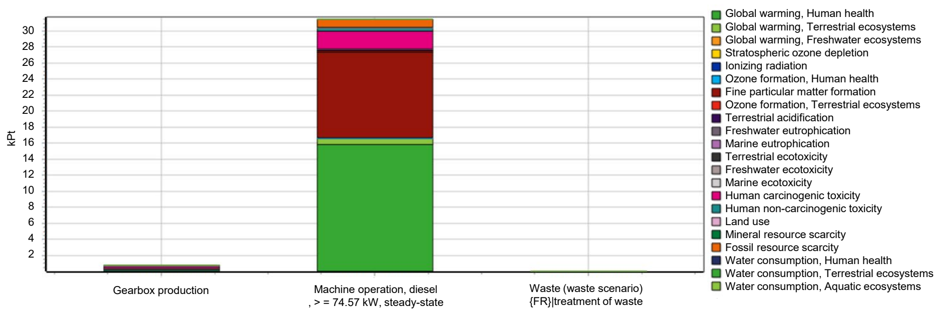

Figure 4: LCA single score results for the life cycle of a conventional gearbox drive. Assessment performed according to ReCiPe 2016 Endpoint (H), results expressed in ecopoints (Pt). (optional step according to ISO 14040)

Source: (SimaPro)

Just like in the characterization phase, the results related to environmental damage (i.e., normalized and weighted results) can also be presented either in aggregated form or broken down in various ways, depending on the intended use of the LCA study results. Figure 5 shows the contributions of individual processes involved in the production of the conventional transmission. Higher bars indicate greater contributions to environmental burdens, while the contributions of individual environmental categories can be interpreted using the accompanying legend. This type of result presentation enables product eco-design, which is not possible with other presentation methods. Therefore, a well-structured LCA study design is essential for ensuring the practical applicability of its results. Presenting results in the manner shown in Figure 5 is not a mandatory step under ISO 14040.

Table 7: LCA weighting results for the life cycle of a conventional gearbox drive. Assessment performed according to ReCiPe 2016 Endpoint (H), results expressed in ecopoints (Pt). (optional step according to ISO 14040)

Se	Impact category	Unit	Total	Gearbox production	Machine operation,	Waste (waste scenario) {FR}|
	Total	kPt	32,2	0,756	31,5	0,00215
	Global warming, Human health	kPt	16	0,148	15,8	0,000501
	Global warming, Terrestrial ecosystems	kPt	0,782	0,00725	0,775	2,45E-5
	Global warming, Freshwater ecosystems	kPt	2,14E-5	1,98E-7	2,12E-5	6,7E-10
	Stratospheric ozone depletion	kPt	0,00329	2,82E-5	0,00326	2,83E-7
	Ionizing radiation	kPt	0,00082	0,000102	0,000718	1,64E-8
	Ozone formation, Human health	kPt	0,0816	0,000357	0,0813	5,58E-7
	Fine particulate matter formation	kPt	11	0,24	10,7	8,56E-5
	Ozone formation, Terrestrial ecosystems	kPt	0,195	0,000875	0,194	1,31E-6
	Terrestrial acidification	kPt	0,147	0,00226	0,145	1,14E-6
	Freshwater eutrophication	kPt	0,00735	0,000975	0,00638	1,08E-6
	Marine eutrophication	kPt	1,07E-5	3,45E-7	1,04E-5	3,35E-10
	Terrestrial ecotoxicity	kPt	0,00404	0,000514	0,00353	6,18E-8
	Freshwater ecotoxicity	kPt	0,0012	0,000296	0,000894	1,41E-5
	Marine ecotoxicity	kPt	0,000274	5,86E-5	0,000213	2,61E-6
	Human carcinogenic toxicity	kPt	2,45	0,251	2,2	0,000235
	Human non-carcinogenic toxicity	kPt	0,54	0,0975	0,442	0,00128
	Land use	kPt	0,0174	0,000555	0,0168	1,02E-7
	Mineral resource scarcity	kPt	0,00333	0,000601	0,00273	3,29E-8
	Fossil resource scarcity	kPt	1,05	0,00418	1,04	2,96E-6
	Water consumption, Human health	kPt	0,0144	0,000786	0,0136	8,3E-7
	Water consumption, Terrestrial ecosystem	kPt	0,00265	0,000111	0,00254	1,18E-7
	Water consumption, Aquatic ecosystems	kPt	4,51E-7	2,15E-8	4,3E-7	8,86E-12

Source: (SimaPro)

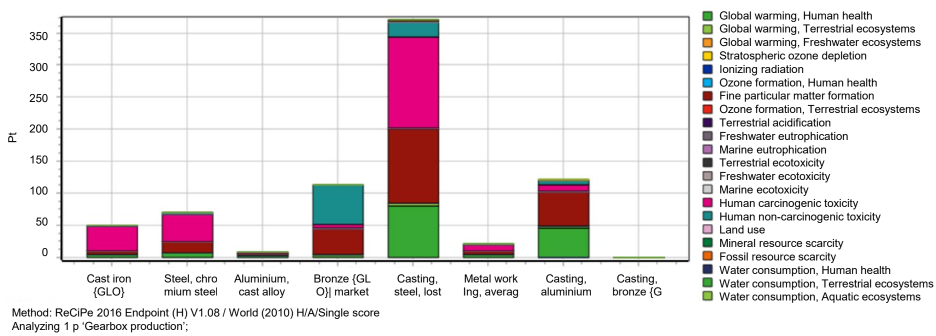

Figure 5: LCA single score results for the production process of a drive with a conventional gearbox. Assessment performed according to ReCiPe 2016 Endpoint (H), results expressed in ecopoints (Pt). (optional step according to ISO 14040)

Source: (SimaPro)

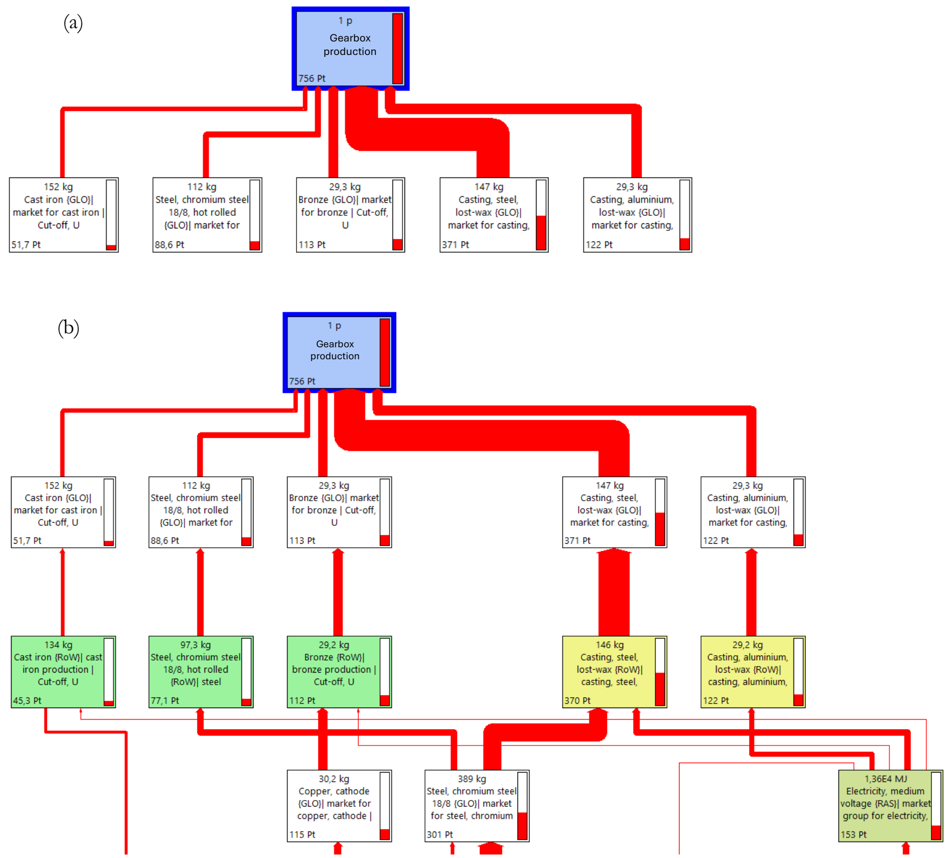

Figure 6: LCA single score results for the production process of a drive with a conventional gearbox: Display of the most influential processes (Figure 6a), More detailed display of the impacts of individual processes (Figure 6b). Assessment performed according to ReCiPe 2016 Endpoint (H), results expressed in ecopoints (Pt). Thicker arrows represent the environmentally more burdensome phases/processes. (optional step according to ISO 14040)

Source: (SimaPro)

Damage data can also be presented using Sankey diagrams. This involves visualizing environmental burdens, where thicker arrows represent more environmentally burdensome phases/processes, and the scope of the processes shown can be adjusted. Such a presentation (Figure 6) is also not mandatory according to ISO 14040, which is why it is less commonly found in LCA study reports. Figure 6a shows a Sankey diagram for the process of manufacturing a conventional transmission, which, similar to Figure 5, highlights the most impactful processes during production. Meanwhile, the Sankey diagram in Figure 6b further clarifies the sources of the results, which is crucial for the environmental optimization of processes and products.

While characterization results in LCA studies cannot be directly compared, comparisons are possible at the level of environmental damage, provided that the assessment results were obtained using the same methodology. Figure 7 presents the results of a comparative analysis for the process of manufacturing an electric powertrain and a conventional powertrain, where the height of the bars represents the total environmental burdens associated with the production of each alternative. From Figure 7, it is evident that the production of the electric powertrain results in half the environmental burdens compared to the production of the conventional powertrain. However, this does not mean that the environmental burdens of the electric powertrain are lower throughout the entire life cycle, which would need to be verified through a full calculation. Such a presentation is also not a mandatory step according to ISO 14040.

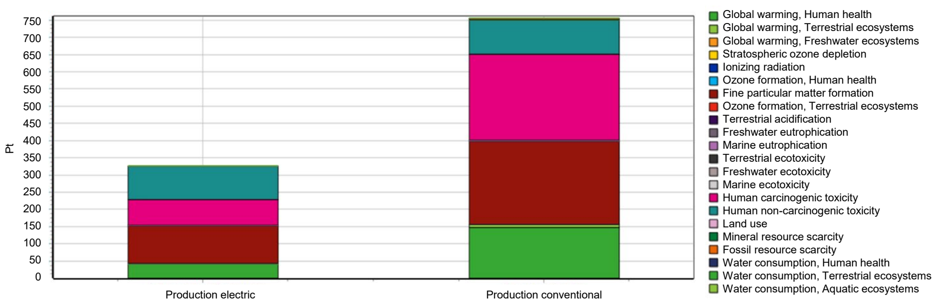

Figure 7: Results of a comparative single score LCA analysis for the production process of an electric drive and a drive with a conventional gearbox. Assessment performed according to ReCiPe 2016 Endpoint (H), results expressed in ecopoints (Pt). (optional step according to ISO 14040)

Source: (SimaPro)

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