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Data-driven life cycle assessment for mechatronic systems: a comparative analysis of environmental impact assessments

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Abstract

The growing emphasis on sustainability integrates eco-design and life cycle analysis into product development. Despite the value of LCAs, data limitations lead to assumptions, impacting accuracy. This study compares an estimation-based LCA with a data-driven approach, focusing on a laser machine's operational phase. The significant influence of resource consumption during operation underscores the necessity of optimization. Applying a data-driven approach reveals a 24% difference compared to the estimation-based method, emphasizing the challenges in obtaining accurate data for effective LCAs.

Keywords: sustainability, data-driven design, life cycle assessment (LCA)

1. Introduction

In recent years, the importance of sustainability and sustainable practices has gained significant importance and recognition across society and industries. To address increasing demands for more sustainable products, processes, and services, companies are required to improve how they operate on the global market. It becomes imperative to improve the environmental performance of manufacturing processes, particularly in the context of complex mechatronic systems. These systems, integrating mechanical, electrical, and control components, play a crucial role in modern manufacturing, enabling increased automation and efficiency. However, even the operation of modern manufacturing systems can lead to significant resource consumption. As these systems become more intricate and interconnected, the generated data grows exponentially, offering valuable insights into operations and resource utilization. With the increasing availability of data on machine operations, data-driven decision-making becomes crucial for managing and optimizing complex mechatronic systems. Analyzing resource consumption and operational machine data can provide invaluable insights to assess the sustainability of a mechatronic system. Such analyses can highlight areas for improvement, potentially leading to significant reductions in environmental impact, while optimizing system performance and efficiency. To assess the sustainability and the environmental impact of a product, process, or service over its entire life cycle, tools and methods such as the Life Cycle Assessment (LCA) already exist (Bauer and Poganietz, 2007). However, the availability and reliability of data pose a particular challenge in carrying out an LCA and hence assessing the sustainability across all life cycles (Hellweg and Milà i Canals, 2014). Despite available methods such as the LCA and various tools and databases containing information about CO2 equivalents with their potential environmental impact, carrying out a life cycle assessment and mining relevant and reliable data pose significant challenges to the industry. To cope with these challenges, a broader range of operational machine data must be assessed and made usable.

2. Current state of research

2.1. Eco-design and product development

Future machines must consider sustainability alongside efficiency and longevity. Legislations as the European Corporate Sustainability Reporting Directive (CSRD)) (EUROPEAN PARLIAMENT, 2022) reflects a growing consensus, compelling companies to enhance transparency and report on sustainability, emphasizing the shift toward more sustainable practices. Eco-Design represents an approach where environmental impacts and requirements are considered in every phase of the development process and the lifecycles of the product. This concept focuses on designing products and services with a minimization of their environmental impact throughout their lifecycle. Beginning from the selection of materials to manufacturing processes, energy consumption, use, and eventual disposal, Eco-Design emphasizes a holistic perspective that prioritizes sustainability. Similar concepts as Design for Environment, Sustainable Product Design or Life Cycle Engineering are characterizing identical objectives (Schäfer and Löwer, 2021).

The environmental impacts associated with a product are largely established during its design phase, underscoring the profound influence of product development on overall sustainability. This highlights the critical role that design decisions play in shaping the environmental footprint of a product. Therefore, the process of product development has a significant influence over the operational performance of a product or system and therefore its sustainability (Jeswiet and Hauschild, 2005). Extensive research has been dedicated to understanding and refining various aspects of the product development process. The Model of PGE - Product Generation Engineering, describes how products are always developed based on already existing products. Therefore, the development of new product generations can be described with the modification and recomposition of systems adopted or derived from already existing products as a starting point. Already existing products or systems are described as reference systems consisting of reference system elements. Depending on the extent of the changes, the developing process of an entire system or a subsystem originates through principle variation, embodiment variation and carryovers (Albers *et al.*, 2018). To support the development of new product generations, the analysis of field-gathered machine data can provide valuable insights into the machine usage and therefore its interconnected reference system elements (Wagenmann *et al.*, 2022). To be able to consider sustainability within the product development process, the potential environmental impact must be assessed. Already existing approaches as the Life Cycle Assessment (LCA), provide the possibility and the respective methodological framework to assess the sustainability of a product across its entire lifecycle. By gathering relevant operational machine data, the assessment of a machines environmental impact and therefore its sustainability can be enhanced.

2.2. The life-cycle assessment

Due to the growing awareness of environmental protection and emission savings, interest in methods that calculate environmental impacts is constantly increasing. The Life Cycle Assessment is a method for evaluating the environmental impact of a product, process, or service over its entire life cycle and is based on the GHG Protocol. The methodology was developed as a result of environmental protection to determine precautionary decisions between products or product variants and to minimize possible effects on the environment (Bauer and Poganietz, 2007). This method is based on a life cycle approach, where all phases of a product's life cycle are considered, from the extraction of raw materials through production, use, and disposal to the end of the life cycle (Frischknecht, 2020).

The procedure within the LCA was standardized by the International Organization for Standardization (ISO). The ISO 14040 norm contains the basic principles of life cycle assessment providing a framework for carrying out a life cycle analysis and specifying requirements for its implementation, documentation, and review. With ISO 14044, an international standard for environmental management systems is provided. It describes the requirements that apply to environmental management systems and their review to achieve improved environmental performance and is part of the ISO 14000 series of standards for environmental management (Deutsches Institut für Normung, 2009). The following Figure 1 illustrates the stages considered in the application of an LCA.

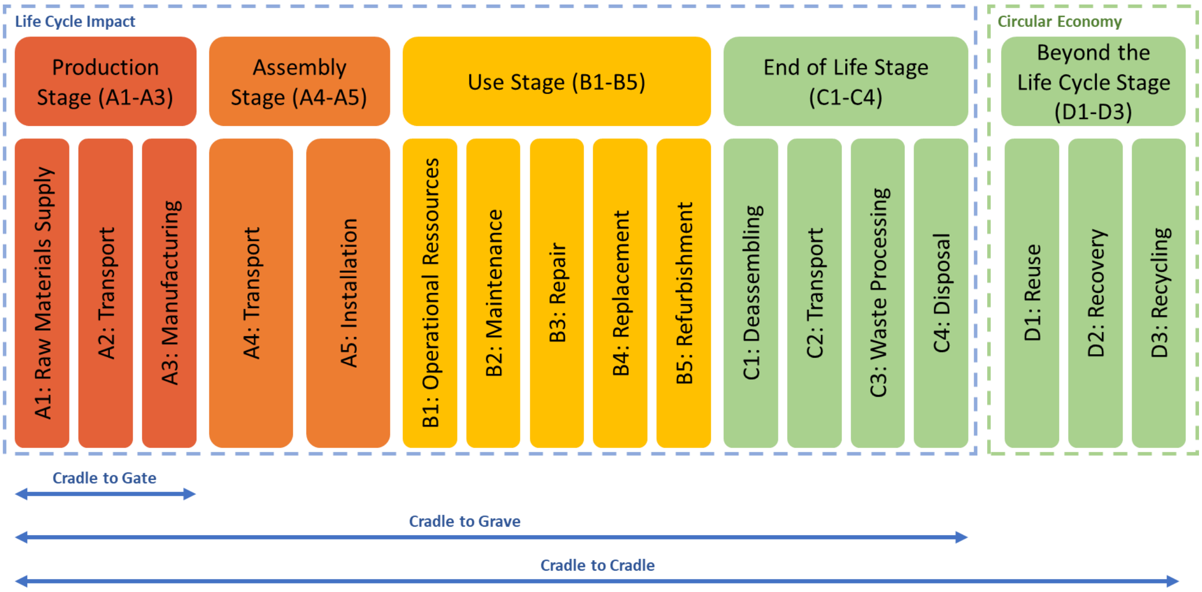

Figure 1. Considered stages in the Life-Cycle Assessment (Bhatia et al., 2011)

In general, an LCA consists of four phases beginning with the Definition of the goal and scope, where the functional unit is determined, system boundaries are clarified, and necessary data quality and requirements are defined. The second phase consists of data collection, refinement of the system boundaries as well as the data calculation and validation. In the third phase, the impact categories to be assessed are determined, classified, characterized, normalized, and weighted. In the fourth and last phase, the critical environmental issues are identified, the results are analyzed and evaluated, and an analysis of the sensitivity, conclusions, and future recommendations are conducted. Despite an increasing necessity to support the evaluation of the potential environmental impacts of a product, the application of an LCA faces challenges due to the complexity of modern products and a lack of data consistency (Inkermann, 2022).

Data is a key factor in the preparation of the Life Cycle Inventory. Ideally, all the necessary information and data relating to raw material extraction, manufacturing, production, transport, utilization, and disposal data should be stored in a company's databases. The method itself already represents a complexity, which is why the start and understanding of the procedure described in DIN ISO 14040 is fundamental (Frischknecht, 2020; Hauschild *et al.*, 2018). In connection with the life cycle analysis method itself, there are several central problems and challenges that researchers and practitioners are confronted with. These challenges relate to the methodology and implementation of LCA (Hauschild *et al.*, 2018). One problem here is the use of simplified models and assumptions to represent complex systems and processes. These simplifications can lead to uncertainties and limitations in the results. It is important to carefully verify the level of detail and accuracy of the models and assumptions used to ensure the reliability of the LCA results. Data availability and reliability play a major role in the LCA to assess environmental impacts. However, the availability and reliability of data can be a challenge, especially for new technologies, novel materials, or specific supply chain information. The lack of comprehensive and accurate data can affect the robustness and validity of the LCA results. Further, an LCA can be a time and resource-intensive process. Collecting, processing, and analyzing the necessary data can be tedious and requires considerable expertise (Hellweg and Milà i Canals, 2014). With the ability of utilizing and analyzing field-gathered machine data, arising challenges can be encountered and the application of an LCA can be supported (Guinée *et al.*, 2021).

2.3. Data-driven sustainability

Sustainable and smart manufacturing has gained increasing attention in the industry as digitalization progresses, the increasing networking of suppliers, manufacturers, and customers as well as the use of a growing number of different information channels is leading to a rapid increase in the availability of data. These exponentially increasing amounts of data contain potential knowledge that can be used to

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meet the constantly growing sustainability requirements (Schmitt *et al.*, 2020). Data-driven sustainability refers thereby to the use of field-gathered data generated from manufacturing processes and machine utilization as well as analytics to drive sustainable practices and decisions in various areas such as environmental protection, resource management, and social responsibility. This includes collecting, analyzing, and interpreting data to gain insights into sustainability performance, identify optimization opportunities, and develop strategic initiatives. By using data, organizations can measure and monitor their environmental impact, track resource consumption, assess social and societal contributions, and evaluate the effectiveness of sustainability initiatives. This data can derive from a variety of sources, including sensors, IoT devices, monitoring systems, surveys, and external databases (Chavez *et al.*, 2022).

In practice, sustainable manufacturing faces a variety of challenges due to complex manufacturing processes. Manufacturing processes generate vast amounts of data from operations management, the production process, and process equipment in a short period. Capturing this data is often a challenge, even with advanced technologies. It is therefore essential to set up a data-driven architecture to process and utilize this data. Despite of these challenges, modern mechatronic systems, equipped with a multitude of sensors as well as respective control and monitoring modules to ensure efficient machine performance, are particularly suitable for a data-driven approach towards sustainability. Data-driven manufacturing can be seen as a necessary condition for intelligent sustainable manufacturing (Ma *et al.*, 2020). According to Stock & Seliger, the entire product life cycle should be considered as a closed loop within different manufacturers, in which the sharing of data, materials, and energy represents a new competitive advantage, and point out that the sharing of data has great potential (Stock and Seliger, 2016).

The development and manufacture of products are inextricably linked to environmental impacts, which are often negative. However, it is crucial to understand these impacts to design products according to ecological requirements. The focus lies on the transition from a society based on mass production, mass consumption, and mass disposal to a sustainable society in which materials are used efficiently throughout the entire product life cycle. This transition requires a change in the way we develop products to minimize environmental impact and promote long-term environmental sustainability (Nakayama *et al.*, 2005). Product development requires a holistic and interconnected understanding, whereby the consideration of production and environmental aspects is of central importance. However, environmental aspects have long been neglected in the phases of the product development process, as production and environmental issues have been treated separately. This led to little attention being paid to environmental issues in product development. The activity that integrates such criteria into the core of design processes is Eco-design. Eco-design integrates environmental aspects into the design process in order to improve the environmental performance of the entire product life cycle. It emphasizes the importance of the first phase in the product life cycle, as several requirements and specifications of the product are defined in this initial phase. Accordingly, it can be said that the sustainability of a product largely depends on this development phase (Kokoschko *et al.*, 2021). In summary, data-driven sustainability enables organizations to make informed decisions based on quantitative evidence rather than assumptions. It helps to identify shortcomings, uncover hidden patterns, and optimize processes to reduce waste, energy consumption, and greenhouse gas emissions. Ultimately, it can also support the measurement of progress toward sustainability goals, enabling benchmarking and reporting on the achievement of sustainability goals (Provost and Fawcett, 2013).

3. Research objectives and methodology

Ecodesign already provides a framework for integrating sustainability considerations into the product development process. Furthermore, the Life Cycle Assessment offers an approach for systematically assessing and documenting the environmental impact associated with a product. However, due to a lack of the availability and potentially the possibilities to assess necessary data, the application of an LCA often relies on assumptions. For this reason, real environmental impacts may not be reflected with sufficient accuracy. Valuable machine data is gathered and utilized within the product development process but without a specific focus on enhancing the sustainability of the machine during operation. Therefore, field-gathered machine data must be utilized with the aim of enhancing the sustainability of complex mechatronic systems. As a contribution to this objective, this work aims at a comparative analysis of an estimation-based LCA and a data-driven LCA, using measurement data as well as field gathered operational machine data to assess possible advantages of a data-based approach. This work is structured according to the Design Research Methodology by Blessing and Chakrarbarti (2009) and is carried out in the research and development department of a German machine tool manufacturer. The aim of this work is operationalized by the following research questions:

1) What environmental impact can be assessed using an estimation-based life cycle assessment approach of a complex mechatronic system?

2) How must a data-driven approach for a life-cycle assessment of a complex mechatronic system be designed?

3) What advantage does a data-driven approach provide compared to an assumption-based estimation for a life-cycle assessment of a complex mechatronic system?

The Descriptive Study I (DS I) aims to answer the first research question by conducting an initial assessment of the environmental impact of a complex mechatronic system by applying an LCA based on the available guidelines. Within this first assessment, field gathered operational machine data is considered and included exclusively for the production output of the analyzed machine type by averaging the produced sheet-metal parts within a year of similar machine types to prevent estimation errors during the estimation-based assessment. The Prescriptive Study (PS) aims to answer the second research question by designing a data-driven approach utilizing field gathered machine data as well as measured resource consumption data during operation. The Descriptive Study II (DS II) aims to analyze the difference between the first LCA based on assumptions and a data-driven LCA utilizing resource consumption measurement data. By comparing the results obtained from the performed measurements curated for this assessment with those derived from free data sources that only provide estimations, the reliability and accuracy of sustainability evaluations when employing different data sets can be evaluated. To provide reliable results in the following, the conducted assessments utilize internal company data, measured resource consumption data, publicly available databases, and expert assessments to aggregate all relevant data for such a comparison.

4. Results

4.1. Environmental impact of an estimation-based life cycle assessment of a complex mechatronic system

For the conduction of an LCA several boundary conditions are defined. For a realistic estimation, a two-shift work environment is estimated with an average effective operation time of 70% to account for possible down-times as well as stand-by times of the analyzed flatbed laser machine. To determine the relevant information regarding raw material supply, the assessment is based on product data sheets, 3D-CAD models, bills of material, and expert knowledge from respective developers. Based on the determined quantities of material contained in the analyzed machine, the carbon equivalents of the used materials and transportation are determined utilizing open-access databases such as ProBas, EEW 2022, GEMIS 5.0, and UMBERTO 5. ProBas represents the main database used and was developed in collaboration between the German Federal Environment Agency and the International Institute for Sustainability Analyses and Strategies (IINAS). ProBas stands for "Process-orientated basic data for environmental management instruments" and is a library for life cycle data. To provide the broadest possible spectrum of life cycle data, the ProBas database integrates numerous publicly accessible data sources. In addition, the "BWIHK-ECOCOCKPIT" tool is used, which was developed in collaboration with the NRW Efficiency Agency and the Baden-Württemberg Chamber of Industry and Commerce. The tool was developed following the GHG Protocol accounting standards and provides access to exclusively recognized databases for the life cycle data of various raw materials.

Regarding transportation, only the main components are considered in determining the distribution channels. Here, the production locations of the individual components were determined and the optimum transport routes and means of transport for the movement of materials and products between the locations were calculated. Factors such as distances and the weight of the goods are taken into account. The calculation of transport emissions is carried out with the initial determination and

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identification of the production sites and means of transport. Based on this information, the ProBas database is used to calculate the emissions in this life cycle stage using the functional unit ton-kilometres which correspond to the kilometres travelled multiplied by the quantity of goods transported. For the system under investigation, a total distance of 4411km could be determined. Due to no data availability regarding the end-of-life and the variance in the time frame a complex mechatronic system is operating on the customers shopfloor, the scope of this assessment is limited to the lifecycle from cradle to gate and the first year of operation. The following Figure 2 illustrates the CO2-Equivalents contained by the analyzed mechatronic system as well as the total assessed CO2e emissions in kg of the utilized material and the total emissions from transportation.

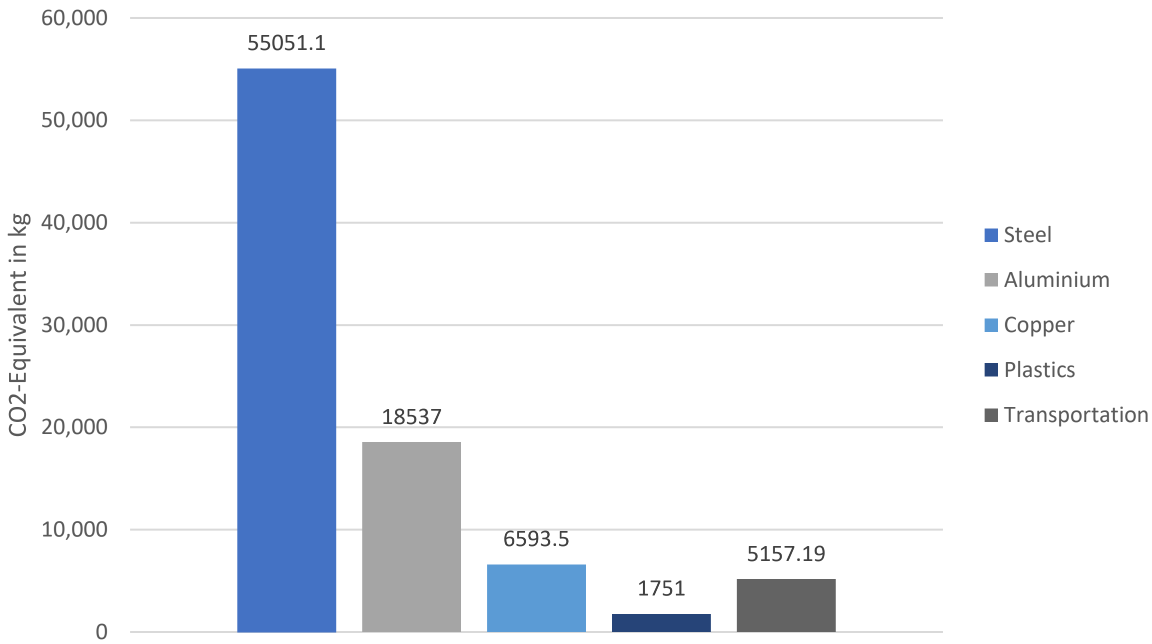

Figure 2. CO2-Equivalentsin kg of the mechatronic system accounting for cradle to gate

With the assessment of the complex mechatronic system, a total environmental impact of 87 tonnes CO2-Equivalent can be estimated. To assess the operational phase of the system under investigation, the utilized resources are calculated. For the operation of a flatbed laser machine, the primary resources considered are process gases as nitrogen, electricity and compressed air used to move pneumatically controlled machine elements. The following Table 1 illustrates the respective CO2-Equivalents for the utilized resources to operate the machine.

Table 1. CO2-Equivalents in kg accounting for the machine operation

Nitrogen	Oxygen	Compressed Air	Electricity	Sheet-Metal
20580	546.37	6367.97	21784.32	*101510.86

*CO2-Equivalent in kg based on a data-driven approach, analyzing field-gathered machine data for the averaged amount of produced sheet-metal parts within a year of similar machine types

The following Figure 3 illustrates the environmental impact between the phases from cradle to gate and the first year in operation. As can be seen, the operational phase contributes with a CO2-Equivalent of 1,060,789.5 tonnes a significantly greater environmental impact than the prior stages in the product life cycle. Due to the daily use of the system in two-shift operations, the operational phase plays a significant role in the generation of emissions. In evaluating the environmental impact of a complex mechatronic system, the LCA shows significant insights where the operational phase exerts the most substantial influence on the estimated total CO2e emissions. Within the assessment of the sustainability of the operational phase, the utilized sheet-metal is primarily contributing to the environmental impact in this phase.

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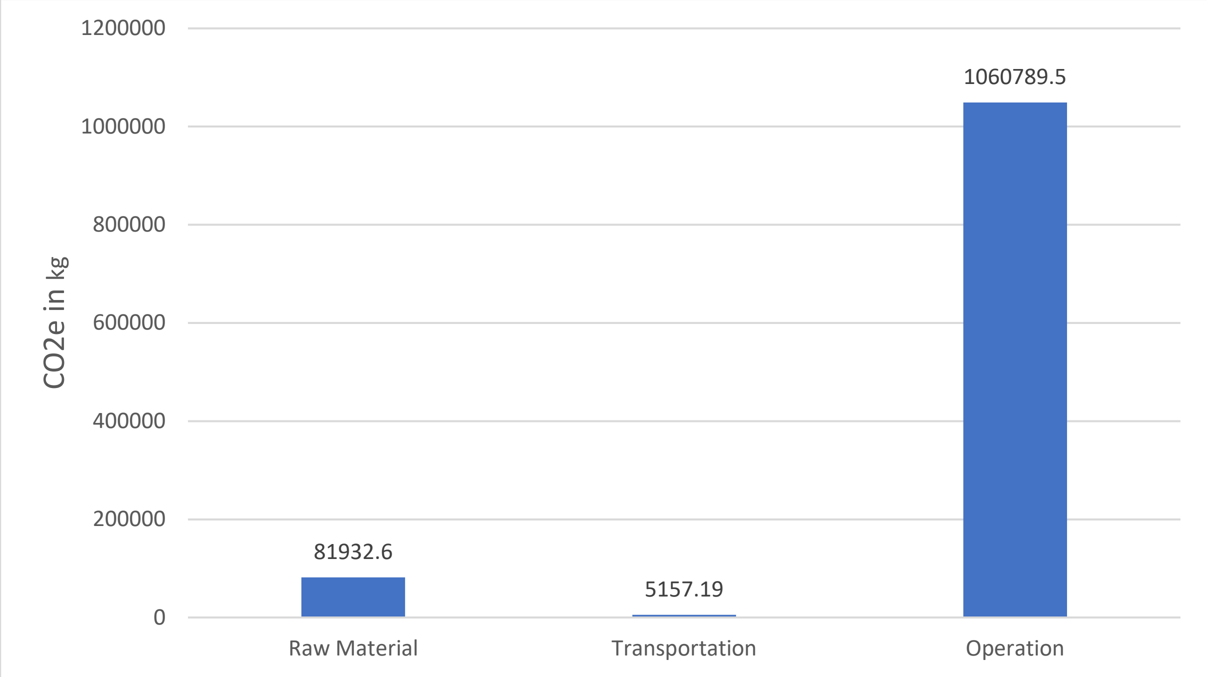

Figure 3. Comparison of the environmental impact between cradle to gate and the operational phase

4.2. A Data-driven approach for a life-cycle assessment of a complex mechatronic system

An estimation-based assessment has been conducted to evaluate environmental impacts. To compare possible differences, a data-driven approach is designed assessing the environmental impact of the same system under investigation using measurement data of the utilized resource consumption during operation.

Data availability and data quality are crucial for the life cycle assessment of any product. To collect all the necessary data during the operating phase, the machine under investigation was retrofitted with sensors and measuring devices to assess the resource consumption of electricity, process gases as oxygen (O2) or nitrogen (N2) to cut sheet-metal as well as compressed air used to move pneumatically controlled machine elements. The consumption of both cutting gases is measured with one flow sensor each. The nitrogen consumption is measured with the "Bronkhorst D-6380-DR" device and the oxygen consumption with the "Bronkhorst D-6370-DR" device. Compressed air consumption is measured using the "ifm SD8000" flow sensor. The flow sensors have a sampling rate of 1 Hertz and therefore output the current consumption value every second. The consumption of the used electricity of the system is measured using the "Chauvin-Arnoux C107" current measuring clamps. The sampling rate of the current clamps is 20 kHz. The effective power is calculated directly in the connected measuring module and output as an arithmetic mean at 1 Hertz, which also results in a consumption value per second. The four consumption sensors are connected to the "imc cronos flex" measuring amplifier with a "HVU-2U2I" measuring module. The measurements are conducted in a period of three months and extrapolated to one year. With the application of the data-driven approach, the assessed results from cradle to gate are adopted. The measured data concerning the resource consumption as process gases N2 and O2, the electricity as well as the compressed air are compared. The utilized sheet-metal and in CO2-equivalent are adopted and used in botch approaches to ensure comparability based on the measurements.

4.3. Comparison of a data-driven approach with an estimation-based life-cycle assessment of a complex mechatronic system

To assess the environmental impact of a complex mechatronic system, two LCAs are conducted using both, a data-driven and an estimation-based approach. With the comparison of both approaches, the

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influence utilizing data to assess the environmental impact is analyzed. The following Table 2 illustrates the comparison of the environmental impact in kg CO2-Equivalents assessed between the data-driven and estimation-based approach.

Table 2. Comparison of the CO2-Equivalent emissions in kg

Resource	Estimated CO2e emissions in kg in one year	CO2e emissions in kg during the measurement	CO2e emissions in kg extrapolated to one year	Delta in %
N2	20580.03	4144.74	16806.92	18.3
O2	546.37	67.4	275.31	49.6
Compressed Air	6367.97	1169.76	4743.38	25.5
Electricity	21784.32	3911.81	15862.39	27.2
Total	49278.69	9293.71	37688	23.5

The following Figure 4 illustrates the comparison of the calculated carbon emissions between estimated emissions and extrapolated emissions based on the measured resource consumption. As can be seen, the CO2-Equivalent emissions of the estimation-based approach are higher than the measured emissions for all four resources by approximately 24%.

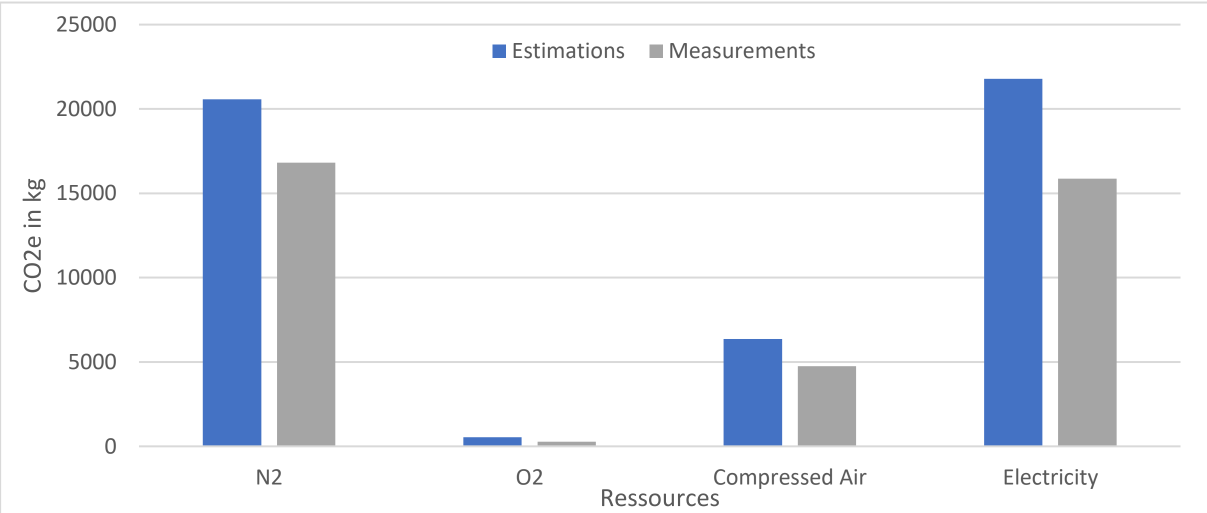

Figure 4. Comparison of calculated emissions based on estimations and measurements

5. Discussion and outlook

This work provides a comparative analysis of an estimation-based LCA and a data-driven LCA, using measurement data of resource consumption during machine operation to assess possible advantages of a data-driven approach. The environmental impact, especially of a complex mechatronic system such as a laser machine, is predominantly influenced by resource consumption during its operation. Recognizing this, effective reduction of the overall environmental footprint necessitates a focused optimization of the system's operational phase. With the application of an LCA, an environmental impact of 1.136 tonnes CO2e in total could be estimated where approximately 92% can be assigned to the operational phase including the processed sheet-metal. The Assessment and analysis of the measured consumption data showed that the utilized material as sheet-metal accounts for 1049 tonnes and therefore the greatest environmental impact during machine operation. With the estimation-based approach an environmental impact of the utilized resources of 49,278.69 kg CO2-equivalents can be assessed excluding the processed sheet-metal. The application of multiple measurement devices to assess the resource consumption during machine operation shows significant differences between an estimation-based and the data-driven approach. Utilizing measured resource consumption, an environmental impact of 37,688 kg CO2-Equivalents is assessed. Comparing both approaches, a difference of approximately 24% can

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be assessed. Despite the obtained results, the environmental impact of a complex mechatronic system can vary significantly based on its utilization on the manufacturing shop floor as well as its overall efficiency during operation influenced by human errors. Although possible highly varying factors due to individual machine and resource utilization, the LCA method serves as a robust approach to widely assess the environmental impact of a product by analyzing each stage from raw material extraction to disposal. However, its efficiency and accuracy hinges on the availability of qualitative data, posing a substantial challenge for developers in usability. The complexity of the LCA further complicates matters, demanding a thorough understanding of the method itself and the broader spectrum of each phase. In the context of mechatronic systems, the intricate interplay of mechanical, electronic, and software components, combined with the number of components within the bill of materials, intensifies the challenges associated with conducting a comprehensive LCA. Addressing these complexities is crucial for leveraging LCA insights to guide sustainable product development. To achieve accurate and meaningful results across all phases of the product life cycle, relevant information, and data, especially about the end of life must be available. These challenges pertain to both, the technical domain, emphasizing that successful implementation relies on the availability of a suitable IT infrastructure and data, as well as methodical challenges in the form of the complexity of the method itself.
By strategically managing resource utilization during operation, significant improvements can be made toward minimizing the environmental impact of the entire system. Retrofitting sensors and measuring devices is an option for mining relevant data to obtain product-specific consumption. Assessing the environmental impact of a complex mechatronic system demands measurements, yet it is not solely reliant on this approach. Especially small and medium-sized enterprises (SMEs) encounter notable challenges in implementing Life Cycle Assessments primarily attributable to less developed IT infrastructure and limited data utilization capabilities in comparison to large corporations. The constrained technological resources making it challenging for these companies to derive informed decisions based on comprehensive life cycle analyses, underscoring the unique hurdles faced by SMEs in embracing sustainable practices. Similar to the shifts brought by globalization and digitalization, the transition to sustainable business practices should be regarded as an opportunity actively embraced by companies. Future research and development should exploit the advantages provided by modern simulation possibilities, evaluated, and validated by real-world measurements to accelerate the application of Life Cycle Assessments. Achieving sustainability entails implementing innovative solutions for responsible resource use, emission and waste reduction, and the adoption of renewable energy sources. The distribution percentages underscore the effectiveness of reducing carbon dioxide emissions during machine operation, resulting in a potent lever for meeting climate protection objectives. A comprehensive approach to decarbonization necessitates industry-wide consideration of products, with a particular focus on understanding and mitigating their environmental impact throughout their entire life cycle.

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