METHOD FOR THE INTEGRATION OF COMPUTER AIDED MANUFACTURING DATA IN LIFE CYCLE ASSESSMENT

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ABSTRACT

Precise sustainability assessment becomes increasingly important in decision-making, marketing, and regulations. Therefore, reliable and comparable LCA becomes mandatory. Currently, primary data is rarely available due to vastly complex value chains. Secondary data from eco-databases provide a remedy to estimate the sustainability impacts of up- and downstream processes. While giving insights and estimations, this data is seldom fitting exactly to the own processes and lacks comparability. Therefore, this paper proposes a method to close the gap between unreliable secondary data and unavailable primary data. This gap is to be closed by the integration of simulated process data. CAM is a tool during the work preparation to assess the design's manufacturability, decrease set-up times and optimize the NC code. However, integrating DES into LCA is still subject to research and will be discussed in this paper. This paper answers the question of the necessary steps to integrate the simulated production process in an LCA to increase the quality and reliability of sustainability indicators. A method is presented, and the implementation of the steps with the help of a developed assistance system on an example is performed.

Keywords: Life Cycle Assessment, Decision making, Computer Aided Manufacturing, Sustainability, Simulation

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1 INTRODUCTION

The reliable assessment and comparable quantification of greenhouse gas emissions like CO^2 have become increasingly important in the production industry due to public awareness of sustainability and competitive advantages. For each progressing phase of the product development, further degrees of freedom are created in the process chain, complicating the decision for the optimal path (Gaha et al., 2014). The long-term goal of Product Life Cycle Management is to provide information for well-founded decisions regarding sustainability as early as possible. In the age of digitalization, there are tools at our disposal that enable us to model a sustainable product life cycle. An important step toward the comparability and validity of these tools is improving data quality. However, much effort is involved in equipping a process, not to mention a whole production network, with sensors and digital infrastructure to make reliable, primary data usable. Secondary data from eco-databases provide a remedy to estimate the sustainability impacts of up- and downstream processes. While providing insights and estimations, this data is seldom fitting exactly to the own processes and thus introduces errors and uncertainties to the assessment. Based on the Product Environmental Footprint (PEF) (DIN EN ISO 14067, 2019), we propose a novel method for supplementing missing primary data with simulated data from the Computer Aided Manufacturing (CAM) process. Primary data are specific data measured directly in the process, and secondary data include assumptions and proxy data. While using simulated data in ecological assessments is not new, this method integrates the CAM simulation in Life Cycle Assessment (LCA) and presents an implementation in Siemens NX. The focus of this paper is to enable reliable monitoring of sustainability as early as possible, even if there are limited primary data available, for example, in brownfield production systems. This paper proposes a novel method of using simulated data from the CAM process as input data for Life Cycle Assessment (LCA). The Product Carbon Footprint (PCF), in turn, results from the LCA and quantifies emissions equivalent to CO^2 emissions (CO^2e). Following this introduction, state of the art is discussed regarding simulations in LCA and the CAM process. The steps of the method are introduced in section 3 and put to use in an exemplary application in section 4 in which a product is assessed using secondary, simulated, and primary data. Section 5 discusses the findings and gives a brief outlook.

2 STATE OF THE ART

There are already numerous methods in the literature for assessing and balancing sustainability in all dimensions. However, to consider sustainability over the entire life cycle, research should be done regarding the accuracy, comparability, and integration of holistic ecological assessments (Albrecht, 2021). This section discusses previous works which lay the groundwork for the proposed solution. The first part covers the current state of LCA and the integration of Discrete Event Simulation (DES). The second part discusses the basic principles of CAM to integrate the two processes later in section 3.

2.1 Discrete event simulation in Life Cycle Assessment

LCA is a standardized method to assess the ecological sustainability of a functional unit (DIN EN ISO 14040, 2021). It consists of four inherent steps, which are the basis for the proposed method in this paper. The steps are goal and scope definition, inventory analysis, impact assessment, and interpretation. Product data such as material and dimensions can be drawn from the digital product model after the CAD phase and used as input in the LCA software to perform an LCA. Some of this data can be extracted from the product model, and some have to be approximated using assumptions and eco-databases (Gaha et al., 2014). Examples of this data typically not included in the Computer Aided Design (CAD) model are raw material production, transport, and in the early phases, machining process information. Liu et al. (2019) show in a meta-study that in recently published research about LCA in production processes, 58% of data is based on estimated, secondary data. Simulation can be used to close the gap between secondary and primary process data to reduce the uncertainty impact of such secondary data. The simulation of production systems is a common tool to improve efficiency in the work preparation phase, but integrating sustainability indicators remains subject of research Schönemann et al. (2019). An early approach to improve assessment quality and scope using CAD/CAM data is presented by Nawata and Aoyama (2001). They use feature-based recognition to connect product and process information to Life Cycle Inventory (LCI) data like material and energy consumption. This method lays the basis

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for integrating more extensive CAM simulations to serve as input flows for an LCA. However, details need to be defined on integrating the two processes. A further approach is given by Thiede et al. (2013) who classify three relationships between DES and environmental evaluation. They range from a separate DES and evaluation to a fully integrated solution in one software tool. Andriankaja et al. (2015) combine the before-mentioned works and develop an approach to fully integrate the two entities by using STEP Numerical Control (NC) as a source of information. They develop a feedback system that includes CAD/CAM steps, an environmental assessment, and the generation of machining guidelines on that basis. This method aims to optimize production processes by improving the NC code through the integration of environmental assessment and machining guidelines.

2.2 The Computer Aided Manufacturing process

Discrete process and factory simulation assist in the design phase to make well-founded decisions and optimize production planning. The CAM process typically occurs in the work preparation phase, the third of the four product creation phases. The main goal is to generate and test NC machine codes, identify problems, and increase values as throughput and resource efficiency (Heilala et al., 2008). The input is usually a CAD model of the component to be manufactured and the blank. With these inputs, the simulation results in the NC-Code for the production machine. Zhang et al. (2010) developed a model for evaluating resources during a manufacturing process. They regard each working procedure as an individual process with inputs and outputs. This method can be adapted using the CAM simulation, which includes parameters for the whole Computerized Numerical Control (CNC) operation. The Common Simulation Engine (CSE) represents a simulator that processes the NC code via virtual controllers. It enables the control of a virtual machine using the NC code. The CSE enables recording virtual sensors during the CAM process, which will be relevant to the proposed method.

3 METHOD FOR THE INTEGRATION OF SIMULATED DATA IN LCA

We identified the following research gaps from the presented literature, which we aim to tackle with the proposed method. Andriankaja et al. (2015) develop a concept that uses STEP NC as a source of information to optimize the CAM chain. While building on the same basic principles, this research focuses on improving the quality and reliability of the ecological indicators to use them as control parameters. In doing so, we provide detailed steps and an application of how to use and integrate outputs of DES with the LCA software Activity Browser based on the framework Brightway. The challenge is to show the integration of simulated process data to increase assessment quality in the product development phase. The necessary steps are discussed in detail and put into the context of the typical LCA process. Figure 1 shows the steps of the methodology needed to include simulated data in an LCA process. The steps are explained in detail in the following subsections, after which they are implemented in section 4.

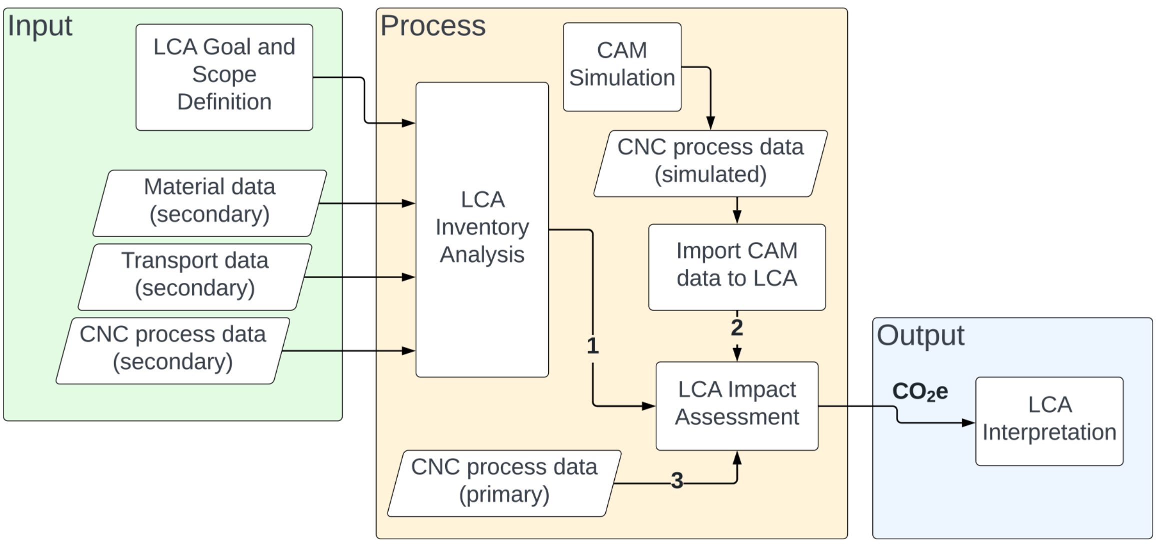

Figure 1. Flowchart of the method to integrate simulated data in LCA

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3.1 Goal and scope definition

The first step of the methodology describes the main setup of the LCA according to DIN EN ISO 14040 (2021). As described in section 2, the first part is the goal and scope definition. The goal describes the intended application, reasons for conducting the study and the target audience, and intended usage of the results. The scope is important to ensure transparency and comparability of the results. Among other things, the product system, functional unit, system boundaries, impact categories, assumptions, and data quality are defined (DIN EN ISO 14040, 2021). The last two aspects are most important as they are control variables for this method, as described at the beginning of this section.

3.2 Inventory analysis

During this step, the inputs and outputs of the LCA process are defined. The definition includes ways to collect and process the necessary data. This methodology expands on the ISO standard because this step includes assessing what data can be simulated using the CAM process. This is done by analyzing the existing processes regarding necessary inputs and which outputs can be helpful for the sustainability assessment. To achieve comparability, the inputs and outputs are regarded with respect to the goal and scope defined in step one.

3.3 Simulate production process with Computer Aided Manufacturing

For the next step, the simulated data are generated using CAM techniques. Besides the CAM software, fundamental questions are the necessary inputs and the generated output data. The output is essential for further processing and integration into the LCA. The basic inputs and outputs of the process are shown in Figure 2.

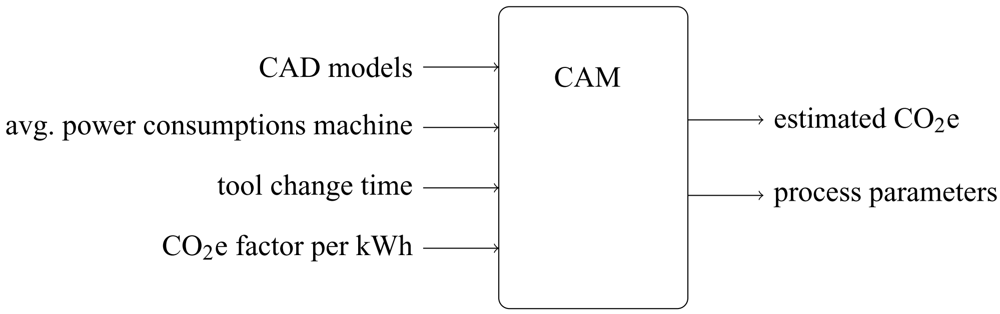

Figure 2. Model of CAM process for LCA

During this phase, the engineer must set up the CAM process. Typically, the process outputs the refined NC machine code for operating the CNC production. To extract and integrate the process into the LCA, an assistance system is developed which uses the CSE to access the simulation data. The assistance system expands the CAM process by custom calculation methods to determine energy consumption and operating materials through the cycle times and user inputs. The estimated energy consumption of the production machines is calculated using the tool change mechanism's energies, the machine's primary energy consumption, coolant pump, and air compressor shown in Equation 1.

$$\text{Total estimated energy:} \quad E_{t,est} = E_{tcm,t} + E_{pr,m} + E_{cp} + E_c \tag{1}$$

$$\text{Tool change mechanism:} \quad E_{tcm,t} = N \cdot E_{tcm} \tag{2}$$

$$\text{Primary machine consumption:} \quad E_{pr,m} = P_{ba,m} \cdot t_p + \sum_{i=0}^{n} (P(i)_{v,m} \cdot t(i)_v) + \sum_{i=0}^{n} (P(i)_{w,m} \cdot t(i)_w) \tag{3}$$

$$\text{Coolant pump:} \quad E_{cp} = P_{cp} \cdot t_{cp} \tag{4}$$

$$\text{Air compressor:} \quad E_c = P_c \cdot t_c \tag{5}$$

Equation 2 produces the total energy of the tool change mechanism by multiplying the mean used energy with the tool change time. An assumption is made that every tool change cycle requires the same amount

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of energy. The primary energy consumption in Equation 3 consists of the basic power and process time, the velocity power and time, work power, and cycle time. The last calculated terms in Equations 4 and 5 are the coolant pump energy consisting of pump power, pump time, and the air compressor. The process times of setup, support, cutting, machining, drilling, and pumping are simulated in the CAM program and extracted using the CSE as virtual sensors. Therefore, the CSE algorithm was modified to match the mentioned cycle times and update them respectively to the user-defined collision control value. In the current state, the user is required to provide specific machine data for the assistance system. This is to be replaced by a machine database in the future. For a direct indicator display in the assistance system, the simulated environmental impact is calculated like in Equation 6 using the estimated energy consumption, and conversion factors from the ecoinvent 3.9 database (ecoinvent Association, 2022). The equation includes a conversion factor from Joule to kWh.

Conversion to environmental impact
$$CO_2e = \frac{I_{CO_2} \cdot E_{t,est}}{3600000} \tag{6}$$

3.4 Import simulated CAM data to the Life Cycle Assessment

This subsection discusses the integration of simulated data into the LCA. The specifics are highly dependent on the used CAM and LCA software. Therefore, an infrastructure analysis is required. This includes the analysis of inputs and outputs of both processes, used data formats, and possible interfaces between them. Furthermore, it needs to be considered where the CAM data are stored and how they can be accessed. One possible solution is using Siemens NX CAM, and the Brightway Activity Browser for the LCA is presented here. The MQTT communication protocol is used to communicate between the assistance system and the CSE and store data. This allows the transfer of messages between the instances according to the publish-subscribe principle. For this purpose, the necessary Message Queuing Telemetry Transport (MQTT) commands for the user input and the CSE were implemented. For the integration into the LCA, data can be extracted in XML format and used as an input database in the LCA tool. In the python framework, Brightway with the Activity Browser custom databases can be integrated into this framework in XML format. This opens the possibility of integrating the outputs of the CAM process into the LCA. For this purpose, an XML file is created from the results of the CAM process described in the previous subsection. This file is loaded as a database, so the results are available for the impact assessment in the next step.

3.5 Impact assessment

The impact assessment calculates the functional unit's environmental impact by connecting the inventory analysis results with impact categories and sustainability indicators. This step is used for iterative testing of the goal and scope of the LCA. The most important factor of the impact assessment is the transparent documentation of utilized models, methods, categories, and indicators. For more details, refer to DIN EN ISO 14040 (2021) and section 4.

3.6 Interpretation

According to DIN EN ISO 14040 (2021), this phase involves the consideration of the results of the impact assessment. The interpretation should provide and visualize results understandably to derive conclusions and recommendations based on the assessment. This includes a transparent discussion of the results in light of the goal and scope, data quality, and the utilized models. Lastly, a profile of the relevant indicator values can help communicate the results.

4 IMPLEMENTATION

This chapter aims to carry out the steps of the method and thus show how it works and the resulting advantages. For this, the explained steps of the method are performed using an example process. The product is a CNC machined part developed at the research workshops at TU Darmstadt to track process parameters for an LCA (ArePron, 2020). The assessment is done on three levels to show performance improvement using the proposed method. The first assessment is done with secondary data, the second

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with simulated data from the CAM process, and finally with primary data of the production. Figure 1 shows this process schematically.

4.1 Assistance system

An assistance system was developed to extract the data relevant to the LCA, which is integrated into Siemens NX CAM. To include the input of user information and the display of results, the journal function is used as an interface to NXOpen which enables the implementation of application extensions to Siemens NX. In doing so, the steps in NX are recorded and written into a file to access the user input and display results via a button in the NX interface. This option is included in NX using the Block UI Styler (Siemens AG, 2016). The functions are implemented in the programming language python, and the data transfer protocol MQTT is used to exchange data between the different levels of the system. The steps of the assistance system are in detail the recording and processing of user input, sustainability assessment, and the preparation of results. To perform these operations, the system consists of three layers. The application layer represents the interface to the user and enables the input and display of the results in the CAM system. The operation layer is used to perform the calculations for the sustainability assessment, which are based on the processing of the user input. The detailed user input information is described during the simulation subsection in Table 2. The CSE is central to the assistance system and serves as the operation and information layers.

4.2 Goal and scope definition

Firstly, the goal and scope of the assessment are described in compliance with DIN EN ISO 14040 (2021). The intended application is for research purposes. The reason is to compare assessments with the integration of simulated data against secondary data from the eco-database ecoinvent cutoff 3.9 (ecoinvent Association, 2022). The intended audiences are experts in the research field and potentially experts from the industry with tasks relevant to the discussed use case. The results are published in this paper to validate the proposed method. The product system is simplified and spans around two CNC machines, one for turning and one for milling, also where the system boundary is drawn. The framework includes the machines, the material, and operational resources such as cooling lubricants as shown in Figure 3.

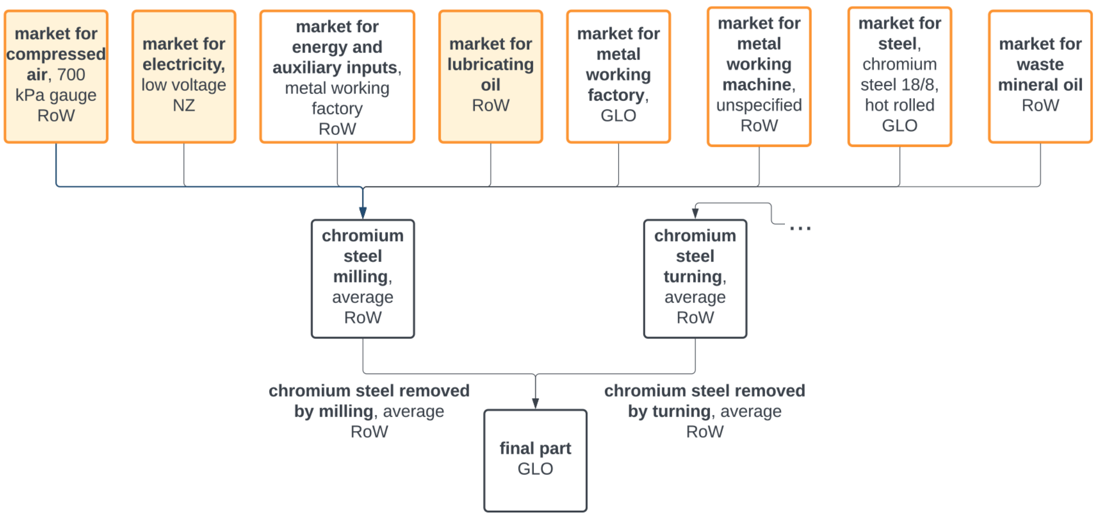

Figure 3. Section of the process model of the part production for the LCA. The processes exchanged by primary and simulated data later are highlighted.

The functional unit consists of one produced part. For this paper, the LCA is performed with three different types of data quality and three levels of assumptions. The first consists of an assessment with secondary data and processes from the ecoinvent database. The second assessment includes simulated data from the CAM process, and the third is an assessment with primary data from an actual production process. The assessment differences are described in subsection 4.6.

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4.3 Inventory analysis

The inventory analysis is confined to a limited number of inputs to maintain transparency and comparability for the application example. According to the research question of this paper, the system boundary set in chapter 4.2 will include the work preparation phase but not the production phase. The secondary processes from ecoinvent are used and supplemented with simulated and primary data for comparison to demonstrate the integration of simulated data in the assessment process. This step is divided into data collection and calculation, which differ slightly in the three use cases.
The material is 18/8 chromium steel, with a raw weight of 694g and a final part weight of 364g. 259g are removed by turning, and 24g by milling. Those values are measured during the production. The first case draws the inputs from predefined processes in the ecoinvent database. From this, the CNC machined chromium steel processes by milling and turning are used as a reference. Table 1 shows the generic input data for the LCA to compare all three processes, which are later compared in subsection 4.7.

Table 1. Generic input data for the LCA

Input	Unit
Chromium Steel	g
Transport	km
Electrical energy	kWh/kg
Compressed air	l/kg
Cooling lubricant	$kg_{oil}/kg_{product}$

4.4 Simulate production process with Computer Aided Manufacturing

A CAM program must first be created based on the sample part in this step. For this purpose, a CAD model of the part and the blank is designed in Siemens NX. The CAM environment is then used to model the manufacturing operations for fabrication. In addition to the geometry models, the assistance system requires some information about the process. It then simulates process parameters based on the user inputs and calculates the CO^2e with the conversion factors as shown in Equation 5. The user input for the assistance system is represented in Table 2.

Table 2. Necessary user input in order to use the assistance system in the CAM simulation

User Input	Value Turning	Value Milling	Unit
Collision control	1	1	$1/s$
Base power consumption	600	400	W
Motion power consumption	500	500	W
Cutting power consumption	1800	800	W
Tool change power consumption	900	900	W
Coolant pump power consumption	700	700	W
Avg. tool change time	10	10	s
CO^2 factor energy mix 2020	485	485	gCO_2e/kWh

The first user input describes the number of collision checks the assistance system performs per second. This checks whether the tool engages with the workpiece and thus calculates the cutting time. In tests, one second has been found to be the lowest value at which sufficient simulation resolution can be guaranteed.
The user enters the machine's performance since they are not stored in the virtual machines of the CAM environment. The values for this model are taken from various studies and manufacturer specifications. The base power remains constant during the machining time. The movement power is composed of the spindle and the feed movements. This typically varies with the profiles machined but is given here as an average value.
The cutting power consumption depends on the material, tool, and cutting parameters. A reference value for the performance from the literature is used during the implementation. From the reference value table of Apprich (2015), the specific cutting force can be read based on some parameters. Via the chip

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geometry, the cutting force can be calculated and converted into cutting power via cutting parameters. The performance of the tool change and the coolant pump is also taken from the literature. The tool change time is taken from the data sheet of the production machine. Based on the CAM program and the user input in Table 2, the assistance system calculates the CO^2e of one produced part after the respective processes. The assistance system's calculated CO^2e can be used as a standalone reference without needing an LCA tool. For this example, the simulated process data are used as input for the assessment and listed in Table 3. To achieve this, the data must be imported into the software described in the following section.

4.5 Import simulated data to LCA

The integration requires the manual creation and import of the simulation results as an XML file. After the simulation, methods are executed, which are used for the calculation, display, and export of the required values. The results file includes the power consumption of the processes shown in Equation 1. This step described in subsection 3.4 will be automated in future developments by creating batch scripts in the assistance system for the individual steps.

4.6 Impact assessment

As described before, the impact assessment is done using the LCA tool Activity Browser in compliance with the LCA standard. Therefore, the process is modeled three times with the available ecoinvent processes, the simulated CAM data, and the measured primary data. The secondary data are drawn from ecoinvent. The other two are simulated in the CAM process and measured as primary data during the production process at the TU Darmstadt labs.
To achieve comparability between the assessments, the secondary ecoinvent process, including the material value chain, is the basis for all three. The process model can be seen in Figure 3 and consists of the milling and turning processes which result in the final part. Each of the two processes from ecoinvent 3.9 consists of several material and energy flows, each referencing for 1 kilogram of produced chromium steel. The inputs which simulated and primary data can supplement are highlighted with a filling.
Based on the inventory analysis in subsection 4.3, Table 3 shows the input data for the LCA, which are supplemented with primary and simulated data to compare the values.

Table 3. Comparison of LCA input parameters of secondary, simulated and primary data

Input	Secondary value	Simulated value	Primary value	Unit
Electrical energy	5,7	0,836	0,735	kWh/kg
Compressed air	2,56	3,05	1,1	l/kg
Cooling lubricant	0,0076	0,887	0,9	$kg_{oil}/kg_{product}$

In the next step, the energy consumption and the consumption of operating resources simulated in subsection 4.4 are integrated in the LCA tool by using the exported XML file as a data base. Finally, the activity data are replaced with measured primary data. After creating the respective activities for each assessment variant, the LCA is set up with the three reference flows and the same impact category for the sake of comparison. As the impact category, the ReCiPe midpoint (H) method of 2016 v1.03 Huijbregts et al. (2017) is chosen which calculates the global warming potential over 100 years and outputs a $kgCO^2e$ for each process.

4.7 Interpretation

The interpretation of the results shows two major findings. Firstly, Table 3 enables a direct comparison of the secondary, simulated, and primary data. It shows a high deviation between secondary and primary data, especially using electric energy and cooling lubricant. The data simulated in the CAM process are much closer to the actual process data and thus prove the concept of supplementing secondary data with simulated data.
The second finding, however, can be seen in Figure 4 that considering material and transport as well as other inputs shown in Figure 3, the deviation in the LCA results is minor for the chosen use case.

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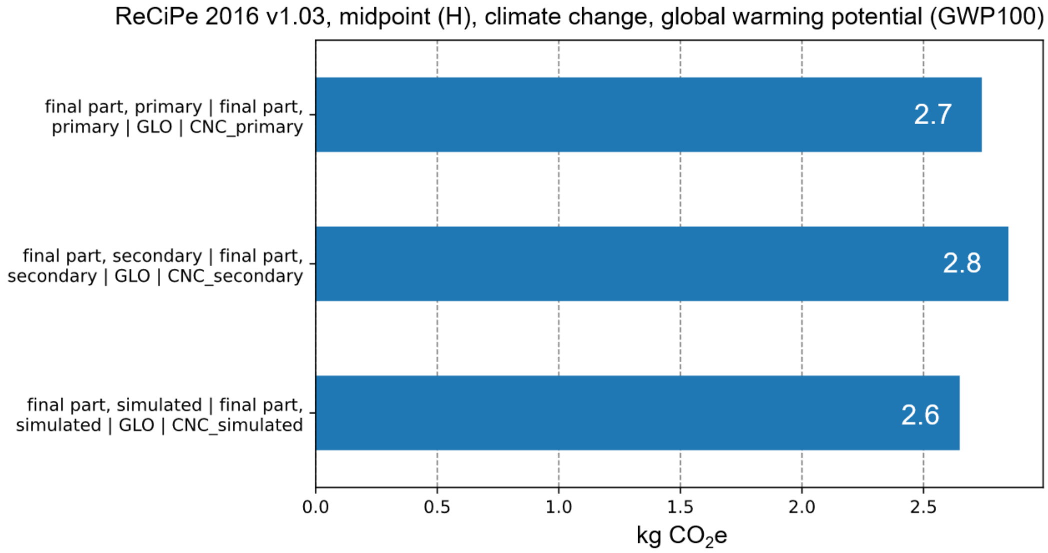

Figure 4. LCA results of the comparison between secondary, primary and simulated data

5 DISCUSSION AND CONCLUSION

This section discusses the obtained results and points out the limitations of the research. A method to integrate CAM simulations in LCA was developed to improve the assessment's reliability and quality. The developed method consists of five steps interwoven with the LCA standard. It expands on the ISO process by adding the steps of CAM simulation and the integration of the simulated data to the impact assessment. The flowchart is depicted in Figure 1 and enables the comparison of secondary, simulated and primary data. The research is based on existing concepts for integrating DES and LCA.
However, the novelties of this approach are twofold: firstly, it is developed to increase the quality of ecological indicators. These will be the foundation for optimizing more sustainable processes like the one presented by Andriankaja et al. (2015). Secondly, we present and implement a method that details the necessary steps for the integration and discuss relevant parameters and the different sources of information. An assistance system was implemented, which simulates process parameters based on user inputs. A comparison of secondary data from the ecoinvent 3.9 eco-database, the simulated CAM process data, and measured primary data are conducted to show the differences in data. The results show that the CAM simulation can depict a more realistic process than using assumptions from the eco-database. However, for this example, the influence of the CAM simulated data on the LCA result is minor due to other contributions to the ecological impact. Mainly, the high impact of the raw material and other auxiliary inputs of the factory are the reasons for that.
The LCA process is still based on many assumptions and is unsuitable for comparability with other production processes. The data for the required user input is mostly taken from data sheets and comparable research. To improve the quality of the simulation, precise consumption data of the available machines are required, which must be determined in field tests. With the help of these machine data, databases can be created in the assistance system, and thus the quality of the simulated data can be increased. During the assessment, it has been shown that the share of CO^2e of the material, in this case, is about 50%. This factor limits the increase in the quality of the LCA. In future research, the proposed method should be adapted to other DES using the same principles, such as a transport simulation tool or a complete factory simulation.

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REFERENCES

Albrecht, S. (2021), *Progress in Life Cycle Assessment 2019*, Sustainable Production, Life Cycle Engineering and Management Ser, Springer International Publishing AG, Cham.

Andriankaja, H., Le Duigou, J. and Eynard, B. (2015), "A sustainable machining approach by integrating the environmental assessment within the cad/cam cnc chain", http://doi.org/10.13140/RG.2.1.1180.9765.

Apprich, T. (2015), *Tabellenbuch für Zerspantechnik*, Europa-Fachbuchreihe für Metallberufe, Verl. Europa-Lehrmittel Nourney Vollmer, Haan-Gruiten, 1. aufl., 1. dr edition.

ArePron (2020), "Agiles ressourceneffizientes produktionsnetzwerk (research project): Entwicklung einer transparenten und vergleichbaren bewertungsgrundlage als entscheidungsbasis für den optimierten ressourceneinsatz innerhalb eines wertschöpfungsnetzwerks", Available at: https://www.arepron.com/ (accessed: November 21, 2022).

DIN EN ISO 14040 (2021), "Environmental management - life cycle assessment - principles and framework", http://doi.org/10.31030/3179655.

DIN EN ISO 14067 (2019), "Greenhouse gases – carbon footprint of products – requirements and guidelines for quantification", http://doi.org/10.31030/2851769.

ecoinvent Association (2022), "ecoinvent", Available at: https://ecoinvent.org/ (accessed: November 21, 2022).

Gaha, R., Yannou, B. and Benamara, A. (2014), "A new eco-design approach on cad systems", *International Journal of Precision Engineering and Manufacturing*, Vol. 15 No. 7, pp. 1443–1451, http://doi.org/10.1007/s12541-014-0489-4.

Heilala, J., Vatanen, S., Tonteri, H., Montonen, J., Lind, S., Johansson, B. and Stahre, J. (2008), "Simulation-based sustainable manufacturing system design", in: S.J. Mason (Editor), *Winter Simulation Conference, 2008*, IEEE, Piscataway, NJ, pp. 1922–1930, http://doi.org/10.1109/WSC.2008.4736284.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A. and van Zelm, R. (2017), "Recipe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level", *The International Journal of Life Cycle Assessment*, Vol. 22 No. 2, pp. 138–147, http://doi.org/10.1007/s11367-016-1246-y.

Liu, Y., Syberfeldt, A. and Strand, M. (2019), "Review of simulation-based life cycle assessment in manufacturing industry", *Production & Manufacturing Research*, Vol. 7 No. 1, pp. 490–502, http://doi.org/10.1080/21693277.2019.1669505. Accessed: November 8, 2022.

Nawata, S. and Aoyama, T. (2001), "Life-cycle design system for machined parts - linkage of lci data to cad/cam data", in: *Proceedings Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, IEEE Comput. Soc, pp. 299–302, http://doi.org/10.1109/ECODIM.2001.992369.

Schönemann, M., Bockholt, H., Thiede, S., Kwade, A. and Herrmann, C. (2019), "Multiscale simulation approach for production systems", *The International Journal of Advanced Manufacturing Technology*, Vol. 102 No. 5-8, pp. 1373–1390, http://doi.org/10.1007/s00170-018-3054-y.

Siemens AG (2016), "Block ui styler", Available at: https://docs.plm.automation.siemens.com/ (accessed: November 21, 2022).

Thiede, S., Seow, Y., Andersson, J. and Johansson, B. (2013), "Environmental aspects in manufacturing system modelling and simulation—state of the art and research perspectives", *CIRP Journal of Manufacturing Science and Technology*, Vol. 6 No. 1, pp. 78–87, http://doi.org/10.1016/j.cirpj.2012.10.004.

Zhang, H., Zhang, X.G. and Wang, Y.H. (2010), "The evaluation of resources and environment attributes of manufacturing process based on scatter degree combination evaluation method", *Applied Mechanics and Materials*, Vol. 37-38, pp. 1466–1472, http://doi.org/10.4028/www.scientific.net/AMM.37-38.1466.