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Sustainable Sheet-Metal Design: Employing the Product Carbon Footprint as Support for Engineers in Developing New Product Generations

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Abstract

This study investigates a data-driven approach for integrating sustainability criteria into the design process to reduce the Product Carbon Footprint (PCF) of sheet-metal parts. In a Live-Lab research environment, the design solutions of four engineering teams were analyzed at each iteration to assess how immediate PCF feedback and detailed sustainability information impacted both the design process and the final Product Carbon Footprint of the sheet-metal parts. The findings show that understanding the influencing factors of sustainable sheet-metal design and receiving PCF feedback led to PCF reductions of over 30 %, highlighting the importance of quantifiable sustainability metrics in industrial design practices.

Keywords: Sustainable Design; Immediate PCF Feedback; Live-Lab; Product Carbon Footprint; Methodological Design Support; Sheet-Metal Design

1. Introduction

The idea of electric vehicles first emerged in the late 19th century, when electric cars outsold every other type of vehicle [1]. Almost two centuries later, a global push for electric vehicles can be observed as an available technology for society's increasing prioritization of sustainability. Governments and industries are investing greatly in EV infrastructure, reflecting a broader commitment to reducing greenhouse gas emissions and reliance on fossil fuels [2]. This trend highlights the pivotal role that engineers play in designing and improving sustainable technologies. By implementing eco-design principles—aimed at minimizing environmental impact throughout a product's life cycle—engineers in many industries can similarly advance sustainability efforts. Sheet-metal design, a core discipline in manufacturing and product development, plays a crucial role in modern product development. As sheet-metal products are widely used across sectors and within many products, their environmental impact is substantial. Especially in the manufacture of sheet-metal parts with machine tools, the material used is a major factor in the resulting environmental impact. Therefore, reducing waste material during the design process is crucial [3]. Further, approx. 30 % of Germany's total energy consumption was attributed to the industrial sector, with a significant portion arising from metal production and processing. Reducing resource consumption and emissions requires a systematic approach to improve sustainability across the product lifecycle, including development, design, and production [4]. To enable more sustainable sheet-metal design practices, the individual engineers involved in the design process must be supported with suitable measures [5]. Therefore, guidelines on how sustainable sheet-metal design can be achieved as well as direct feedback during the sheet-metal design process are necessary. To support individual engineers, this study investigates a data-driven approach for integrating sustainability criteria and guidelines into the design process to reduce the Product Carbon Footprint (PCF) of sheet-metal parts.

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2. Literature Review

2.1. Data-driven Sustainability in Product Development

Sustainability is broadly described as satisfying the needs of the present in a manner that the opportunities of future generations are not being restricted [6]. Within this definition, sustainable design may refer to a holistic approach to the manufacturing of environmentally friendly, socially acceptable and economical products and systems. A somewhat more specific approach would be to enable more efficient resource utilization and decrease the contribution of products to global greenhouse gas emissions as the two essential goals to create more sustainable products. These definitions however neither pose a clear directive nor show distinguishing factors to support sustainable product development and sheet-metal design. To develop verifiably sustainable products, an appropriate scale must be introduced to quantify and compare to environmental impact of products. With the Product Carbon Footprint (PCF) the carbon dioxide emission equivalent (in kg) is attributable to a part or product as normed in DIN ISO 14067 [7]. It can be assessed over the whole life cycle of a product, from the extraction of the raw material to its disposal – often referred to as the cradle-to-grave approach. Since the usage of items is difficult to predict, a more common approach is carrying out a life cycle analysis and concluding the PCF accumulation at the factory gate with the cradle-to-gate approach [8]. For mechatronic systems, the main environmental impact is caused during operation by continuous resource consumption. Despite prevalent challenges in mining and analyzing necessary operational machine and consumption data, deriving insights to support decision-making and therefore to enhance the sustainability of a product early in the product development process is imperative. To create a reliable and consistent approach data-driven PCF calculation and assessment rather than an estimation-based consideration is necessary. This can pose an ongoing challenge, especially for small and medium-sized enterprises, due to the lack of technical equipment and available competencies necessary for data mining, engineering, and analysis [3].

To improve the PCF and, consequently, the sustainability of sheet-metal components, a comprehensive analysis of both design and manufacturing processes must be conducted to identify opportunities for reducing resource consumption. Field-gathered data allows for the identification of key factors that influence resource usage in sheet-metal manufacturing, providing actionable insights for sustainable improvements. For sheet-metal components, information on critical attributes accounting for the resource consumption during machine operation —such as material type, total surface area, as well as quantity and geometric features (e.g., outer and inner contours)—can be extracted from existing designs and mapped on field-gathered machine data to assess environmental impact accurately. Using this data enables a more precise evaluation of a component's environmental footprint, guiding engineers toward design modifications that reduce resource use and lower emissions throughout the product lifecycle. Such data-driven analyses are invaluable for refining design practices and supporting sustainable engineering objectives effectively [9].

2.2. System Generation Engineering

The environmental impact of a product is fundamentally determined in the development process. Therefore, individual engineers must be supported early in the product development process with suitable measures to derive optimal decisions. In the concept of System Generation Engineering (SGE), the development process for a new technical products or subsystems, which are based on a Reference Product or System, that serves as the foundational structure. A Reference Product is defined as a predecessor, competitor product, or a comparable source of direct inspiration, a new system generation in the model of SGE, is based on. This approach leverages the established design and functional elements of the Reference Product to guide and enhance the development of the new system generations [10]. The model of SGE is characterized by three types of variation that are applied in the development of the system of objectives: Carryover Variation (CV), Attribute Variation (AV) and Principle Variation (PV) [11].To enhance the sustainability of a sheet-metal part, data from the reference system and operational data of the system involved in its manufacturing can be analyzed resulting in a clear understanding of how design decisions regarding the part geometry as well as its features influence resource utilization and therefore the PCF of the part itself [9]. By optimizing the PCF of individual sheet-metal parts, the sustainability of subsystems and therefore the overall system of objectives can be enhanced.

2.3. Research Environment – Live-Lab

To investigate how different support measures affect sustainable sheet-metal design, a suitable research environment is necessary. Aiming to support the development process of organizations in the industry, the application of methods, processes, and tools often encounters practical challenges. Such discrepancy between expected and actual benefit arises because methods, processes, and tools often are primarily developed in academic settings, with evaluations typically conducted in controlled laboratory studies or limited to specific companies. Laboratory studies, while offering high internal validity and reduced complexity, lack the complexity of real-world conditions. Field studies, on the other hand, reflect practical realities more accurately but often produce results that are specific to individual environments and may lack broader applicability [12,13]. Live-Labs bridges this gap by combining the controlled conditions of laboratory settings with realistic development scenarios. Therefore, a Live-Lab is understood as a research environment designed to simulate authentic development processes while maintaining a high degree of control over experimental conditions. In this setting, participants assume the role of developers rather than research subjects, allowing for an evaluation of factors such as quality, acceptance, applicability, and the integration of various methods for addressing design challenges [14]. By utilizing possible Live-Lab settings such as the Engineering Simulator as a validation environment for sheet-metal design methods, the support of different measures can be evaluated to enhance sustainability in sheet-metal design [15].

3. Research Methodology and Objectives

To enhance the sustainability of technical products, design modifications must be incorporated at the subsystem and component levels during the development process. Therefore, systematic, methodological support for individual developers throughout the product development process is essential to facilitate sustainable design decisions. This research is structured according to the Design Research Methodology by Blessing and Chakrarbarti [16] and aims to support individual developers methodologically in the product development process of sustainable sheet-metal design. The aim of this work is operationalized by the following research questions:

Q1: What are the challenges and needs product developers face when integrating sustainability criteria into the product design process of sheet-metal parts?

Q2: How is a method to be designed to support developers in integrating sustainability criteria into the product design process of sheet-metal parts?

Q3: What are the benefits of applying the developed methodology in supporting developers in integrating sustainability criteria into the product design process of sheet-metal parts?

The Descriptive Study I (DS I) aims to answer the first research question by conducting a literature review and an analysis of the current design process by observing and interviewing participants in the research environment of an engineering simulator for sheet-metal design to gain insights into specific needs and challenges of engineers during their development and design stages for integrating sustainability criteria. For this purpose, a total of 10 undergraduate and graduate engineering students with experience in product development and design are interviewed. Within the Prescriptive Study (PS) support measures in the form of guidelines and immediate response information by a PCF are designed. It entails the most influential factors contributing to a product's sustainability. In the Descriptive Study II (DS II) guidelines and the effect of a PCF response to design changes made by the participants is evaluated in three conducted Live-Labs of an engineering simulator for sheet-metal design. The participants of the study are in total 10 undergraduate and graduate engineering students with experience in the development and design of sheet-metal components. Within the first two Live-Labs, the team consist of three participants each. In the third Live-Lab, four participants are grouped into two teams with two participants each.

Table 1. Group set-up for the conducted Live-Labs

Information provided	Group 1	Group 2	Group 3a	Group 3b
General information of sustainable sheet-metal design.	x	x	x	x
Specific information on controllable variables for sustainable sheet-metal design.			x	x
Immediate PCF-Feedback .	x		x	

4. Challenges and Needs of Product Developers in Sheet-Metal Design

In the Descriptive Study I, the challenges and needs of product developers in sheet-metal design are examined. Participants in prior engineering simulator studies on sheet-metal design exhibited challenges in producing manufacturable sheet-metal components, largely attributable to their limited practical experience with the bending process. As the number of bends and the complexity of the part increased, predicting the resultant spatial transformations in the 3D space became progressively more difficult, further complicating the design process [15,17]. These observations align with existing literature, highlighting the particular complexity of sheet-metal design compared to other traditional manufacturing processes. The transition from two-dimensional to three-dimensional geometries introduces an additional challenge, as designers must adhere to guidelines and frameworks to prevent design errors, such as neglecting minimum edge lengths, improperly positioning holes within the bending zone, and overlooking the limitations of available bending tools, all of which critically influence the bending, and therefore the manufacturability of a flat sheet-metal part into its final three-dimensional form [18]. Especially incorporating multiple functionalities into one sheet-metal part could frequently be observed to be overwhelming. Further, the participants lacked an understanding of how the part geometry behaves during the bending process, which can lead to failures and therefore to potential collisions with the bending machine, a critical consideration that must be accounted for during the design phase to avoid manufacturing issues. The participants demonstrated a lack of understanding regarding possible factors influencing the sustainability of a sheet-metal part, as well as the impact of design decisions on the sustainability of the resulting sheet-metal part. In the following Table 1, the identified challenges of product developers in sheet-metal design are summarized.

Table 2. Identified challenges of developers in sustainable sheet-metal design

No.	Challenges	Sheet-metal Design	Sustainability
1	Limited practical experience with manufacturing processes	x	
2	Limited understanding of the effects of the part geometry and complexity on manufacturability	x	x
3	Effects of design decisions on general manufacturability	x	
4	Limited to no understanding of factors influencing sustainability		x
5	Limited to no understanding of the effects of design decisions on sustainability	x	x

In order to support the sheet-metal design process, early and continuous validation of the manufacturability by e.g. simulation of the bending process is necessary, indicating a need for immediate feedback on how design decisions are affecting the resulting sheet-metal part [19]. Further, the provision of feedback regarding the impact on sheet-metal part sustainability by design decisions appears to be necessary. By providing immediate feedback for manufacturability as well as the sustainability of the sheet-metal part, the design process can be enhanced to conduct more possible iterations. The following Table 3 summarizes the identified needs of product developers in sheet-metal design.

Table 3. Identified needs of developers in sustainable sheet-metal design

Needs to address the identified challenges 1-5 (Table 2)	1	2	3	4	5
Provision of sheet-metal design guidelines and frameworks	x	x	x		
Early validation of the manufacturability	x	x	x		
General information of sustainable sheet-metal design.				x	x
Specific information on controllable variables for sustainable sheet-metal design.		x		x	x
Immediate PCF-Feedback .		x		x	x

The provision of sheet-metal design guidelines and frameworks, along with early manufacturability validation, aims to address the general challenges associated with sheet-metal design. By offering general information and specific controllable variables for sustainable sheet-metal design, combined with immediate PCF-Feedback, these measures primarily target the issues related to designing sheet-metal parts with improved sustainability.

5. Methodological Design Support for Developers

Based on the identified challenges and needs of product developers in sustainable sheet-metal design, three primary concepts of support are specified: *Early validation of the manufacturability*, *specific information about controllable variables for sustainable sheet-metal design* as well as an *immediate PCF-Feedback* during the design process. The provision of sheet-metal design guidelines and frameworks as well as general information of sustainable sheet-metal design are introduced selectively, mainly when the participants encounter obstacles or make notable design errors, positioning these as secondary support measures that may offer limited benefits for highly experienced developers. General sustainability information, encompassing life cycle environmental impact assessments of technical products, provides a broader context for specific, controllable variables essential to sustainable sheet-metal design. However, this information is not strictly necessary if developers already understand and manage the key variables effectively.

Within the engineering simulator, participants are initially provided with general information on sustainable sheet-metal design to help them understand the design task and the associated challenges. In addition, Groups 3a and 3b receive specific information on controllable variables that can enhance sustainable design outcomes. According to Krause et. al. [9] these variables are closely linked to resource consumption during the 2D flatbed laser cutting process. Key factors include controlling the length of the outer contour, the length and number of inner contours, and understanding how modifications to part geometry can reduce scrap-metal and material waste in general. By managing and minimizing these variables, material waste, electrical energy, and process gas consumption required for cutting operations can be reduced, leading to a more sustainable sheet-metal design.

In contrast to Group 2, Groups 1 and 3a receive immediate PCF-Feedback after each design iteration. During the simulation of the bending process to verify the manufacturability of the designed sheet-metal part, the NC-Code required to manufacture the part is generated using a separate CAD/CAM software. This NC-Code allows for an analysis of each movement of the mechatronic system, assigning estimated values for electrical energy and cutting gas consumption associated with the manufacturing process. These individual consumption estimates are then aggregated for the entire part. Using this total resource consumption estimation, along with the associated CO_2-equivalent in kilograms, the PCF of the sheet-metal part is calculated. This PCF is provided to the participants as feedback, enabling them to assess how their design decisions and modifications influence the environmental impact of the part after each iteration. This enables the participants to validate their chosen design decisions and reevaluate their current sheet-metal design.

6. PCF Optimization in Sustainable Sheet-metal Design

All groups followed an iterative design process based on the same reference system. The following Figure 1 illustrates the reference system as the starting point of the sheet-metal design process as well as the selected design each team selected as the optimal solution based on a subjective evaluation of sustainability, functionality, and manufacturability. This subjective selection process allows participants to weigh the various trade-offs encountered during design iterations, ensuring that the final choice reflects not only technical feasibility and performance requirements but also alignment with sustainability objectives.

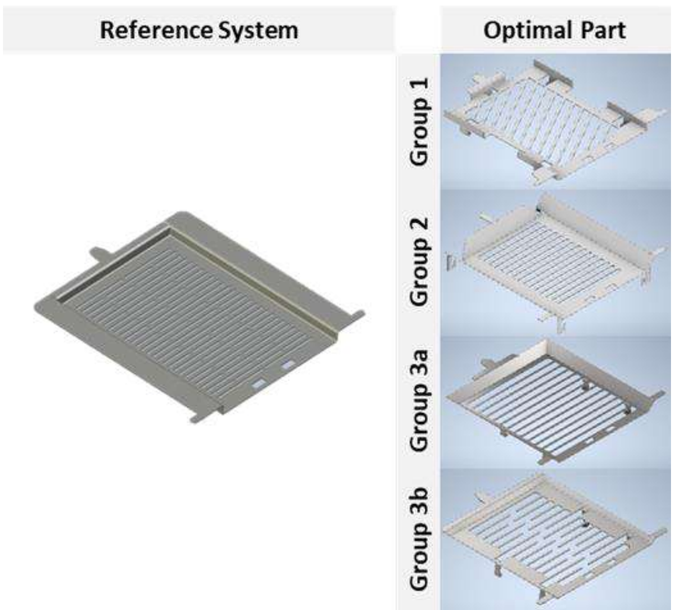

Figure 1. Reference System and the subjective optimal solution of the sustainable sheet-metal part design

All calculated PCFs are derived from the STEP-files and NC code corresponding to each part's geometry. This data enables predictions of cutting time and estimated resource consumption, including material, electrical energy, and cutting gas usage, which collectively are used for the PCF calculations. The following Figure 2 illustrates the PCF values for each design iteration across the four groups.

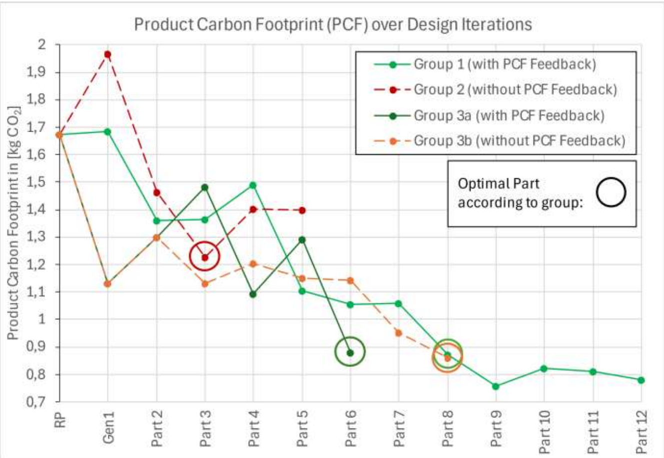

Figure 2. Product Carbon Footprints over Design Iterations

A distinct downward trend in PCF values can be observed across all four groups. Group 1, which received general information regarding sustainability in sheet-metal design and immediate PCF-Feedback, shows some fluctuation across its twelve design iterations. Beginning with a PCF of 1.68 kg CO_2 equivalent in the first generation, the group ultimately selected Part 8, with a PCF of 0.87 kg CO_2 equivalent, as the optimal design, while the lowest PCF achieved was 0.76 kg CO_2 equivalent in Part 9. Despite the absence of detailed information on specific controllable variables, the iterative reductions in PCF suggest that immediate PCF-Feedback supported incremental improvements in the sustainability of the sheet-metal designs. Observed fluctuations in PCF values, particularly between Iterations 2 and 5, an exploratory trial-and-error approach in adjusting designs could be observed to reduce the environmental impact effectively.

Group 2 received the same general information on sustainable sheet-metal design, but without details on specific controllable variables or an immediate PCF-Feedback. Starting with a relatively high initial PCF of 1.97 kg CO_2 equivalent in Generation 1, the calculated values show fluctuations in the achieved PCF values. However, iterations were discontinued after five design cycles. The minimum PCF calculated for Group 2 was 1.23 kg CO_2 equivalent in Part 3, which was subsequently selected as the optimal part. Notably, this optimal part exhibited a higher PCF than those of all other groups. The lack of immediate PCF-Feedback limited insight into the impact of design decisions on the sustainability of the respective sheet-metal designs, with PCF reductions occurring primarily due to attempts to reduce part weight, without awareness of the material's significant contribution to the overall PCF.

In addition to the general sustainability information provided to Group 1 and 2, the Groups 3a and 3b received detailed information on specific controllable variables to improve the sustainability of sheet-metal parts during the laser-cutting process. Both groups commenced with a similar initial design in Generation 1, receiving a calculated PCF of 1.13 kg CO_2 equivalent. Group 3a, with access to immediate PCF-Feedback, demonstrated a fluctuating PCF progression and accomplished their iterations after six cycles, achieving a minimum PCF of 0.88 kg CO_2 equivalent. In contrast, the Group 3b, which did not receive immediate PCF-Feedback, exhibited a more stable PCF curve across iterations, reaching their final design in Part 8 with a lowest PCF of 0.86 kg CO_2 equivalent, which was selected as the optimal part. Providing either immediate PCF-Feedback or specific information on the characteristics and variables influencing the PCF of a sheet-metal part, both contribute valuable support to the sheet-metal design process. Despite the lack of significant measurable benefit from providing both types of information, observations during the Live-Lab indicate that participants subjectively perceive the combination of information on specific influencing variables and immediate PCF-Feedback as the most effective form to support the design process. Information on specific variables enables a more targeted approach to reducing the PCF, while immediate feedback establishes a clear connection between individual design modifications and their corresponding impact on the PCF. This combination facilitates a more effective and responsive design process focused on sustainability outcomes.

The following Figure 3 illustrates a Grill utilized as the example in the conducted Live-Labs. Modifying a single component, e.g. the grill grate, by adding the functionality to fit the standard gastro tray beneath the grill grate instead of the bottom of the system, inevitably influences other system components. Such modifications eliminate the need for the initial function of channeling grease and waste into the standard tray below. Therefore, the highlighted sheet-metal component of the system "grill" can be removed. The total PCF for the grill system, including waste material, is calculated at 24.4 kg CO_2e, with the sheet-metal component highlighted accounting for 2.15 kg CO_2e. Removing this component by integrating its functionality into the grill grate achieves an overall system PCF reduction of approximately 8.8 %.

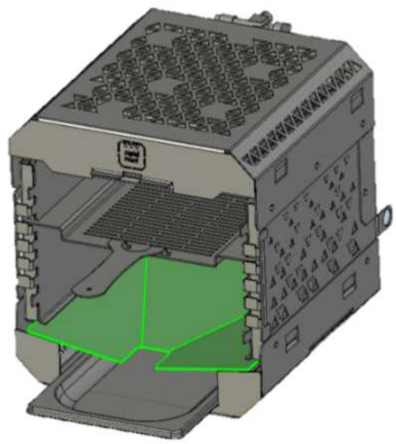

Figure 3. PCF Reduction of the system by modifying individual components

The participants of both groups that received immediate PCF-Feedback during their iterative design process (Group 1 and 3a) were surveyed to assess if the received PCF-Feedback influenced the decision-making in the design process. The subjectively perceived influence of the PCF-Feedback is rated by the participants of both groups on a Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). The ratings are shown in the following Table 4.

Table 4. Participant ratings of the influence by the PCF on design decisions

Ratings of Group 1			⌀	Ratings of Group 3a		⌀
5	4	4	4.33	4	4	4

The ratings from both groups indicate that immediate PCF-Feedback consistently influenced decision-making throughout the design process. On average, interim design decisions were more affected by the feedback than the selection of the final optimal part. Additionally, participants reported that the immediate PCF-Feedback contributed to subjectively increased engagement and task enjoyment, with the gamified aspect of feedback perceived as motivating.

7. Discussion and Outlook

This study highlights that, despite the increasing emphasis on sustainability in public discourse, its integration into the product development process in the industrial sector remains limited. Significant advancements in this area require a focused approach at the product development and design stages, which are inherently complex and often lack standardized sustainability criteria. Establishing clear and actionable directives, combined with a quantifiable and data-driven approach for assessing product sustainability, is essential for embedding sustainability effectively into the design process of technical systems. Findings from this study demonstrate that when sustainability optimization is prioritized, each group approximately halved the PCF of the resulting sheet-metal designs compared to the initial reference system. Using the PCF information in the development process, the groups utilized the information on sustainability parameters to make improvements in the design process, resulting in more sustainable products without compromising technical functionality. This is demonstrated by the integration of individual functionalities into other components of the system, resulted in the removal of one component. Eliminating the sheet-metal plate used for channeling grease and liquids into the standard collection tray reduced the system's total PCF from 24.4 kg CO_2e by 2.1 kg CO_2e, representing an optimization of 8.8 %. It can be assumed that the information about the PCF and the direct feedback enable the reduction of the PCF.

Given the small sample size and varied expertise of participants, statistical validation of these trends is limited, and statistical significance cannot be assumed. Nonetheless, a clear pattern emerges prioritizing sustainability from the beginning, supported by clear design directives and influential parameters, clearly improving product sustainability. Immediate PCF-Feedback has proven effective in accelerating decision-making, guiding the development process towards more sustainable sheet-metal designs. To achieve statistical significance, further Live-Labs must be conducted to evaluate the findings of this study. Despite these limitations, the overall benefit and support for product developers is apparent. Utilizing a data-driven approach to assist individual developers in the product development process is crucial, as it enables the design of more sustainable technical systems without compromising functionality.

References

[1] Burton Nigel. History of Electric and Hybrid Vehicles. Eng Technol Ref 2015;2015. https://doi.org/10.1049/etr.2014.0040.

[2] H.-O. Günther, M. Kannegiesser, N. Autenrieb. The role of electric vehicles for supply chain sustainability in the automotive industry 2014.

[3] Krause A, Wagenmann S, Ritzer K, Albers A, Bursac N. Data-driven life cycle assessment for mechatronic systems: a comparative analysis of environmental impact assessments. Proc Des Soc 2024:1339–48. https://doi.org/10.1017/pds.2024.136.

[4] AGEB. Auswertungstabellen zur Energiebilanz Deutschland: Daten für die Jahre von 1990 bis 2023. AG Energiebilanzen e.V.; 2023.

[5] Avilés-Palacios C, Gutierrez M, editors. Ensuring Sustainability: New Challenges for Organizational Engineering. Cham: Springer International Publishing; 2022. https://doi.org/10.1007/978-3-030-95967-8.

[6] Short T, Lee-Mortimer A, Luttropp C, Johansson G. Manufacturing, sustainability, ecodesign and risk: lessons learned from a study of Swedish and English companies. J Clean Prod 2012;37:342–52. https://doi.org/10.1016/j.jclepro.2012.07.037.

[7] DIN EN ISO 14067, Treibhausgase-Carbon Footprint von Produkten-Anforderungen an und Leitlinien für Quantifizierung 2018.

[8] He B, Pan Q, Deng Z. Product carbon footprint for product life cycle under uncertainty. J Clean Prod 2018;187:459–72. https://doi.org/10.1016/j.jclepro.2018.03.246.

[9] Krause A, Dannerbauer T, Wagenmann S, Tjaden G, Ströbel R, Bursac, Nikola, et al. Enhancing efficiency and environmental performance of laser-cutting machine tools: An explainable machine learning approach. 14.05.2024, Portugal: 2024.

[10] Albers A, Rapp S, Spadinger M, Richter T, Birk C, Marthaler F, et al. The Reference System in the Model of PGE: Proposing a Generalized Description of Reference Products and their Interrelations. Proc Des Soc Int Conf Eng Des 2019;1:1693–702. https://doi.org/10.1017/dsi.2019.175.

[11] Pfaff, Felix, Götz, Gregor Theodor, Rapp, Simon, Albers, Albert. EVOLUTIONARY PERSPECTIVE ON SYSTEM GENERATION ENGINEERING BY THE EXAMPLE OF THE IPHONE 2023.

[12] Brian E. Roe, David R. Just. Internal and External Validity in Economics Research: Tradeoffs between Experiments, Field Experiments, Natural Experiments and Field Data 2009.

[13] Albers A, Bursac N, Heimicke J, Walter B, Reiss N. 20 years of co-creation using case based learning An integrated approach for teaching innovation and research in Product Generation Engineering. 2017.

[14] A. Albers, N. Bursac, C. M. Eckert, B. Walter, M. Wilmsen, J. Heimicke. AGILE METHOD DEVELOPMENT: A LIVE-LAB CASE STUDY ON PRODUCT PROPERTIES FOR PROCESS PLANNING 2018.

[15] Maass B, Ritzer K, Ammersdörfer T, Krause A, Inkermann D, Bursac N. Engineering Simulator as a validation environment for sheet metal design methods. 125 Proc. 34th Symp. Des. X DFX2023, 2023, p. 085–94. https://doi.org/10.35199/dfx2023.09.

[16] Blessing LTM, Chakrabarti A. DRM, a Design Research Methodology. 1st ed. Springer Publishing Company, Incorporated; 2009.

[17] Bursac N, Krause A, Batora M, Ritzer K. Live-Lab GSD – Generational Sheet Metal Development: a validation environment for methodological design support in sheet metal development. 33rd CIRP Des Conf 2023;119:41–6. https://doi.org/10.1016/j.procir.2023.03.082.

[18] Hügel H, Graf T. Materialbearbeitung mit Laser. Wiesbaden: Springer Fachmedien Wiesbaden; 2023. https://doi.org/10.1007/978-3-658-41123-7.

[19] Doellken M, Lorin A, Thomas N, Sven M. Identifying an opportunistic method in design for manufacturing: an experimental study on successful a on the manufacturability and manufacturing effort of design concepts. Procedia CIRP 2021;100:720–5. https://doi.org/10.1016/j.procir.2021.05.090.