Digitally integrated sustainability assessment of design characteristics – A systematic review

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Abstract

The optimization of a product design with regard to sustainability criteria requires a predictive assessment of the lifecycle-wide impact. This paper presents a Systematic Literature Review to explore the integration of sustainability assessments in product design. It highlights the lack of correlation between lifecycle assessment results and design characteristics (DC). To address the gap in current approaches, it proposes a conceptual architecture, which semantically connects design characteristics with lifecycle impacts throughout a lifecycle design schema, facilitating automated lifecycle assessment (LCA) and enhancing design optimization. Future research topics are presented which focus on developing the semantic representation and the implementation in an industrial use case.

Keywords

Design for Sustainability, Life Cycle Assessment (LCA), Digital Integration, Computer Aided Design (CAD)

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1. Introduction

Due to the increasing scarcity of resources and upcoming regulations, it is of great importance for enterprises to assess and optimize their products regarding their environmental impact [1]. This paper focuses on mechatronic products with available digital data (e.g. CAD data). The majority of the environmental impact of a product is determined during the product development phase [2]. Therefore, it is essential to consider environmental aspects during the design of products. However, designers have a limited knowledge about how design affects the product lifecycle and environmental impacts related to it [3]. Advanced tools are therefore needed to enable the assessment of the environmental impact of a product within the process of computer-aided engineering (CAE).

Assessing sustainability is standardized through the framework of lifecycle assessment (LCA) [4]. As part of an LCA, all relevant lifecycle (LC) processes and data are aggregated during the lifecycle inventory (LCI) and evaluated regarding their environmental impact as part of the lifecycle impact assessment (LCIA). Therefore, conducting an LCA requires an extensive amount of data and process-knowledge and is a time-consuming process [2]. Additionally, does the process-oriented perspective of LCA not reflect dependencies regarding design characteristics (DC, e.g. form features, parameters, part connections), therefore limiting the identification of optimization potentials through designers [5–7]. Consequently, streamlined and automated LCA approaches have to be developed and implemented into CAE to ensure an efficient environmental impact evaluation of DC. Furthermore, the automated data aggregation and reasoning of LC processes holds great benefits for LCA experts for streamlining the conduction process [8, 9].

However, realizing a CAE-integrated LCA comes with certain challenges and requirements. A tool-independent and standardized solution is needed, which can be implemented into different, heterogeneous IT landscapes [10]. Consequently, the integration of data from various enterprise systems (e.g. CAD, ERP, MES) is required [9, 11]. Another challenge arises from the issue of missing detailing and definition of LC processes during early design phases [12]. This exploratory research regarding the current state of design-integrated LCA serves as a base for the identification of focus topics and keywords for further systematic investigation carried out in this paper.

This paper addresses the lack of correlation between LCA results and DC in current CAE tools and standards [5, 6]. The authors hypothesize, that this gap could be bridged through the development of a formal schema for the semantic linking of DC to LC data. Semantic linking is defined as a formal description (machine-readable) of relations between instances, which enables automated reasoning for dependencies and correlations [13]. A corresponding systematic evaluation of the literature is not provided by existing studies. For example, Naser et al. list application-specific approaches in the areas of additive manufacturing (AM) and machine learning (ML) [14]. In their evaluation, Tao et al. focus on a tool-oriented overview of CAD-LCA integrations [9]. Finally, the work of Vernica et al. concentrates on approaches for the design-oriented visualization of LCA results [15].The research goal within this paper is to identify approaches by conducting a Systematic Literature Review (SLR) and derive research gaps. Therefore, the following research questions are derived: (1) Which approaches are currently addressing the integrated sustainability assessment of discrete DC and how can they be classified/categorized? (2) Which generic functionalities are needed for implementing the integrated sustainability assessment of discrete DC?

2. Methodical approach

The underlying methodical approach for conducting the research follows the Design Research Methodology [16]. Addressing the first step of the methodology, this paper includes a SLR and the development of a concept draft to illustrate the overall objectives. The SLR is conducted to gain an overview on existing approaches and follows the PRISMA approach [17].

A search string was defined based on the combination of representative keywords derived from the preliminary explorative research. The keywords were clustered into three main blocks. The first block addresses the overarching research context through the combination of synonyms for product design and environmental assessment. This context gets more specified through the implementation of explicit DC integrated in the second block. The last block addresses the integration of digital data models (e.g. simulation models). The blocks were combined consecutively forming a string for searching within title, abstract and keywords in the database Scopus (s. fig. 1).

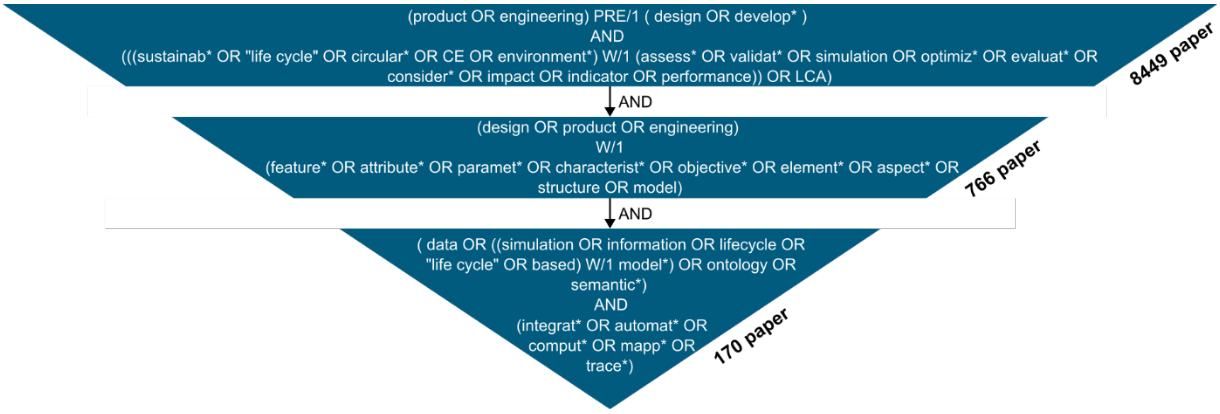

Figure 1: Search string for the SLR at Scopus.

A total of 170 papers was identified through the database search in June 2024 (s. fig. 2). By restricting the search to the subjects “Engineering” and “Computer Science” a number of 33 records were removed from the list. The remaining records were screened by abstract and title respective to following criteria (C): Approaches focusing on mechatronic products on industrial scale (C1), description of environmental impact assessment including LCA, CE-strategies and indicators (C2), (partially) automation of assessment regarding the reasoning for LC data and/or impact values based on a digital design model (C3), availability in English or German (C4). The final assessment of eligibility was carried out using full-text analysis. In this process, 11 papers were excluded due to the reason of not fulfilling the criterion C3. Consequently, 26 papers remain for detailed analysis.

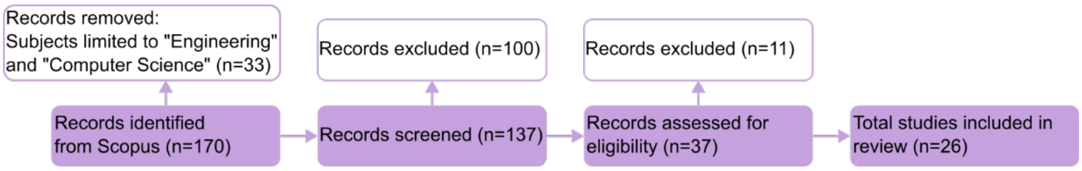

Figure 2: PRISMA approach for SLR.

A gap analysis regarding the level of generalization is conducted by assessing the following aspects for the reviewed approaches: *covered LC phases of assessment*, *addressed stages of product design and type of considered design characteristics*, *level of implementation*, *standardization* and *integration of enterprise data*. In addition, a mapping of core functionalities to associated technologies is carried out to describe the current development context. Finally, a first concept draft is described based on the integration of generic elements identified throughout the analysis of the researched approaches.

3. Systematic literature review

3.1. Literature overview

Papers by identical authors specifying the same approach were clustered into 22 approaches. The consideration of distinct LC phases was evaluated through a clustering into Beginning of Life (BoL: product design and production), Middle of Life (MoL: distribution, usage and service) and End of Life (waste treatment). The evaluation of addressed design stages was realized according to the four main digital data models of Model Based Systems Engineering (MBSE). These are requirements (R: list of requirements), functions (F: functional structure), logical solution elements (L: system model) and physical models (P: CAD-model) [18]. Additionally, the associated DC are evaluated. A distinction is made between conceptual design attributes (e.g. requirements), a holistic component (e.g. volume) and more detailed design elements (parameters, features, voxels). Furthermore, the level of implementation was assessed according to the nine Technology Readiness Levels (TRL) provided by the European Commission [19]. In addition, the implementation of standards for the representation, linking and transfer of data is validated as well as the integration of data from existing enterprise systems (e.g. ERP, PLM, CAD).

Results of the SLR are shown in table 1. The evaluation highlights that only eight approaches take the entire product LC into account. Furthermore, none of these approaches incorporates comprehensive LC data from all LC phases as the integration is restricted to selected criteria (e.g. energy consumption in manufacturing, emissions during use, recyclability). Most approaches (16) are limited to the physical design level. Only one approach describes the conceptual integration of all design levels [18]. The type of considered DC is primarily limited to a holistic component and a parametric CAD model. However, LCIA results are only partially explicitly traced back to the parameters under consideration (e.g. via correlation analysis [14]). In addition, most approaches (18) have a low TRL between (1-3). Furthermore, the consideration of standards is only described by a minority of the approaches (4) and therefore not listed in the table. Mentioned standards are the unit manufacturing process (UMP) model [10], the ISO10303 STEP standard [20] and the NIST Core Product Model [3, 21]. Finally, the integration of enterprise data highlights the focus on CAD data (16 approaches). An extension to other systems such as CAM, PDM, PLM is only mentioned occasionally without a technological specification.

Table 1: Overview of approaches identified through the SLR.

Approach	**LC phases**	**Design Stages (R, F, L, P): DC**	**TRL (1-9)**	**Enterprise Systems**
Voxel-based design with process modeling [22]	BoL, MoL, EoL	P: Component	3	CAD
Predictive LCIA of conceptual design with ML [23]	BoL, MoL, EoL	L: Attribute	3	
Predictive LCIA of AM models with ML [14, 24]	BoL	P: Parameter	4	CAD, CAM
Digital Twin for the integration of product and process [25]	BoL, MoL, EoL	P: Component	1	
Volumetric visualization of LCIA results [15]	BoL	P: Voxel	4	CAD
CE Assessment of a parametric design model [26]	BoL, MoL, EoL	P: Parameter	3	CAD
Integrated LCIA of a graph-based design model [12]	BoL	R, F, L: Attribute	3	
Integrate requirement management with LCIA of parametric CAD model [27]	BoL	R, P: Component	3	CAD, PLM, PDM
Agent based modeling for impact assessment [28, 29]	MoL	P: Component	2	
Green features for mapping of LC information [30]	BoL	R, F, L: Attribute	3	
Integration of sustainability models with product simulation models [31]	BoL, MoL, EoL	P: Parameter	3	CAD
Automated LCIA of parametric design models [10]	BoL	P: Parameter	4	CAD, CAM

Approach	LC phases	Design Stages (R, F, L, P): DC	TRL (1-9)	Enterprise Systems
Feature-based CAD-LCA integration [8, 9, 32]	BoL	P: Feature	3	CAD
Simulation-based assessment of recycling [33]	EoL	P: Component	4	CAD
Standardized information model for the integration von CAD and LCA data [20]	BoL	P: Component	2	CAD
Conceptual integration of environmental criteria into MBSE [18]	MoL	R, F, L, P: Component	2	PLM
Ontology-based representation of a products environmental profile [11]	BoL, MoL, EoL	P: Component	2	CAD, PDM
Standardized information model for product, lifecycle process and LCI dada [21]	BoL, MoL, EoL	P: Component	2	CAD
Graph-based information model for product and LC process modeling [34]	EoL	P: Component	2	CAD
Standardized information model for (partly) automated LCIA of product design [3]	BoL, MoL, EoL	P: Component	2	CAD, ERP, SCM
System architecture for integration of product and process data into LCA [35]	BoL	P: Feature	2	CAD
Approximated LCA of design concepts through ML [36]	BoL	L: Attribute	3	CAD

In order to answer research question 1, a design-oriented categorization of approaches is presented. A distinction is made between approaches with a non-dividing and a subdividing design representation. Non-dividing approaches realize an environmental impact assessment at the component level of a product without further subdividing its design representation. Considered DC are therefore primarily limited to the holistic geometry, material and weight properties. Examples therefore are approaches that describe the training of a machine learning algorithm enabling the prediction of environmental impacts by evaluating entire CAD models [14, 24, 25]. Other approaches describe a software-based/graph based link of an assembly structure with LC process models (e.g. disassembly and recycling), that allow for the integrated assessment of environmental indicators [20, 33, 34].

Subdividing approaches are based on distinct sub-elements of a design representation. A distinction can be made between three type of sub-categories. As part of the assessment of core parameters, both geometric guidance parameters of a 3D model (e.g. dimensions) [3, 10, 21] and conceptual parameters/requirements (e.g. maximum load) [11, 12] are validated. Additionally, design features represent sub-components of a design model, which can be differentiated from each other by functional properties and the relation to downstream LC phases (e.g. certain step of manufacturing). The automated retrieval of LC data by extracting features from design models is described by several approaches [9, 12, 30, 35]. Finally, volumetric approaches should be mentioned [15, 22]. These use voxels as a sub-element to map and visualize the results of an environmental impact assessment on three-dimensional geometries. In this context, voxels represent discrete volume-elements, which can be regarded as the three-dimensional equivalent of pixels [15].

3.2. Mapping of core functionalities and technologies

In the following, core functionalities and related technologies are presented which are described by the analyzed approaches (s. fig. 3). Fundamental to the automated assessment of a design concept is a machine-readable *Design Representation*. The most frequently mentioned technology therefore is the CAD model as a source for geometric and material-related information [10, 24]. A subdivision of corresponding 3D models is realized by the feature (FT) and voxel technology (VT) approaches described above [9, 15]. Additionally, graph-based approaches (e.g. And/Or Trees) [12, 30], and standardized information models (e.g. STEP based, NIST core model) [20, 21] provide formal design representations. of geometric information and conceptual product parameters/requirements during early design phases.

The majority of approaches also integrate a corresponding *Process Representation* of the product LC to enable the assignment of LCI data to certain LC phases. The technological implementation includes the previously mentioned concepts of FT, graph-based description and standardized information models. In addition, simulation models are described which can be derived directly from the design model through a simulation software [24, 33].

An overarching functionality is represented by *Data Linking*, which incorporates semantic linking of product, process and LC data. Associated technologies are graph-based links and standardized information models [18, 30, 34]. Rule-based approaches use manually defined expressions (e.g. formula) to describe the relationship between different type of data [8, 10, 27]. Additionally, ontologies are described as a tool-independent schema for the representation of dependencies between data objects [11]. Strongly related to the functionality of *Data Linking* is the aspect of *Automated Reasoning*. This includes the reasoning for information based on a formal representation without the need to manually define product-specific dependencies. In addition to the technologies already described for linking data, machine learning (ML) is presented as an implementation for this purpose [25]. Furthermore, *Data Integration* is required for the incorporation of data from different sources. Relevant product- and process data gets integrated from enterprise systems [3, 27] and additional databases [24, 30]. The same applies to LCI data that is integrated from LCI databases (e.g. SimaPro) [23, 33]. In order to quantify the environmental impact of a product, an *Impact Assessment* must be realized. Most approaches are addressing this topic by the accumulation of impact data regarding certain indicators (e.g. according to LCA framework, CE indicators), without describing a certain technology related to it [25, 26, 31]. Other refer explicitly to the integration of LCA software [10, 23, 33]. Furthermore, the use of ML algorithms for impact prediction is described [23, 24, 36].

Throughout the entire process chain, it is important to enable appropriate *Visualization* of product, process and impact data. Most implementations provide a design model visualization through CAD tools and graphical user interfaces (GUI) [8, 33, 35]. Only one approach realizes the design-oriented visualization of impact results through voxel technology [15].

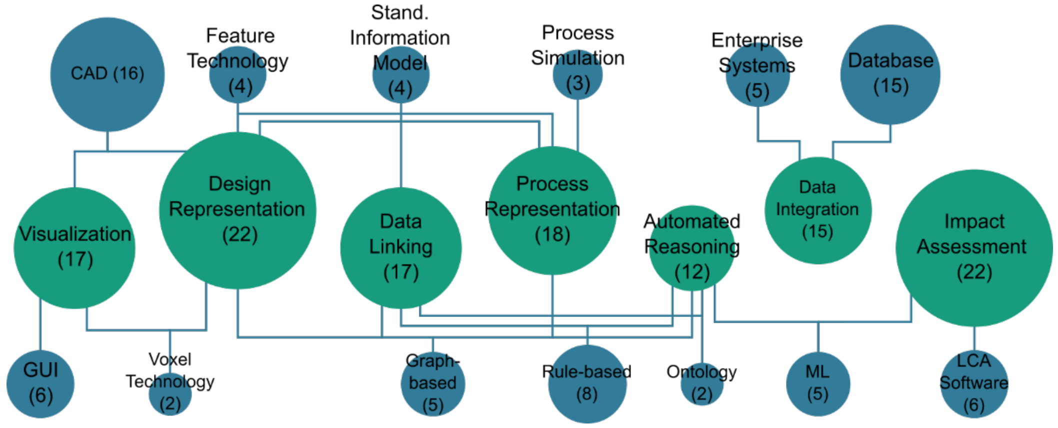

Figure 3: Overview of functionalities (green) and technologies (blue) addressed by the searched approaches.

The evaluation highlights that not all approaches implement the entire range of functionalities. The core aspects *Design Representation* and *Impact Assessment* are fulfilled by all approaches as this was required to fulfill the selection criteria (C2, C3) of the SLR. Additionally, most approaches include types of *Process Representation* and *Data Linking*. Related technologies are feature technology or graph- and rule-based approaches which implement very application-specific data linking using tree structures and parametric formulas. Only a small number are based on ontologies and standardized information models, which provide a more generic schema for data representation. The functionality of *Automated*

Reasoning is very relevant in order to be able to derive product-specific information from a comprehensive design and process knowledge. Nevertheless, it is only mentioned by just more than half of the approaches. Furthermore, the evaluation highlights the fact, that only a few approaches consider the integration of enterprise data, stored in different IT systems. It is also notable that only in a small number of approaches the impact assessment is supported by the use of an LCA software. A corresponding tool interface is very relevant in order to be able to realize a transparent assessment within the framework of existing standards and reporting guidelines. Finally, the visualization is primarily limited to CAD information. Only one approach provides a design-oriented visualization of impact results.

3.3. Gap analysis

Based on the literature review and the mapping of core functionalities and technologies, the following research gaps were identified:

G1: Lack of implementation and validation of approaches in an industrial environment (low TRL of approaches)
G2: Lack of detailed specification for the integration of enterprise data stored in heterogeneous IT Systems
G3: Lack of standardization regarding the structuring and formalization of information models (product and process related)
G4: Insufficient definition and implementation of a generic schema, which is compatible with existing design models (e.g. CAD) and allows for the semantic representation and linking of product and process data in the context of LCA
G5: Lack of data continuity in terms of tracing back impact assessment results through all design phases (R, F, L, P)
G6: Missing design-oriented visualization of impact assessment results regarding distinct design characteristics

4. Concept presentation

The literature research has shown a variety of domain-, technology- or LC-specific research. But it lacks a generic approach for realizing an integrated sustainability assessment of discrete DC. In this context, generalization implies the consideration of standards for data modelling, the flexible integration of enterprise data and the realization of an expandable mapping of product DC to LC processes and data. Therefore, a functional architecture is developed based on the identified core functionalities (s. fig. 4). The technical specification and implementation are part of future research and not described subsequently.

The architecture consists of four main modules. The first module comprises enterprise data stored in different IT-systems and provides two data shadows of design data and LC data that are processed by the other modules. The central element of the architecture is the Lifecycle Design (LCD) schema. Within the schema, available LCD characteristics, LCA processes and LCI data are stored in semantically interlinked knowledge bases. Standardized interfaces to the enterprise systems provide persistent referencing of LCI data such as material information, energy consumption and transport routes. Examples for schematic interlinks are geometric undercuts (LCD characteristic) that define the energy consumption (LCI data) of a manufacturing process (LCA process) or connecting elements (e.g. snap fit), that enable a mono-material recycling process. The product-specific configuration of instances within the LCD schema is represented in an LCD model (LCDM), which serves as the central link between design and LCA data.

The LCD module comprises functionalities regarding the creation of the LCDM. Initially, fundamental DC (e.g. CAD model features) are extracted from design data, retrieved from the enterprise system (PDM). The configuration of the LCDM is automatically derived from the reasoning for LCD characteristics and the correlated LCA processes and LCI data stored in the LCD schema (s. fig. 4, path 1-2).

The LCDM serves as an input for the LCA module, where the creation of an LCA model is realized (s. fig. 4, path 3). In this step, a process sequence is generated based on the identified LCA processes from the LCDM, which reflects the entire product LC and incorporates the referenced LCI data. Subsequently, the calculation and visualization of environmental impacts is performed as part of the LCIA (s. fig. 4, path 4-5). Finally, the semantic linking of the steps taken allows the impact results of LCIA to be traced back to the LCDM and mapped onto the initial design data (s. fig. 4, path 6-9). A visualization of the results is implemented in suitable design tools (e.g. CAD). Consequently, the approach enables both the efficient identification of design optimization potentials by designers and the accelerated conduction of an LCA by sustainability experts.

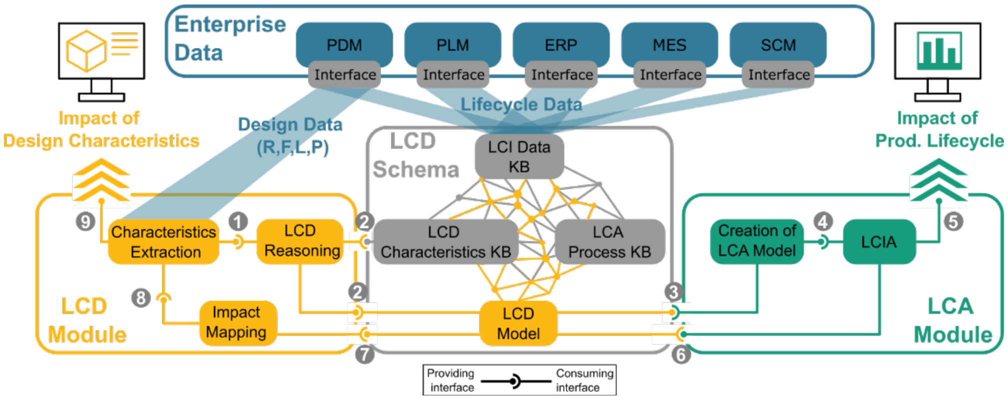

Figure 4: Architecture for the integrated sustainability assessment of design characteristics.

5. Discussion

In this study, 22 approaches were identified that address the research topic of integrated environmental assessment of DC. The evaluation has shown that there is currently only limited traceability of impact results to discrete DC. Most approaches describe an assessment at the component level, which makes it difficult for designers to identify optimization potentials. Other aspects such as the consideration of the entire LC, the integration of standards and enterprise data are insufficiently implemented. This may be due to the low TRL (1-3) and the associated conceptual implementation. The evaluation of core functionalities and their technological implementations shows a great diversity, which confirms the lack of a generic solution within the scope of the identified approaches. Limiting properties of an SLR must be pointed out when interpreting the results. The choice of keywords in the database search may exclude other relevant research. In addition, the search is limited to scientific works and thus possibly excludes the most recent, non-published implementations of technology vendors.

The described functional architecture serves as the basis for future technological implementation. An automated LCA at the design phase requires integrated reasoning for LC processes and data. This is only possible in the detailed design stage (e.g. detailed CAD model), when the choice of DC imposes appropriate restrictions for specific LC phases. The traceability of LCA results to earlier design stages therefore requires consistent linking of the phase-specific design elements (R, F, L, P). This integration of design phases also forms the basis for effective knowledge reuse in the sense of a predictive LCA in the conceptual design stage. Therefore, repetitive DC are evaluated by incorporation of LCA results from previous design configurations. Consequently, the integration of DCs from all design phases must be considered in the development of the LCD scheme. Furthermore, existing open standards for data modeling and cross-tool linking (e.g. Linked Open Data, Resource Description

Framework, Open Services for Lifecycle Collaboration) must be considered. In addition to company-specific process models and LC data, cross-company approaches for data exchange (e.g. Asset Administration Shell) must be considered in order to ensure capturing of the entire supply chain [25]. The approach also requires company-specific LCA process knowledge. This must be described semantically and continuously updated. Even if this is not yet a standard procedure in companies, the latest regulations and reporting obligations will accelerate development in this direction. Therefore, the presented approach builds on this development to effectively integrate LCA knowledge to support both the streamlined environmental validation of design concepts and the creation of a product-specific LCA.

6. Conclusion

A SLR was conducted to capture the current state of research regarding the integrated sustainability assessment of DC. The evaluation of the literature reveals development potentials concerning the implemented technological readiness level, the integration of enterprise data, the implementation of standards for data modeling, the schematic representation and linking of product and process data, the seamless integration of all design phases, and the design-oriented visualization of LCA results. A functional architecture was developed to address these development potentials. The core component is the LCD schema, which provides the semantic representation and linking of DC, LCA processes, and LCI data. The schema enables automated reasoning for process data based on given design data and the subsequent implementation in an LCA. In the opposite direction, the integrated traceability of LCA results to DC is established. Through an appropriate tool implementation, designers with limited process and sustainability knowledge are empowered to identify optimization potentials related to a certain product design. The further elaboration involves developing the fundamental structure of the LCD schema, considering existing standards and technologies. Additionally, modular interfaces for the integration of enterprise data from existing IT systems need to be developed to enable effective integration into different enterprise environments. Finally, the implementation and evaluation in an industrial use case is intended.

References

[1] EU: Directive (EU) 2022/2464 of the European Parliament and of the Council (in Kraft getr. am 2022) (2022).

[2] Ramani, Karthik, et al.: Integrated Sustainable Life Cycle Design: A Review. In: Journal of Mechanical Design 132 (2010), Nr. 9, 091004 1-15.

[3] Faneye, Ola. B.; Anderl, Reiner: Optimizing product life cycle processes in design phase. In: Gupta, Surendra M. (Hrsg.): Environmentally Conscious Manufacturing II, 2002 (SPIE Proceedings), S. 138–148.

[4] DIN EN ISO 14040:2021-02, Umweltmanagement - Ökobilanz - Grundsätze und Rahmenbedingungen (2021).

[5] Chen, Zhaorui; Tao, Jing; Yu, Suiran: A Feature-based CAD-LCA Software Integration Approach for Eco-design. In: Procedia CIRP 61 (2017), S. 721–726.

[6] Rio, Maud; Reyes, Tatiana; Roucoules, Lionel: Toward proactive (eco)design process: modeling information transformations among designers activities. In: J. Clean. Prod. 39 (2013), S. 105–116.

[7] Brundage, Michael P., et al.: Analyzing environmental sustainability methods for use earlier in the product lifecycle. In: J. Clean. Prod. 187 (2018), S. 877–892.

[8] Chen, Zhaorui; Tao, Jing; Yu, Suiran: A Feature-based CAD-LCA Software Integration Approach for Eco-design. In: Procedia CIRP 61 (2017), S. 721–726.

[9] Tao, Jing; Li, Lu; Yu, Suiran: An innovative eco-design approach based on integration of LCA, CAD\CAE and optimization tools, and its implementation perspectives. In: J. Clean. Prod. 187 (2018), S. 839–851.

[10] Bernstein, William Z., et al.: An automated workflow for integrating environmental sustainability assessment into parametric part design through standard reference models. In: Procedia CIRP 90 (2020), S. 102–108.

[11] H. Ostad-Ahmad-Ghorabi, T. Rahmani, D. Gerhard: An Ontological Approach for the Integration of Life Cycle Assessment into Product Data Management Systems. In: CIRP Design 2012, S. 249–256.

[12] Kong, Lin, et al.: A life-cycle integrated model for product eco-design in the conceptual design phase. In: J. Clean. Prod. 363 (2022).

[13] Stuckenschmidt, Heiner: Ontologien : Konzepte, Technologien und Anwendungen. 2. Aufl. Berlin, Heidelberg: Springer, 2011.

[14] Naser, Ahmed Z., et al.: Automating life cycle assessment for additive manufacturing with machine learning: Framework design, dataset buildup, and a case study. In: J. Manuf. Syst. 71 (2023), S. 504–526.

[15] Vernica, Teodor, et al.: Volumetric mapping and visualization of life cycle assessment results on computer-aided design models. In: J. Clean. Prod. 418 (2023), S. 138035.

[16] Blessing, Lucienne T.M.; Chakrabarti, Amaresh: DRM, a Design Research Methodology. London: Springer London, 2009.

[17] Page, Matthew J., et al.: The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. In: BMJ (Clinical research ed.) 372 (2021), n71.

[18] Eigner, Martin, et al.: System Lifecycle Management: Initial Approach for a Sustainable Product Development Process Based on Methods of Model Based Systems Engineering. In: IFIP WG 5.1 International Conference, PLM 2014, S. 287–300.

[19] European Comission: Horizon 2020. Work programme 2014-2015: Annex G: Technology readiness levels (TRL). 2015.

[20] Li, Yunpeng; Roy, Utpal: A STEP-Based Approach Toward Cooperative Product Design for Sustainability. In: Volume 1A: 34th Computers and Information in Engineering Conference : ASME, 2014.

[21] Jianjun, Yi, et al.: Research on evaluation methodologies of product life cycle engineering design (LCED) and development of its tools. In: J. Comput. Integr. Manuf. 21 (2008), Nr. 8, S. 923–942.

[22] Hoshiba, Kanta; Arai, Hibiki; Fukushige, Shinichi: Development of a voxel-based CAD system for upstream life cycle design and its application to LCA. In: Procedia CIRP 122 (2024), S. 605–610.

[23] Manuguerra, Luca, et al.: A Method Based on Machine Learning Techniques for the Development of a Parametric Environmental Impact Model for Industrial Electric Vehicles. In: Carfagni, Monica, et al. (Hrsg.): Design Tools and Methods in Industrial Engineering III. Cham : Springer Nature Switzerland, 2024 (Lecture Notes in Mechanical Engineering), S. 83–90.

[24] Naser, Ahmed Z., et al.: Toward automated life cycle assessment for additive manufacturing: A systematic review of influential parameters and framework design. In: Sustain. Prod. Consum. 41 (2023), S. 253–274.

[25] He, Bin; Mao, Hangyu: Digital Twin-Driven Product Sustainable Design for Low Carbon Footprint. In: Journal of Computing and Information Science in Engineering 23 (2023), Nr. 6

[26] Aher, Gaurav; Boudjadar, Jalil; Ramanujan, Devarajan: Towards Simulation-Based Circular Product Design. In: Procedia CIRP 116 (2023), S. 690–695.

[27] Zhou, Jiwei, et al.: An Approach to Extend the Digital Thread From Requirements to Model Geometry. In: Volume 1: Additive Manufacturing; Biomanufacturing; Life Cycle Engineering; Manufacturing Equipment and Automation; Nano/Micro/Meso Manufacturing : American Society of Mechanical Engineers, 2022.

[28] Mabey, Christopher S., et al.: A framework for predicting potential product impact during product design. In: Proceedings of the Design Society 1 (2021), S. 101–110.

[29] Mabey, Christopher S., et al.: A computational simulation-based framework for estimating potential product impact during product design. In: Design Science 7 (2021).

[30] Fu, Yan; Wang, Liming; Li, Long: Conceptual design scheme automatic generation and decision-making considering green demand. In: Procedia Manufacturing 43 (2020), S. 407–414.

[31] Bertoni, Alessandro, et al.: Integration of value and sustainability assessment in design space exploration by machine learning: an aerospace application. In: Design Science 6 (2020).

[32] Tao, Jing; Yu, Suiran: Development of LCA Module Integrated With CAD for Eco-Assessment of Machined Products. In: Volume 4: 23rd Design for Manufacturing and the Life Cycle Conference; 12th International Conference on Micro- and Nanosystems : ASME, 2018.

[33] Reuter, M. A.; van Schaik, A.: Product-Centric Simulation-Based Design for Recycling: Case of LED Lamp Recycling. In: Journal of Sustainable Metallurgy 1 (2015), Nr. 1, S. 4–28.

[34] Fangyi, Li, et al.: Green design assessing system model of products. In: Conference Record : IEEE, 2002, S. 123–127.

[35] Otto, H. E.; Mueller, K. G.; Kimura, F.: A framework for structured data retrieval in LCA using feature technology. In: Proceedings Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing : IEEE Comput. Soc, 2001, S. 250–255.

[36] Eisenhard, Julie L., et al.: Approximate Life-Cycle Assessment in Conceptual Product Design. In: Volume 3: 5th Design for Manufacturing Conference : ASME, 2000, S. 177–185.