Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 136 (2025) 207–212

www.elsevier.com/locate/procedia

35th CIRP Design 2025

Model-based Impact Analysis for Engineering Sustainable Products in Value Creation Networks

Iris Graessler[a], Sven Rarbach[a,*]

[a]Heinz Nixdorf Institute, Paderborn University, Fürstenallee 11, 33102 Paderborn, Germany
* Corresponding author. Tel.: +49-5251-60-6257; fax: +49-5251-60-6280. *E-mail address:* sven.rarbach@hni.upb.de

Abstract

Engineering decides upon the environmental impact of technical products. In corresponding decision-making, ecological factors are still undervalued compared to economic and technical factors. The complexity of ecological factors and their interdependencies in value creation networks require a model-based approach for sustainability impact analyses. For such analyses, relevant sustainability decisions are identified. Influencing factors are derived, combined, and modelled. A new approach is developed in five steps: collection of impact analysis approaches through literature review (1), analysis of included sustainability influencing factors (2), derivation of a viable model (3), application to a case example (4) and validation (5).

Keywords: Design for Sustainability, Impact Analysis, Effect chain analysis Value Creation Networks, Model-Based Systems Engineering

1. Introduction

As part of global efforts to address environmental issues, industry is increasingly focusing on sustainability indicators when engineering products. Despite these efforts, products often only meet minimum environmental requirements, as sustainability is not fully integrated into the engineering process. The environmental impact of a product throughout its life cycle is largely determined by the decisions made during product engineering [1]. Fig. 1 illustrates the correlation between the consequences of a decision and its environmental impact. The impact dependencies resulting from a given decision are determined in particular by consequences of that decision [2]. A comprehensive understanding of the environmental impacts throughout the value creation process is required to ensure that the engineered product can meet its sustainability goals throughout its product life cycle (PLC). Impact analysis and in particular model-based effect chain analysis are of central importance in this process, offering a systematic methodology for the assessment and optimisation of

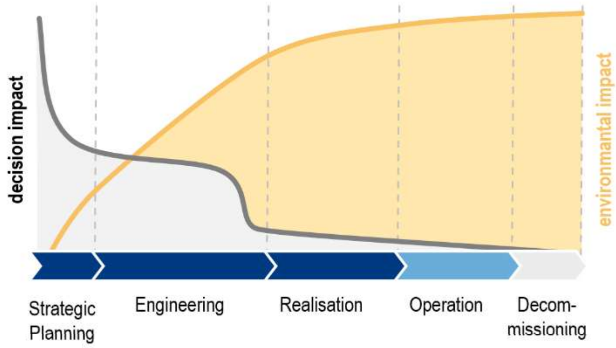

Fig. 1: Cumulative environmental impacts over PLC based on [3, 4]

the sustainability performance of products at every stage of their lifecycle, from strategic planning to decommissioning. Assessing and managing these impacts is essential for sustainable production and effective sustainability decision-making [5]. The integration of comprehensive environmental data into model-based approaches facilitates more informed decision-making, thereby enabling flexibility in responding to the diverse sustainability requirements that arise during the

10.1016/j.procir.2025.08.037

product engineering process [6]. Current decision support approaches for assessing the product sustainability are mostly based on Life Cycle Assessment (LCA). LCA is a well-established methodology described by the European Commission as the most appropriate way to measure the environmental impact of the entire supply chain [7]. Although LCA provides a comprehensive framework encompassing all life cycle information, in practice, engineers frequently encounter difficulties in identifying critical environmental linkages across different stages and product levels. This hinders the effectiveness of LCA in supporting decision-making processes [8]. This lack of transparency makes it difficult to trace decisions, make an informed assessment of the environmental impacts of product engineering, and thus to support sustainability decisions. Based on the limitations described, the two research questions are investigated:

RQ 1: Which success factors need to be considered in an impact analysis for engineering sustainable products?

RQ 2: How do existing effect chain analysis approaches need to be adapted to implement sustainability assessment?

To answer the questions the paper at hand first presents the state of the art. Based on this, the scientific approach is described and the scientific methodology is defined. Firstly, relevant literature is identified, success factors are worked out, relevant approaches are evaluated and a suitable model is derived. Finally, the effect chain analysis approach is applied in a case study and then validated using the success criteria.

2. State of the Art

The concept of sustainable product engineering is approached by considering the entire product life cycle, from strategic product planning to decommissioning, with all relevant information, material and energy flows [9]. A variety of methods and tools have been developed to provide support. These approaches can be divided into six categories: frameworks, checklists and guidelines, and rating/ranking tools, analytical tools, software/expert systems, and organising tools. Analytical approaches are predominantly quantitative, comprehensively measuring and evaluating the environmental performance of products. The Life Cycle Assessment (LCA) represents the most established approach, upon which a substantial number of assessment procedures are based [10]. The standards DIN EN ISO 14040 [11] and DIN EN ISO 14044 [12] define the four phase approach for the assessment of environmental impacts over the whole life cycle of a product. The four phases of the LCA are Goal & Scope, Life Cycle Inventory, Impact Assessment and Interpretation. The life cycle is defined as a series of sequential and interrelated stages from raw material extraction to final disposal [11]. The LCA is often extended or adapted to take better account of additional environmental factors or specific requirements. Such extensions allow a more detailed assessment. Examples of this are the ReCiPe and Eco-Indicator 99 extensions to the indicator system of the LCA [13, 14]. The effectiveness of the LCA is constrained by the accessibility and quality of the data [15]. Consequently, it is typically deployed only in the latter stages of product engineering [2]. Sustainability is embedded in development processes through approaches like Ecodesign and Design for Environment (DfE). The objective of ecodesign is to minimise the environmental impact of the PLC through design efforts. DfE emphasises environmentally conscious design, considering design performance in relation to environmental systems. [16] Value chains with extensive supplier networks provide the foundation for comprehensive analysis [17]. Current data space approaches, exemplified by Prontus-X and Manufacturing-X, are based on findings from Gaia-X and aim to facilitate the creation of collaborative and open data ecosystems by participating stakeholders [18]. The resulting availability of data throughout the value chains forms the basis for new approaches to evaluating sustainability.

Despite the similarity in name and the ambiguous use of the term impact assessment as impact analysis, impact analysis is a concept that exists independently of environmental impact. ARNOLD and BOHNER define impact analysis as the activity of identifying what needs to be changed or identifying the potential consequences of a change [19]. Potential applications include using traceability relationships to detect changes to artefacts, and consultation of designs and specifications to determine the changes. The evaluation of this cause and effect dependencies can be conducted through the utilisation of the model-based effect chain analysis, enabling the mapping and interpretation of dependencies between a set of elements of an overall system [20]. This model-based approaches can be distinguished by the information model that is employed. Commonly utilised forms include matrix-based modelling, graph-based modelling and object-oriented modelling approaches [21]. Graph-based methodologies and applications are enabled by technologies like knowledge graphs, particularly in the context of heterogeneous data that are machine-readable [22]. Knowledge graphs are defined by WANG et al. as multi-relational graphs consisting of entity and relations. Each edge is represented as a triplet consisting of the head entity, the relation, and the tail entity [23]. Knowledge graphs are utilised for semantic modelling of domain-specific knowledge, thereby facilitating the provision of support in responses to specific queries, the extraction of pertinent information and operation of recommendation systems [24].

3. Scientific methodology

A six-step research approach is used to answer the two research questions (cf. Fig. 2). In the first step, a literature analysis containing a scoping review and a systematic literature

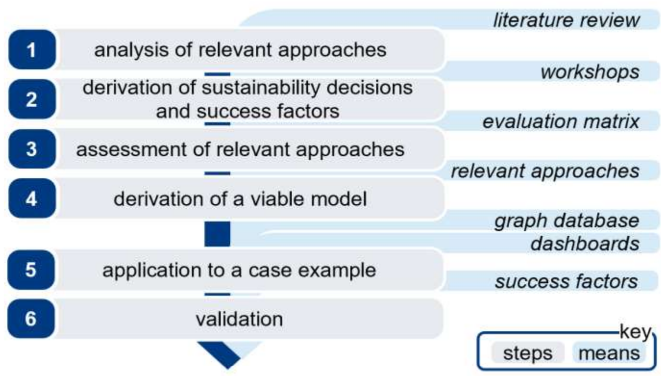

Fig. 2: Scientific approach

review are conducted to identify relevant approaches of impact analysis for the engineering of sustainable products. In the second step relevant sustainability decisions and success factors for the evaluation of the impact analyses are derived. In the third step the relevant approaches are analysed and evaluated based on the success factors. In the fourth step a conceptual meta model for effect chain analysis is build. In the fifth step the model is applied to case example. In the sixth step the model is evaluated based on the success factors.

4. Model-based impact analysis for sustainable products

This section outlines results of the initial four stages of the research design, which are then broken down into the following subsections. The model developed is subsequently applied and validated in a case study.

4.1. Literature study for impact analysis approaches

The literature study comprises a scoping review and systematic literature analysis. A scoping review is conducted based on the methodology proposed by ARKSEY and O'MALLEY with the objective of acquiring a comprehensive overview of the research field of impact analyses in the context of sustainability [25]. In line with the findings of the preceding investigation, the subsequent systematic literature analysis aims to identify and examine specific approaches to model-based impact analyses and effect chain analysis for sustainability assessment, employing the PRISMA approach [26]. The Scopus and Web of Science (WoS) databases were selected for their inclusion of engineering-related content and their adherence to enhanced quality standards. Additionally, Google Scholar (GS) was incorporated to enhance the breadth of results and check for completeness. The findings of the scoping reviews and the search string are presented in Table 1. The search string has been constructed in a way that guarantees the inclusion of all reviews related to sustainability and impact analyses. The number of documents from GS was limited to 200 to supplement the findings of the other sources. Following the initial screening of 381 documents, 16 reviews were identified as meeting the inclusion criteria. The majority of the literature focuses on the specific determination of environmental impacts associated with a technology or product, with a notable emphasis on LCA [27–29]. Two reviews address the adaptation of assessment methods to align more closely with sustainability considerations without considering traceability impact analysis in the context of product creation [30, 31].

Table 1: Results of the Scoping Review

	Scopus	WoS	Google Scholar
search string	("Sustain*" OR "Circ*") AND ("Impact Analysis" OR "Impact Analyses") AND "Review"		
identified reviews	106	78	197
selected reviews		16	

The findings of the scoping review underscore the absence of research in this area and the necessity for a comprehensive, systematic literature-based investigation. The search string employed for the systematic search, along with the resulting data, is presented in Table 2. Based on the findings of the scoping review, the search string was refined to focus more explicitly on the model reference and the evaluation. To ensure manageability, terms on “traceability” and references to “product development” OR “product engineering” were included specifically at Google Scholar. The articles were selected based on their contribution to the advancement of impact analysis in the context of product engineering of sustainable products, including their engineering, adaptation, and application. Based on the 878 initial documents, seven approaches were identified using the inclusion criteria.

Table 2: Results of the Systematic Literature Review

	Scopus	WoS	Google Scholar	∑
search string	"model" AND ("impact analys*" OR “effect chain analysis”) AND ("life cycle" OR "sustainab*" OR "circul*") AND "assessment" -"medicine*" -"security		AND "traceability" AND ("product development" OR “product creation” OR “product engineering”)	
identified approaches	274	198	406	878
select approaches	2	1	4	7

4.2. Sustainability decisions and success factors

Following the analysis of literature, additional workshops were conducted in collaboration with industry partners specialising in plastic injection moulding, automotive engineering and audio electronics. Based on the analysis of the current product engineering processes and the identification of relevant sustainability decision points, roles, questions and required information are determined [32]. These decision points are distributed across the product engineering process, from the conceptual definition of the product in the early stages, through to the selection of suppliers based on sustainability indicators and the choice of machinery within the production phase.

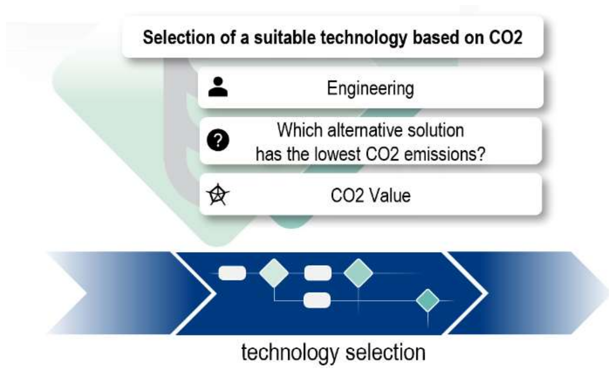

Fig. 3: Formalisation of sustainability decision points

Fig. 3 provides a visual representation of the template for recording these decision points in the context of the product engineering process. In accordance with RQ 1 success factors (SF) were established to facilitate the decision-making process for the engineering of sustainable products.

These SF encompass:

- SF1: Incorporation of the entire PLC
- SF2: Ability to integrate relevant data sources
- SF3: Flexibility to adapt to changes
- SF4: Transparency in the presentation of dependencies
- SF5: Utilisation of role-specific visualisation
- SF6: Inclusion of sustainability indicators

4.3. Evaluation of relevant impact analysis approaches

Table 3 illustrates the assessment results using three categories: not, partially, and completely fulfilled.

Table 3: Evaluation matrix for sustainable impact analysis approaches

	SF1	SF2	SF3	SF4	SF5	SF6
[7]	●	◑	◑	○	○	●
[8]	◑	●	◑	○	○	●
[5]	◑	◑	●	◑	○	●
[33]	◑	●	◑	○	○	●
[34]	●	◑	●	●	●	◑
[2]	◑	○	◑	●	○	●
[35]	◑	◑	○	●	○	◑

○ not fulfilled ◑ partially fulfilled ● completely fulfilled

ESCRIG-OLMEDO et al. have developed and implemented a sustainability risk assessment framework that incorporates environmental and social footprint calculations, along with a hotspot analysis [7]. ZHANG et al. present a multi-model product lifecycle analysis model that incorporates baseline, evaluation, structure and constraint information into a scenario-based LCA framework. This approach aims to expand the temporal and contextual scope of LCA, enabling a more timely and diverse understanding of the PLC [8]. GBEDEDO and LIYANAGE undertook an analysis of methodologies, tools and approaches for determining the impact of manufacturing processes. They employed inductive methods and conceptual synthesis of key sustainability approaches to develop a descriptive framework. This framework enables the conceptual modelling of an integrated simulation-based sustainability impact analysis [5]. FERRARI et al. examine the potential of Internet of Things (IoT) technologies and Industry 4.0 to enhance the efficiency of the inventory analysis phase of the LCA. The objective of the dynamic environmental impact assessment system is to standardise and optimise the quality of data, addressing inconsistencies between primary and secondary data [33]. GRAESSLER et al. further develop a generic method for the development of systems of systems impact analysis, which is tailored to the specific needs of the identified actor. Relevant functionalities are identified and implemented, including sustainability assessment, which is integrated into a knowledge graph and presented in a customised dashboard. BUCHERT et al. present a formalisation of the interdependencies between environmental impacts, design principles and product characteristics, offering support to engineers engaged in the challenging task of decision-making throughout the product engineering process [2]. LIPŠINIĆ et al. examine the potential of the current Systems Modelling Language (SysML) to facilitate the development of a system model for the implementation of circular economy strategies [35].

The approaches presented are versatile and offer valuable perspectives for sustainability assessment. The generic approach of GRAESSLER et al. provides a foundation for further development of the model-based impact analysis and especially effect chain analysis. By integrating the results from other approaches, such as the multi-module PLC analysis model and the IoT data integration by FERRARI et al., the generic framework can be extended and adapted to different use cases.

4.4. Deriving a viable model

The generic method proposed by GRAESSLER et al. is based on the previously developed method for developing graph-based analyses with role-specific dashboards. The method comprises four phases. In the initial phase, the expected outcomes associated with specific roles are documented and translated into detailed questions and visual representations. Based on the identified expectations, the relevant elements, properties and relations required to fulfil the stated statements are identified. In the third step, the identified models are merged into one model and stereotypes are created in the meta model to model the specific situation. In the final step, role-specific dashboards are created depending on the required visualisation based on the graph-based implementation.

Based on the comprehensive analysis of the approaches, the modelling of relevant data and the integration of sustainability indicators need to be further considered. To facilitate the implementation of sustainability-oriented effect chain analysis, it is necessary to define a set of pre-established information parameters that can be used by engineers in a variety of decision points (cf. RQ2). This enable a comprehensive and traceable evaluation process to be conducted throughout the product engineering phase. By combining the findings of the various approaches analysed and the workshops held, an abstract meta model (cf. Fig. 4) is established, which can be adapted and refined in the context of more precise implementation.

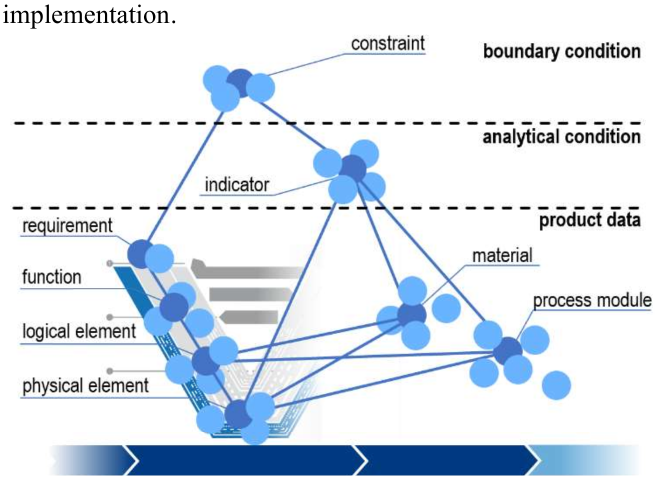

Fig. 4: System model for model-based effect chain analysis

In the meta model, the engineering artefacts Requirement, Function, Logical and Physical Elements, Verification and Validation (RFLPV²) [36] are expanded by four supplementary elements regarding the incorporation of cross-PLC data and analysis data, in addition to external boundary conditions. The different model versions of the approaches under consideration can be located in the nodes. For a particular implementation, the meta model still needs to be tailored to the specific requirements of that implementation. The product-related data, which was previously represented by the engineering artefacts, is extended by material and process modules (cf. related to previous work [37, 38]). The process modules represent the smallest components of a life cycle inventory, comprising all phases. For an independent analysis of the impact, the consideration of materials and processes was differentiated. Additional relations are constituted by "caused by" relationships. Based on the defined logical and physical elements, the additional ones can be employed to generate evaluation capability. An example of the nodes and basic properties is presented in Fig. 5.

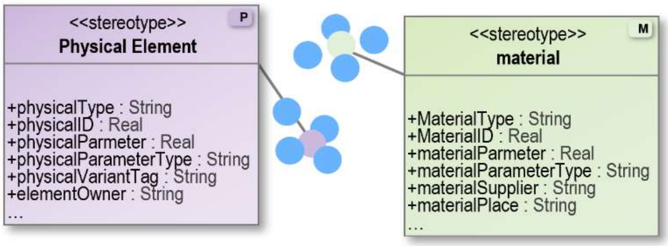

Fig. 5: Extract of the meta model for sustainable effect chain analysis

The data contained within the supplementary nodes serves as the foundation for calculating the environmental impact. A further node is created for the specific allocation of indicators, which contains the allocation keys and equivalents for calculating the environmental impact. The constraint node allows the definition of relevant constraints, which can be derived from regulations or customer specifications, depending on the scope of the application. The generic meta model enables the implementation of model-based effect chain analysis. The generic meta model needs to be implemented under the conditions required for the required use cases and expected outcomes.

5. Application

The meta model is applied to a robotic arm in the Smart Automation Laboratory at the Chair for Product Creation. The engineering of two possible solutions for the gripper unit is analysed. The analysis is based on a central system model. The specific decision point is the choice of gripper technology, which is selected based on a constraint of 9kg of CO_2 emissions. For this purpose, the two solutions "clamping gripper" and "magnetic gripper" are evaluated in terms of their CO_2 footprint. The required model is implemented in the Neo4J graph database and analysed using the NeoDash tool. Based on the defined meta model, the data is imported into the graph database in CSV files. The development artefacts and information on use and decommissioning are provided from the engineering perspective. Material data is obtained from suppliers and production processes through historical and database values. The relevant equivalents and calculation formulae are imported from a separate created database. Fig. 6 shows an extract of the modelled elements on the "clamping gripper".

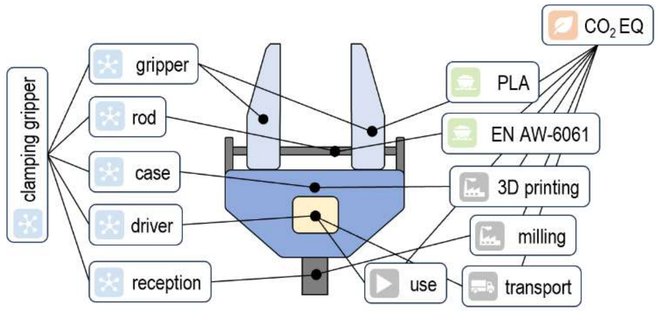

Fig. 6: Exemplary visualisation of the gripper system model

The engineering of the gripper is based on several logical elements, with relevant materials connected via the "caused by" relationship. Depending on the selected elements, CO_2 equivalents are linked from different databases. The resulting system model can be visualised in role-specific dashboards. From an engineering perspective, the carbon footprint can be calculated based on the selection of a logical element. An abstract representation of this part of the

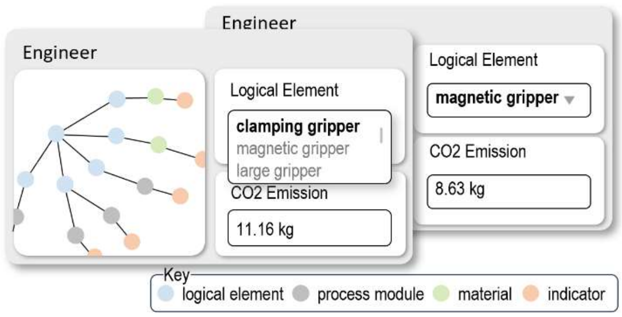

Fig.7: Extract of the dashboards for sustainable effect chain analysis

dashboard is presented in Fig. 7 with two different logical elements. The specific case study demonstrated the impact of modifying a logical component on the CO_2 footprint. The constructed system model provides support for additional decision points throughout the engineering process. Further implementation may be achieved through the fulfilment of a requirement regarding CO_2 emissions, which can be analysed using the calculation. This analysis enables evaluation of the effect on the fulfilment of the requirement.

6. Validation

The application of the extended meta model shows that the method is suitable for analysing impacts in the engineering of sustainable products. A comprehensive analysis can be carried out by representing data along the entire PLC in the model (SF1). The implementation in form of a knowledge graph allows the implementation of all data. However, the diversity and complexity of the relevant data does not allow a simple implementation (SF2). The generic formulation of the meta model allows the system model to be easily extended or adapted (SF3). The comprehensive query capabilities allow a transparent representation of dependencies (SF4) as well as additional role-specific visualisations (SF5). The extension of the meta model allows the implementation of concrete sustainability indicators and calculation formulas (SF6).

7. Conclusion

In this paper, a meta model is extended to enable impact analyses for engineering sustainable products. The approach is adapted in a six-step research approach. Starting from a literature review, sustainability decision points and success factors are derived (RQ1). Based on the success factors, existing impact analysis approaches are evaluated. The most suitable approach for effect chain analysis is advanced for analysing sustainable impacts (RQ2). The approach is applied in a case example, including engineering decision regarding CO_2 footprint of a gripper for a robotic arm. The extended meta model supports engineers with traceable decision in the engineering of sustainable products. Further research will be conducted to examine the meta model in greater detail, with the objective of optimising its application in the context of the engineering process and strategic planning [39].

Acknowledgements

The authors gratefully acknowledge funding from the German Federal Ministry of Economic Affairs and Climate Action (BMWK) within the project Decide4ECO Model-based, predictive and flexible decision support in the development of ecological, circular value creation through data ecosystems (13MX002G).

References

[1] Thomas G, Paul R. C, Janine S. Green Product Design. AT&T TECHNICAL Journal. 1995.
[2] Buchert, Tom, Pförtner, Anne, Bonvoisin, Jérémy, Lindow, Kai, Stark, Rainer. Model-Based Sustainable Product Development.
[3] Gräßler I, Pottebaum J. Generic Product Lifecycle Model: A Holistic and Adaptable Approach for Multi-Disciplinary Product–Service Systems. Applied Sciences. 2021;11:4516. doi:10.3390/app11104516.
[4] Han J, Jiang P, Childs P. Metrics for Measuring Sustainable Product Design Concepts. Energies. 2021;14:3469. doi:10.3390/en14123469.
[5] Gbededo MA, Liyanage K. Descriptive framework for simulation-aided sustainability decision-making: A Delphi study. Sustain. Prod. Consum.
[6] Freese F, Ludwig A. A conceptual framework for supply chain digital twins – development and evaluation. International Journal of Logistics Research and Applications. doi:10.1080/13675567.2024.2324895.
[7] Escrig-Olmedo E, Fernández-Izquierdo MÁ, Ferrero-Ferrero I, Rivera-Lirio JM, Muñoz-Torres MJ. A framework for assessing corporate sustainability risks along global supply chains: an application in the mobile phone industry. Journal of Environmental Planning and Management. 2024;67:3244–75. doi:10.1080/09640568.2023.2219828.
[8] Zhang L, Zheng Y, Jin R, Pan S, Huang J. Considering product life cycle characteristics and industry background in environmental impact analysis and application: a case study of a television.
[9] Su D, editor. Sustainable product development: Tools, methods and examples. Cham: Springer; 2020.
[10] H. B, F B, A B. Mapping the green product development field: engineering, policy and business perspectives. Journal of Cleaner Production. 2002.
[11] DIN EN ISO 14040: Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen.
[12] DIN EN ISO 14044: Umweltmanagement – Ökobilanz – Anforderungen und Anleitungen.
[13] Goedkoop, Mark, Heijungs, Reinout, Huljbregts M, Schryver A de, Struijs J, van Zelm R. A life cycle impact assessment method which comprises harmonised category indicators at the midpoitn and the endpoint level.
[14] Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira M, et al. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess.
[15] Conor S, Cathal H, Martijn dR, Flávia dAP, James O. An end-to-end Asset Life Cycle Knowledge Graph. 2024.
[16] Bhander GS, Hauschild M, McAloone T. Implementing life cycle assessment in product development. Environ. Prog.
[17] Joséphine R, Andrée-Anne L, Samir L. Lifecycle traceability towards sustainable and circular value chains: analysis framework and state of the art in the fashion industry. IFAC-PapersOnLine. 2022.
[18] Pomp A, Jansen M, Berg H, Meisen T. SPACE_DS: Towards a Circular Economy Data Space. In: Ding Y, Tang J, Sequeda J, Aroyo L, Castillo C, Houben G-J, editors. WWW '23: The ACM Web Conference 2023; 30 04 2023 04 05 2023; Austin TX USA. New York, ACM; 2023.
[19] Arnold RS, Bohner SA. Impact analysis-Towards a framework for comparison. In: 1993 Conference on Software Maintenance; 27-30 Sept. 1993; Montreal, Que., Canada: IEEE Comput. Soc. Press; 1993.
[20] Gräßler I, Wiechel D, Koch A-S, Preuß D, Oleff C. Model-Based Effect-Chain Analysis for Complex Systems. Proc. Des. Soc. 2022;2:1885–94.
[21] Gräßler I, Wiechel D. Systematische Bewertung von Auswirkungsanalysen des Engineering Change Managements. In: Proceedings of the 32nd Symposium Design for X (DFX2021); 2021.
[22] Peng C, Xia F, Naseriparsa M, Osborne F. Knowledge Graphs: Opportunities and Challenges. Artificial intelligence review. 2023:1–32.
[23] Wang Q, Mao Z, Wang B, Guo L. Knowledge Graph Embedding: A Survey of Approaches and Applications. IEEE Trans. Knowl. Data Eng. 2017;29:2724–43. doi:10.1109/TKDE.2017.2754499.
[24] Buchgeher G, Gabauer D, Martinez-Gil J, Ehrlinger L. Knowledge Graphs in Manufacturing and Production: A Systematic Literature Review. IEEE Access. 2021.
[25] Arksey H, O'Mailey L. Scoping studies towards a methodological framework. Social Research Methodology. 2002:19–32.
[26] Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ. 2021;372:n71. doi:10.1136/bmj.n71.
[27] M Moretti, SN Djomo, H Azadi, K May, K De Vos A systematic review of environmental and economic impacts of smart grids 2017.
[28] MAP Mahmud, SH Farjana. Comparative life cycle environmental impact assessment of renewable electricity generation systems: A practical approach towards Europe 2022.
[29] Q Wang, W Liu, X Yuan, H Tang, Y Tang Environmental impact analysis and process optimization of batteries based on life cycle assessment. 2018.
[30] MA Gbededo, K Liyanage, JA Garza-Reyes. Towards a Life Cycle Sustainability Analysis: A systematic review of approaches to sustainable manufacturing. J. Clean. Prod. 2018.
[31] Chang D, Lee C, Chen C-H. Review of life cycle assessment towards sustainable product development. Journal of Cleaner Production. 2014.
[32] Basili V, Calderia G, Rombach HD. The goal question metric appraoch.
[33] Ferrari AM, Volpi L, Settembre-Blundo D, García-Muiña FE. Dynamic life cycle assessment (LCA) integrating life cycle inventory (LCI) and Enterprise resource planning (ERP) in an industry 4.0 environment. Journal of Cleaner Production. 2021.
[34] Graessler I, Wiechel D, Rarbach S. Model-based impact analysis in dynamic Systems-of-Systems. In: ; June 3.-5.; Cranfield; 2024.
[35] Lipšinić Z, Husung S, Pavković N, Weber C. Supporting circular economy strategies for design of sustainable mechatronic systems using MBSE. Proc. Des. Soc. 2024;4:2645–54. doi:10.1017/pds.2024.267.
[36] Gräßler I, Wiechel D, Oleff C. Extended RFLP for complex technical systems. In: 2022 IEEE International Symposium on Systems Engineering (ISSE 2022); October 24.-26.; Vienna, Austria; 2022.
[37] Gräßler I, Wiechel D, Roesmann D, Thiele H. V-model based development of cyber-physical systems and cyber-physical production systems. In: Lutters E, editor. 31st CIRP Design Conference 2021.
[38] Gräßler I, Bodden E, Wiechel D, Pottebaum J. Defense-in-Depth als neues Paradigma der sicherheitsgerechten Produktentwicklung: interdisziplinäre, bedrohungsbewusste und lösungsorientierte Security. Konstruktion 2023. doi:10.37544/0720-5953-2023-11-12-60.
[39] Graessler I, Pottebaum J, Scholle P. Integrated Process and Data Model for Agile Strategic Planning. In: Vajna S, editor. IDE Workshop; Magdeburg; 2017