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Achieving Circularity through LCA Integration in Product Life Cycle Management Systems

***Abstract**: Integrating life cycle assessment (LCA) into early product design is necessary for achieving environmental sustainability and circularity. Yet, it remains difficult to implement due to the complexity of design spaces, computationally expensive models, and methodological inconsistencies. This work proposes a two-level perspective on LCA integration, addressing both mathematical decision support methods and data-management workflows. The analysis demonstrates that common methods are suitable for distinct problem types and current method selection based on convention rather than suitability. Next to mathematical decision support methods, product life cycle management (PLCM) systems are examined as a holistic framework for structuring, linking, and tracing product data across life cycle stages. Combining the most suitable frameworks for both decision support, as well as data-management, environmentally informed decision making can fundamentally influence the sustainability and circularity of a product early on.*

1 Introduction

To further promote the circularity of materials and products, it is important to take appropriate measures for a successful circular economy right from the start of a product's development (Santochi et al. 2002). At the same time, it is important to prevent negative environmental impacts as early as possible (Chu et al. 2012). To this end, the iterative process of product manufacturing, usage, subsequent environmental impact analysis, and redesign should be avoided. Instead, precautions should be taken during the design phase. However, the seemingly endless decision-making options in product design not only lead to organizational difficulties, such as coordination between teams, standardization of design updates, or compatibility between data formats. Challenges also arise when performing life cycle assessments (LCA) for each decision path (Bouyarmane et al. 2019). LCA is the standard method for evaluating environmental impacts. The integration of LCA into the design phase is required to make design decisions based on the impacts each decision could have on the environment. This could concern the material selection and its recyclability potential, a product's longevity through physical design variations or the potential for repairing and replacing components, or the efficiency of a process. Depending on the complexity of the product, there may be far too many design variants to realistically perform a comprehensive LCA for each one. On the one hand, the data basis for each variant must be detailed enough to realistically represent each life cycle and its impacts. On the other hand, this high volume of LCA implementations also requires significant computing power (Greif et al. 2025). To address the problems of data-management and early decision making based on environmental influences, the different methods of integration on a mathematical and data-management level are presented here, with a focus on product life cycle management (PLCM) systems. PLCM, on the data-management level, ensures transparent collaboration between different work groups so that everyone is up to date, with access to necessary documents, models, or guidelines, and all data has already been adapted for compatibility. The state of the art in PLCM systems currently covers the disciplines of mechanics, electronics, software, and systems engineering, without incorporating any type of LCA models (Chenavaz et al. 2025). The integration of LCA into PLCM systems opens up a new basis for decision making in the product design

phase by providing information on environmental impacts linked to a decision made (Chenavaz et al. 2025). At the same time, LCA decision-making methods are being developed and evaluated at the mathematical and computational level.

This work first outlines existing approaches for integrating LCA into early product design based on a systematic literature review. The review reveals two different challenges. On one hand, decision makers require mathematical methods that allow comparing design alternatives based on environmental impacts. On the other hand, the availability, structure, and traceability of life cycle data across disciplines poses a complex data-management task. Thus, a two-level perspective on LCA integration, differentiating between (i) mathematical decision-support methods, and (ii) workflow-oriented data-management frameworks is adopted and described within the following sections, with PLCM systems as a central structuring element.

2 An overview on mathematical approaches and integration options in PLCM

2.1 Mathematical integration methods

Literature research including over 196 articles from 2000 onwards indicates the use of several mathematical methods to computationally support the decision making within the product design phase based on LCA results. Those methods concern multi-criteria discrete alternative problems (MCDA) as part of multi-criteria decision making (MCDM), multi-objective optimization problems (MOO), machine learning-based decision support (ML), simulation, and assisting surrogate models (SM). Each method is suitable for a different problem, as each method requires varying amounts of data availability, distinct degrees of detail in problem definitions, or computational effort, which also correlates with monetary properties. Taking MCDA and MOO, also known as the MCDM subcategory multi-criteria optimization problems, for an exemplary comparison, differences in required parameters, problem definitions, and computational effort can be concluded. MCDA, as the name suggests, deals with a limited, discrete, number of problem alternatives, where mainly parameters are needed for the criteria to be evaluated. Additionally, a basis for preference weighting is required, to set a foundation for subsequent criteria scoring (Wallenius et al. 2008). On the other hand, MOO does not deal with discrete product alternatives. Instead, a problem needs to be described in detail based on equations for physical properties and correlations. To constrain the subsequent calculations, parameters portray the bounds within realistic problem-specific ranges. The subsequent optimization is then carried out, searching (near-)optimal solutions within the extensively defined solution space (Belton and Stewart, 2003; Floudas and Pardalos, 2009). This search within a continuous range can quickly become an expensive task in comparison.

As products can vary in properties, data availability, or complexity, the choice of a suitable decision method is necessary. So far, decision-makers predominantly choose a decision-making method with LCA integration based on popularity or familiarity (Guitouni and Martel, 1998), even if the chosen method might not be the most suitable. Within future research, I aim to provide a guideline on finding the appropriate mathematical method for varying product types.

2.2 Workflow support and product life cycle management

In previous research, data-management for LCA integration within a product's design phase is conducted randomly without following common guidelines. Proposed frameworks aim to provide data across systems, e.g., via linking Excel tables, automated coupling of modeling software, or manual iterative extraction of data between LCA model results and mechanical models (Javanmard and Nava, 2025; Fang et al. 2024; Greif et al. 2025). For identifying hotspots or structuring a system's data, several screening tools and problem specif-

ic structuring frameworks are proposed (Li et al. 2024; Goridov et al. 2025; Cheali et al. 2015). While those methods depict a basis for design phase data-management, only a few are offering a holistic framework that is transferable onto several product types.

PLCM represents such a holistic product system-wide framework for dealing with data. The fundamental idea of PLCM is to provide correct information at the correct time in the correct data format to every person, institution, or system involved in a product's life. Most definitions of PLCM categorize it as a business activity for managing products (Stark et al. 2022). In context of integrating life cycle impact information into the design phase of a product, PLCM is viewed less from a business and more from an engineering viewpoint. This includes managing product data via product models, linking information and data across the whole life cycle for traceability and across different systems, providing a "Single Point of Truth" for the source of data, and supporting decision making through allocated information. The information for a product can be subdivided into three categories: (1) steps of a product's life cycle, (2) disciplines that describe a product's characteristics, and (3) the stakeholder network for the aspect of interest in a product. In PLCM, product data is divided into three entities, i.e., a set of articles, a set of documents, and a set of files. Those three entities are separate from each other and are not linked until the relations are added. The first linkage, 'Bill of Materials', assigns subordinate articles to their superordinate article. Each subordinate article can also consist of several sub-subordinate articles, all listed hierarchically (Eigner and Stelzer, 2009). By structuring product information consistently across life cycle stages, PLCM does not solve LCA integration by itself, but it offers the structural and organizational framework for a holistic, system-wide LCA integration in early product design.

3 Outlook and conclusion

Future work will systematically clarify in detail what each mathematical integration method requires, what their advantages and limitations are, and what product type they are most suitable for. Rather than treating methods like MCDA, MOO, or ML-based approaches as interchangeable tools, their applicability will be differentiated based on product complexity, data availability, required problem knowledge, and provided computational effort. This addresses the current state of authors mainly choosing a method for LCA integration based on popularity, familiarity, or convention instead of suitability. Next to the mathematical support for decision making, the integration of LCA into product development is limited by data availability, structure, and traceability. Therefore, a second focus, a holistic data-management support, shall be investigated. With PLCM suggested as a framework, it is mandatory to analyze data requirements, data formats, and modeling systems associated with LCA. Additionally, the timing on integrating LCA information into product design phases needs to be evaluated as well. Resulting from this, the data from and for an LCA model can be made available with the most suitable properties. In conclusion, the results indicate that by combining suitable integration methods with structured data-management enables environmentally informed design decisions at early development stages. This integrated perspective has the potential to significantly influence product sustainability and circularity before design freedom is constrained. For both, the mathematical and data-management level, the theoretical guidelines will be validated using practical case studies on fiber-reinforced polymer composites. Those composites represent an example of a problem with high design freedom, complex material structures, and challenging end-of-life scenarios. Outcomes will display the practicality of proposed method selection guidelines to support sustainable product design.

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