A Methodological Approach to Sustainable Product Development by Combining Life Cycle Assessment and Systems Engineering

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***Abstract*— Product requirements and the reduction of its ecological footprint are often in conflict with each other. However, sustainable development is seen to be important as shown by international agreements. Environmental improvement of a product, e.g., with material substitution, might change a product-significant physical parameter. Therefore, a methodology is conducted which combines the result of Life Cycle Assessment with modelling and simulation concepts to design an environmentally friendly and physically functional product. By applying life cycle impact data to different system model configurations, their results can be compared to show a more sustainable product design, mitigating global warming for example. This is achieved by linking Life Cycle Assessment to the topology of a system in a five-step method. The conducted five-step method consists of Life Cycle Assessment, hotspots, data sorting, system topology and solutions. The developed method enables the identification of materials and components with high environmental impact already in early design stages, even before the physical product exists. This allows targeted decisions for sustainable design by evaluating environmental performance alongside functional requirements at a conceptual level.**

Keywords - Modelling and Simulation; System Enginnering; Life Cycle-Assessment ; Hotspots; Stereotypes

I. Introduction

The European Commission estimates that over 80 % of all product-related environmental impacts are determined during the Product Development (PD) phase of a product [1]. To ensure that the needs of future generations are met as well as the needs of the present, a shift in current product design towards sustainable development is essential. This aligns with the principles outlined in the Brundtland Report in 1987 [2]. The decreasing of the environmental impact of PD is also relevant to the EU goal of becoming carbon neutral by 2050 [3]. Sustainability has become a requirement for companies to make conscious decisions for the design and production phase regarding the environmental impact of their products [4], [5].

In order to achieve that goal, da Luz et al. developed a five-point assessment scale. Here, the numbers say how significant the improvement of each impact category of the Life Cycle Assessment (LCA) and the Product Development phase is [4].

Besides da Luz et al. other studies have also shown that the combination of LCA and PD is one of the most powerful tools for sustainable product design. The results of the LCA of a product show which parts of the product might need improvement even before it is on the market [6].

However, an environmental improvement of a product, for example with material substitution, might change a physical parameter which is significant for the product. A new methodology is needed which combines the results of the LCA with modelling and simulation concepts to get a combination of an environmentally friendly and physical functional product. This methodology could function as a guidance for product developers.

Model-based systems engineering (MBSE) provides a structured approach to managing complex systems by utilizing models instead of traditional document-based methods. It supports the entire product lifecycle, from conception to decommissioning, ensuring greater efficiency and consistency in the development process. By integrating MBSE into Product Development, complex interdependencies can be systematically analyzed, facilitating better communication and decision-making. This approach is particularly relevant for sustainable product design, as it enables the structured evaluation of different design alternatives, including those aimed at reducing a product's carbon footprint. To achieve this, clear frameworks are essential to provide transparency and to ensure that large amounts of data can be effectively analyzed and utilized [7].

In section two of this paper, Life Cycle Assessment and Sustainable Product Design are defined as well a state-of-the-art of the current development. In section three, the conducted method is presented in five consecutive steps. Afterwards, the method is applied to an exemplary design workflow of an electric motor. The benefits and limitations of this method are pointed out, as well as an outlook for future research on the topic.

II. Literature

The state of the art of integrating resource efficiency into product development is described here.

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A. Life Cycle Assessment

Life Cycle Assessment allows to analyze the environmental and human health impact of a product from production until recycling for example. Thereby, LCA shall help to provide opportunities to improve the environmental performance at different stages of the product. Moreover, it should help to select relevant indicators of environmental parameters and to find hotspots. All in all, an LCA of a product helps to give a whole overview over the environmental impacts of a product. Furthermore, it helps to find specific components which are affecting impact categories a lot, e.g., global warming potential (GWP).

The methodology of the LCA is set in the DIN EN ISO standards (14040 / 14044) and conducts four stages which can also be found in Figure 1; goal and scope, inventory analysis (LCI), impact assessment (LCIA) and interpretation.

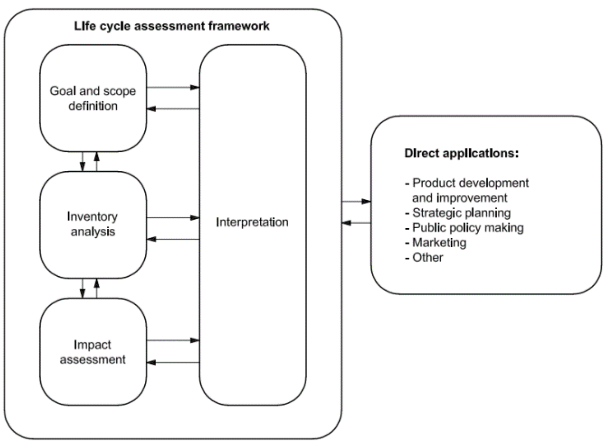

Fig. 1: Stages of an LCA [14], [15].

The first stage of an LCA is the definition of the goal and scope, as shown in Figure 1. A functional unit must be defined first. Also, the lifespan, assumptions, as well as the system boundary (e.g., "cradle to gate", "cradle to grave" ...) need to be documented. In the inventory analysis inputs and outputs of the material flows of the product are analyzed. During the impact assessment, different impact categories are evaluated by assigning equivalent emission factors to the inventory flows. Impact categories can be global warming potential or the freshwater ecotoxicity potential for example [8]. After the first iteration, the results are interpreted, and a sensitivity analysis is conducted. A sensitivity analysis helps to make a statement about the uncertainty of the assumptions supposed earlier.

B. Sustainable Product Design

According to Chang et al. Product Development can be divided into four different stages: concept design, part design, process design, and decision making.

Design stages of interest would be part design and process design because parts of these stages are material selection, waste minimization as well as identification of alternatives [9].

As mentioned by da Luz et al. [4] the PD process can be split into six different phases: planning, conceptual design, detailed design, testing / prototype, production and market launch as well as product review. Thereby, LCA is mostly integrated into the first three stages. The LCA results are analyzed with a SWOT analysis and hotspots can be elaborated. In a SWOT analysis strength, weaknesses, opportunities and threats are determined.

Hotspots are the most environmentally contributing elements inside of a product and can be identified with literature or by using the LCA-method described later. Furthermore, computer-aided design (CAD) can be additionally used not only for meeting physical or design requirements but for collecting data about material flows which are used for the LCA inputs during the LCI [10].

To get an overview of the information required for performing an LCA a table can be created which includes data about the component, the type of info required, characteristic parameters as well as indicators which are needed for the parametrization (e.g., spatial dimensions, energy balance) [11].

Baumann and Tillmann [12] offer a solid overview of the general life cycle assessment methodology and its application in product comparisons. However, their work is more about standalone life cycle assessments and does not show how life cycle assessment can be effectively connected with the actual product development process, especially not in a digital or model-based way.

Suh and Hwang [13] take a step further and present a design for environment (DfE) framework. They emphasize the integration of environmental considerations, including digital tools or simulations that could help to understand the physical impact of environmental changes on the product performance.

The method presented in this work aims to combine the results of the life cycle assessment directly with modeling and simulation techniques based on MBSE. By doing so, the impact of design changes can be evaluated not only in terms of sustainability, but physical performance as well. This helps to find a better balance between environmental improvements and technical functionality.

III. METHOD

To pursue a more sustainable development, ecological effects of a product need to be considered in its design phase already. However, combining a sustainable design with the physical requirements of a product can be challenging. Therefore, a new method was developed in this study to address this issue, which makes use of connecting Life Cycle Assessment and system modelling. The priority of the conducted methodology is the combination of design and resource conservation on a physical level.

Fig. 2: Overview of the five-step method

The connection is needed to bridge the gap described and to ensure a more sustainable Product Development which includes the design phase and environmental data. The method (see Fig. 2) is divided into five distinct steps.

A. *Initial LCA*

In the preliminary stage of the process, a Life Cycle Assessment is conducted on a specific component of the product, for example, the stator or rotor of an electric vehicle. This may be accomplished in accordance with the DIN EN ISO 14040 and 14044. Firstly, the objective and purpose of the product are established, the so called goal and scope. It is important to emphasize that the functional unit (FU) of the product must be identical to the FU of the improved product in the third working step. It is also critical for the Life Cycle Assessment and step 4 of the methodology to set the system boundaries, which means it must be defined which system boundary, e.g., cradle to gate, is being observed. Once the goal and scope of the product have been established, the materials utilized in its construction must be identified through the analysis of primary or secondary data sources. Subsequently, the LCA can be conducted in an LCA program, such as LCA for Experts or OpenLCA [17]. This allows for the identification of components that exert a significant influence on the ecological footprint of the product. It is also important to note that the chosen impact assessment method, e.g., CML or ReCiPe, affects the results.In the conducted LCA, different impact categories are selected such as the global warming potential (GWP) or the freshwater ecotoxicity potential (FAETP), which are important according to the set goal and scope of the analysis.

B. *Working out hotspots*

In the subsequent step, the results of the Life Cycle Assessment are subject to rigorous examination and analysis. Subsequently, the results of the various impact categories must be tabulated in order to ascertain which flows and components of the selected product exert the greatest influence within the respective impact categories.

However, this stage often results in the identification of numerous specific areas of concern within each impact category. In this process, the most significant hotspots with the highest environmental impact of the product must be identified.

Should the relevant hotspots be selected, assumptions must then be made regarding material substitution or reduction. Such assumptions may be based on existing literature or on new ideas. It is crucial to ensure that all assumptions are adequately justified and documented.

For instance, material substitution or the alteration of a component’s weight, which has a significant impact on the overall assessment, can serve as a novel data point for the enhanced Life Cycle Assessment in the third phase of the process.

C. *Data sorting*

In the third step of the shown method a second LCA is conducted based on the assumptions and materials substitution, depending on the goal which must be achieved.

For the second LCA, the material data or masses are changed for processes linked to relevant hotspots. Thereby, it is crucial that the improved LCA has the same FU and selection of impact categories as the original LCA.

After the improved LCA is conducted the results are tabulated in the same way and in the same order as in the original LCA. It is important for further steps that the results must be stored in a certain way, this can be done with separate tabulations, for example. These tabulations can be used to change relevant physical parameters in the chosen simulation software.

Furthermore, it can be quantified which components of a product have the highest impact. Either the chosen components can be analyzed more individually or the whole LCA, this depends on the determined goal and scope of the product. In the following steps, it will be identified how the changes affect the environmental impact of the product.

D. *System topology transfer*

The generated information, which are conducted in step three, are transferred to a system topology. The goal of the topology is that the impact categories can be used and assigned as stereotypes for technical components. The fourth step entails the utilization of modelling and simulation software. In the selected software, the topology of the product or the selected components must be implemented.

As part of the methodology, several codes are developed, which are key elements in the subsequent process. At the start, the topology is modelled, which resembles the old state of the product to be improved.

Second, a program is run which assigns the tabulated LCIA-data to the respective components in the topology. This can be done by allocating impact categories in the form of stereotypes. Stereotypes can be used to allocate special properties to components.

The stereotypes can be divided into the different life cycle phases of the product. For each phase the impact is given as LCIA data. Subsequently, the resulting sum of environmental impacts is stored, e.g., in a file format, to compare it to the results of other topologies.

This format must be uniform for comparison. The process is repeated for the improved system topology.

Once the new environmental impact has been summed up and stored, it can be contrasted.

The comparison is accomplished by a final code, which is parametrized by the two results of the previous actions.

The output of this function should contain numerical or graphical information about the relative improvement between the old and improved system.

E. Finding Solutions

In the last step of the conducted method the results are shown in a table, which can be seen in the example of section four in this paper. The table is relied on the Degree of Improvement (DI) of da Luz et al. [4].

The DI is based on the results of the first conducted LCA compared to the results of the improved LCA. The DI is calculated with the following equation (1):

$$DI = (\sum \text{Value obtained in the matrix}) \,/\, (\sum \text{maximum matrix sore}) \times 10 \quad (1)$$

The number 10 is the maximum number that the DI can achieve. The higher the DI, the better the improvement achieved. The results of each phase are colored, indicating in which impact category of the LCIA an improvement was achieved the most.

IV. EXEMPLARY APPLICATION

In the following section, an exemplary application of the method presented above is demonstrated. For this purpose, a simplified model of an electric motor is created.

A. Initial LCA of a PMSM

To perform an initial Life Cycle Assessment, a permanent magnetized synchronous motor (PMSM) is modelled inside the LCA software LCA for Experts ® [18]. The system components are determined and weighed according to an open source LCA-study [12], meaning that secondary data is being used instead of taking own measures for primary data. Since the secondary data and the associated LCA are performed with different LCA software, comparative flows and materials are used if the original are not included in the GaBi ® database [20]. Once the system is implemented in the LCA software and the masses are set based on the functional unit, the life cycle impact assessment (LCIA) can be calculated using the GaBi ® database [20] for further processing.

B. Identification of hotspots

Next up, the hotspots of the LCIA need to be identified. In the case of using LCA for Experts ® [18], this could be seen in resulting diagrams. Another way to reveal impactful components can be to research the topic and see if other LCAs have been conducted for similar and comperable technologies. It is important to note that these results must be detailed, because without good information about the impact of different components of the analyzed product, it is difficult to identify hotspots.

In this example, the rotor and stator are seen as impactful system parts. The rotor is resulting the highest impact category values and the stator is chosen as a way to demonstrate another interchangeable component, e.g., in the form of reducing copper wiring. For the comparison of the LCIA-results later, the material inputs of the components with the highest impact are changed to new input materials for the following comparative LCA. The aim is to see if the change made a difference to the LCIA results.

C. Sorting the LCIA data

Subsequently, the LCA needs to be re-done for the identified hotspots and the associated changes which are made, e.g., material substitution. In the conducted example shown in this study, this step is simply displaced by varying the LCIA data by a random factor for demonstration purposes. In reality this would of course be done by performing another environmental Life Cycle Assessment based on the identified hotspots of step 2 of the methodology to evaluate real recommendations for action.

This step is essential for the linkage between the LCA data and the system model. The LCIA results need to be filtered and sorted, consisting of the classification of processes inside of the flow diagram in LCA for Experts ® [18] into several groups. A group could be one component of the product, for example, the rotor production or the rotor operation, including detailed impact assessment results.

Each group of processes matches a phase inside of the life cycle of the product. The values for the components and corresponding phases are separated and stored individually in different tables to be easily read by a script.

The choice of phases depends on the set functional unit and system boundaries. In this case the system boundary is set to cradle to gate which means, in the case of this demonstration, that two phases were distinguished: Base material acquisition and production. Drawing boundaries between phases is not always easy, however, so discussing it is recommendable.

D. Adapting LCIA data to the system model

After having drawn the system boundaries and assessed the life cycle impact, the data is applied to the topology of the electrical machine. The modelling has been examined in MathWorks ® System Composer [16] and is shown in Fig. 3.

As the stator and rotor were set as hotspots, they have been assigned as variable components. In this case, two variables, namely A (e.g., the original copper winding) and B (e.g., an optimized aluminum winding), have been chosen as demonstrative alternatives.

The Profile Editor was used to declare stereotypes.

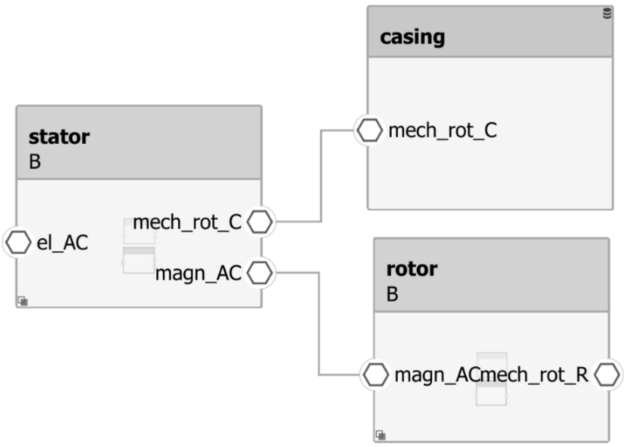

Fig. 3: PMSM model with applied stereotypes shown in System Composer [16]

Impact categories are assigned from the CML 2001-2016 method [19]. The connection between the system topology and LCIA is important to harmonize the technical requirements and the ecological footprint for example. The systemic linking of physical parameters to the LCA must be integrated into the general process for creating system models. The aim should be to optimize proven MBSE methods or to develop new methods [13], [14].

E. *Evaluation of possible solutions*

After calculating and simulating the conducted product in step 4 of the methodology the so-called DI is calculated with equation (1) in chapter III E.The equation is performed with a specialized MATLAB-code which calculates the DI and includes the results into a table which shows a color coded degree of improvement in each analyzed impact category of the LCIA. Figure 4 shows the table of improvement, the darker the impact category the better the improvement.

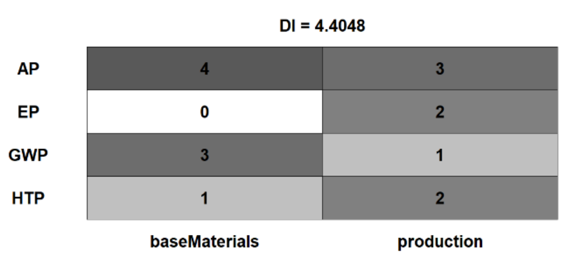

Fig. 4: Exemplary diagram of the degree of improvement (DI) based on [4]

For the case that data should not be available, it could be indicated by a separate color.

The table is divided into the two phases of the system boundary: base material acquisition and production. It is crucial to examine various phases to gain comprehensive understanding of the potential impact of improvements.

For instance, improvement in one impact category may be beneficial in the initial phase but may not yield the same results in the subsequent phase. The production phase for example could be enhanced to reduce the human toxicity potential (HTP) without affecting the GWP as much.

Ultimately, the table presents potential avenues for further enhancements to the LCA, which means the methodology can be repeated until the desired outcomes are attained adequately.

V. BENEFITS AND LIMITATIONS

The method conducted brings a lot of benefits but also some limitations which will be discussed in the following section. A significant advantage is that the methodology can be employed even in the absence of carrying out an LCA. A sufficient basis for the analysis can be provided by literature that includes detailed LCA results and allows the identification of hotspots.

Furthermore, while familiarity with the process of conducting an LCA is advantageous, it is not a prerequisite for success. This may be an advantage in the Product Development sector, where the methodology of an LCA is not widely disseminated. It is only necessary to possess knowledge of the LCA methodology if primary data pertaining to a given product is available and secondary data is not sufficient enough for the analysis. In such instances, the creation of a new LCA may be required and a comprehensive understanding of the subject matter would be indispensable. To facilitate a comparison between the enhanced LCA and the original LCA, one may utilize a calculation program, potentially relatively inexpensive in comparison to the cost of an LCA license.

The methodology enables the identification of environmental hotspots associated with a given product, facilitating a comparison with an improved product if the latter exhibits a reduced environmental impact relative to the former. The methodology employed is limited in that it requires both familiarity with modeling and simulation software and knowledge of how to write code in MATLAB ® [16] for the DI. Another limitation of MATLAB ® [16] is the necessity of a license, which is also a costly requirement. Furthermore, it has been necessary to enter all the analyzed stereotypes into the System Composer [16] tool, which has also required a significant investment of time. The primary reason for selecting System Composer [16] is that the program offers a user-friendly yet effective modeling environment for complex systems.

In conclusion, the conducted method presents a greater number of advantages than limitations, as it outlines the process of environmental development and improvement.

VI. CONCLUSION AND OUTLOOK

The methodology presented offers a way to integrate Life Cycle Assessment into the design phase of a product. This linkage can allow for uncovering weak points in terms of the

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environmental impact of certain components and ideally indicates in which life cycle phases improvements are most helpful. The process of doing the LCA, identifying hotspots (and possible enhancements), sorting the data and applying it to an interchangeable system model could potentially be adapted into the workflow of common system engineering.

However, there are a few challenges. Currently, the integration process is not automated. The manual steps required to import, process, and export data add complexity and time, which limits usability in early design phases. Automating the workflow and linking LCA data more directly with system modelling tools (e.g., MBSE environments or digital twins) would enable more efficient ecological comparisons between system configurations.

In future work, the methodology will be extended by coupling it more closely with physical simulation models, allowing environmental impacts to be assessed in parallel with technical performance indicators. This would create a combined framework where engineers can directly evaluate the trade-offs between sustainability and stem functionality during early design and development decisions. For doing so, the variations made to the hotspot-components need to be linked to the physical parameters in the simulation software. This involves further research on how changes to the material or mass fractions affect the physical characteristics of the analyzed components. Applying an improved version of the method to real-world cases across different industries will help to validate its scalability. However, automation is crucial for integrating it into a product development process. Ultimately, this would allow for easier access to ecological comparisons between system topologies.

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