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Development of a Methodology for Containment of Solution Spaces to Identify Eco-Friendly Product Concepts

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Abstract

Recently, awareness of environmental issues like resource scarcity has increased sharply. Consequently, governments and international organizations have enacted regulations, prompting companies to establish sustainability targets. In the concept phase of product development, foundations are laid for the product's environmental impact. However, assessing these impacts is challenging due to insufficiently specified product details especially in the early development phase. The aim of this approach is to develop a method for breaking down ecological sustainability targets into product concepts and to narrow down the solution space in order to support decision making in early development stages towards reaching regulatory sustainability targets.

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1. Introduction

As a result of increasing environmental problems such as water scarcity and climate change, six of the nine planetary boundaries, which indicate the Earth's safe operating range, have already been exceeded [1]. Simultaneously, social support for climate protection measures is growing. 69% of the people stated that "they would be willing to contribute 1% of their household income every month to fight global warming" [2]. To respond to social pressure and address environmental problems, the United Nations has formulated targets for responsible consumption and sustainable industrial production in recent years [3]. The EU aims to be climate-neutral by 2050 and to reduce GHG emissions by 55% until 2030 [4]. Also from 2025, the Corporate Sustainability Reporting Directive (CSRD) will become active, which will enable better verifiability and more consistent presentation of non-financial data from industrial companies [5]. To comply with the newly formulated laws and regulations, it is essential to examine during product development. It is estimated that around 80% of

a product's environmental impact is determined in the early phases of the development process [6]. The concept phase, in which the product architecture as well as technical solutions are largely determined, makes it possible to influence performance in various sustainability dimensions [3]. Tools for determining the environmental impact of products can aid in meeting the emerging demands for more sustainable products [7].

The consideration of sustainability aspects in early development phases entails three significant hurdles. The additional consideration of requirements regarding the sustainability of products increases the complexity of the development process and promotes the occurrence of unexpected side effects [8, 9]. Furthermore, the lack of time and data limits the selection of technical solutions. Finally, the communication and evaluation of a products sustainability is difficult for developers today [10]. In order to tackle these hurdles and identify the environmental impacts of design decisions in the early development phases, new methods and tools are essential [11]. Only by considering all the environmental impacts of a product during its various life

phases, sustainable and resource-efficient products can be developed [12]. Existing methods usually only focus on the selection of individual technologies and do not allow the evaluation of the complete product. Furthermore, it is difficult to integrate company-specific sustainability targets and corresponding key figures into existing approaches. However, if technical solutions could be evaluated in terms of different environmental aspects, it would be possible to efficiently select technical solutions under prevailing uncertainty in early development phases. With help of a limited solution space, the existing solutions can be developed in a more targeted manner. This requires a systematic approach to linking sustainability goals with different technical solutions.

The aim of this paper is to develop a methodology that allows companies to evaluate technical solutions in different sustainability categories. Thus, a procedure is presented that enables the decomposition of ecological sustainability goals to narrow down the technical solution space. After an initial introduction, the second section provides an overview of relevant terminology. Existing approaches are then presented, and the theoretical deficit explained. Afterwards, a three step concept for narrowing down the solution space is introduced. Finally, the last section contains a summary and an outlook that highlights the need for further research activities.

2. Relevant Terminology

This section deals with the definitions and terminology required for the understanding of the key figure-based analysis of the ecological environmental impact of product concepts. After the basics of concept development have been described, important aspects of sustainability assessment are presented.

2.1. Concept development

In the concept phase of the product development process, alternative solutions are developed and combined with help of morphologies [13]. The key to the development of complex products is based on a transparent description of the product architecture [14]. It consists of the function as well as the product structure and the transformation relationships that link functions with technical solutions [14, 15]. As the two structures are usually developed in parallel, the transformation relations are defined iteratively [16].

Once a basic understanding of the function is available, the associated partial solutions are developed in form of technical solutions. These consist of the combination of the physical effects and the material and geometric characteristics [6]. The set of all potential technical solutions forms the solution space, which describes the freedom regarding the development of the overall solutions [17]. To open the solution space, suitable technical solutions are sought based on the main function. These are analyzed with regard to their functional context in order to deduce further sub-functions and associated technical solutions [6]. The derived functions are directly linked to customer requirements. This is why the function-oriented development of technical solutions helps with the efficiently targeted development of products in the early development phases. It helps to focus the needs of the products users [18].

2.2. Measurement of sustainability targets

Sustainability is understood as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [19]. The concept of the development of sustainable products consists of three components. It must be ecologically compatible, economically efficient and socially equitable [20].

To achieve sustainable development, the UN formulated 17 goals in 2015 - the Sustainable Development Goals (SDGs). These are specified by 169 targets and 270 indicators and addressed with the help of reporting by industrial companies [21]. In the area of sustainable corporate processes, the European Sustainability Reporting (ESR) standards provide an overview of the standardized reporting format. They specify the information required in the Corporate Sustainability Reporting Directive in an application-oriented manner [22]. The Global Reporting Initiative (GRI) standards (famous Non-Governmental Organization) are often used to make compliance with the ESR Standards measurable. These help companies to answer the question of how to report [23].

Both standards use measurable indicators that describe a specific condition of a company or also a product [24]. Thus indicators enable the observation of certain developments and make the degree of target achievement quantifiable [24, 25]. The quality of indicators is guaranteed as long as they are relevant, accepted, credible, easy to measure and robust against manipulation [26]. In order to create a holistic picture of a situation, it is necessary to combine individual indicators into a set [27].

3. State of the art

This section describes existing approaches that focus on solution spaces, the decomposition of sustainability goals and the evaluation of sustainable concepts. In addition, the identified research gap is described. Solution spaces describe technical solutions systematically and make them comparable. Two examples, that can be used for systematic solution finding, are the “the model space of design” and the “Munich Product Concretization Model” (MKM) [17]. Both models visualize how requirements can be systematically transferred to the design level and are shown in figure 1.

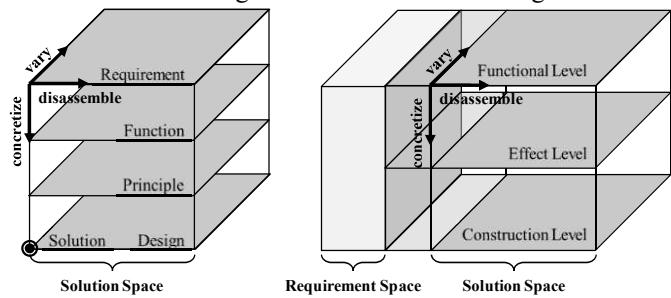


Fig. 1: Model space of constructing (left) and MKM (right) [17]

They enable a multidimensional view of the technical solution space and support the specification of technical products. The product architecture can be developed step by step through variation and disassembly. Other approaches like the morphological box according to ZWICKY are also used for the

systematic description and comparison of solution concepts [28]. It assigns technical solutions to the sub-functions to be fulfilled in a matrix [17]. BUCHERT ET AL. follow this approach and use the separation of functions and solutions to enable systematic configuration. Technical solutions, which can be described by different function carriers, are assigned to different functions [3]. Thereby BERTONI ET AL. [7], BUCHERT ET AL. [29] and OMODARA ET AL. [30] all use quantitative and qualitative criteria to specify technical solutions to make them more comparable and thus support decision-making in the concept phase. The specification also covers the various phases of the product life cycle [7]. The approaches show that the evaluation of solutions should be carried out based on characteristics that correlate with environmental impacts to systematically narrow down solution spaces and configure products to be ecologically sustainable.

There are many approaches to examine environmental impacts in early stages of development [31]. The sustainability targets set must be made measurable so that the degree of implementation can be continuously monitored [8]. A frequently used method for the systematic decomposition of goals is the X-matrix of the Hoshin Kanri methodology. It enables the planning of strategic changes with the help of the targeted linking of targets, resources and key figures [32]. BUCHERT ET AL. present a multi-step procedure in their approach to be able to transfer sustainability goals to technical solutions and then compare them. Selected functionalities are assigned target areas of sustainability indicators and the results are visualized graphically [3]. SINGH ET AL. also use a systematic breakdown of objectives into criteria and sub-criteria to select the best solution alternative in a goal-oriented manner. The strategies are implemented by dividing the objectives into four levels [33]. The approaches examined show that the implementation of strategies in the form of goals should be supported by the systematic decomposition of objectives into several levels.

The evaluation of solutions based on different characteristics in early development phases is another relevant problem when narrowing down solution spaces. According to BUCHERT ET AL. it is necessary to structure information within a product family, in order to make development information comparable and therefore assessable [3]. One method of implementation chosen by SCHULTE ET AL. is the use of graduated scales. These comprise ten levels for classifying opportunities and risks with regard to sustainability [34]. A comparable approach is the Sustainable Compliance Index with five levels presented by HALLSTEDT ET AL. It can be used to evaluate various product characteristics from different life cycle phases [35]. The Sustainability Fingerprint Tool presented by HALLSTEDT ET AL. has a special feature that also enables the qualitative assessment of different characteristics from the production, use and end-of-life phases [36]. The approach of HEHENBERGER ET AL. resorts to a normalization of results to be able to make results better comparable. For this purpose, all evaluated characteristics are scaled with a reference value and the best alternative is then selected [37]. How the importance of elements within the product architecture can be described in this context is presented in the approaches by BÖCKIN ET AL. [38] and RUIZ-PASTOR ET AL. [39]. On the one hand, the relative importance of functions can

be derived from the number of components involved in the specific function [39]. On the other hand, the importance of individual components can be based on the respective component mass [38]. The analyzed approaches show that the combination of qualitative and quantitative key figures is necessary while analyzing environmental impact. Mechanisms should be found to normalize and weight values to ultimately identify the best solutions in a solution space.

The analysis of existing approaches shows that the use of solution spaces simplifies the comparison of technical solutions. The analyzed approaches rarely make use of elements of the functional and solution structures that are essential for the development of complex products. For this reason, evaluations are mostly of a qualitative nature and decisions are difficult to comprehend. It also becomes clear that an evaluation of solutions regarding various sustainability criteria is only possible if product concepts are specifically described. To this end, various ways of describing concepts qualitatively and quantitatively using characteristics and features are presented. The systematic linking of the technical solution with focused development goals does not take place in the approaches analyzed. Most approaches merely concentrate on the optimization of individual components regarding various sustainability goals or focus on the use of different sustainability goals without transferring this to the technical solution space. An assessment of environmental impacts is also not carried out in the approaches presented.

4. Concept for the Methodology

The approaches presented show that a holistic methodology is needed that enables a systematic narrowing down of solution spaces, considering sustainability goals in the early phases of product development. To this end, the solutions must be described in a standardized way using characteristics and features to assess specific environmental impacts and select the most sustainable solution regarding the goals set. Therefore, the central research question in this article is stated as follows: *How can the technical solution space be systematically narrowed down in the early phases of product development with reference to ecological sustainability?*

To answer the main research question, a concept with three sub-elements is presented, which is shown in figure 2.

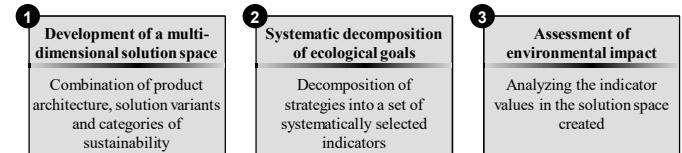


Fig. 2: Visualization of the three-step approach

The first element focuses on the description of technical solutions in a multidimensional solution space against the background of sustainability assessment. The second element is a procedure for systematically transferring sustainability goals to parts of the solution space. The third element comprises the evaluation of the solutions based on the characteristics and features as well as the presentation of the approximated environmental impacts of a product concept.

4.1. Development of a multidimensional solution space

To enable a simple evaluation of different possible solutions, a precise classification of concepts into a solution space must be carried out. The dimensions must be specified in an application-oriented manner so developed technical solutions can be systematically examined. Therefore, a solution space with three dimensions is proposed as shown in figure 3.

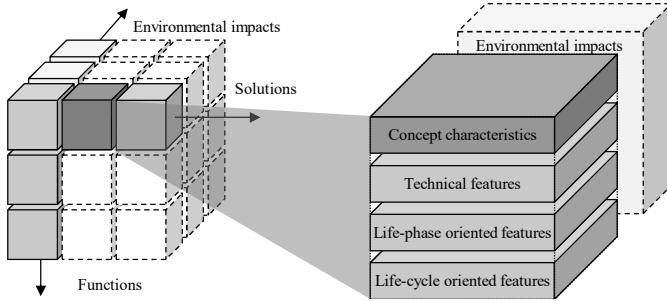


Fig. 3: Developed solutions space (left) and solution elements (right)

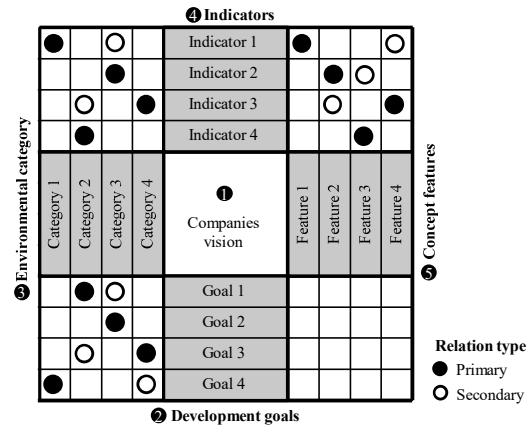
The front of the solution space allows the combination of technical solutions into an overall solution concept that is aligned with the required functions [28]. The third dimension enables the evaluation of technical solutions regarding their environmental impacts. The result is a solution space linked to functions, which contains a detailed description of the technical solution (represented as a cube on the first level) and can be evaluated using indicators. For this purpose, the technical solutions are specified on different levels in accordance with BUCHERT ET AL [11]. These enable the amalgamation of technical characteristics into features that can be evaluated using selected indicators and provide a holistic approximation of the environmental impact in the products life cycle. The four levels at which the solutions are evaluated are: concept characteristics, technical features, life-phase oriented features and life-cycle oriented features. While life-phase oriented features focus on the efficiency of an individual phase, life-cycle oriented features are aimed at closing material flows in the sense of a circular economy.

Within the various layers, the solutions are described using characteristics and features to enable a characteristic-based assessment of environmental impacts. At the concept characteristics level, there are three categories for describing the product concept, which are based on the three elements of a technical solution: the physical effect, the material and the effective geometry. The physical effect can be determined using system analyses and determines the transferring characteristics of the technical solution. The material is specified by material characteristics. Various analyses can be used to determine the according characteristics such as modulus of elasticity or density. The effective geometry can be described by geometric characteristics (e.g. volume) and production-related characteristics (e.g. production complexity). The concept characteristics described can be aggregated into three categories at the level of technical features. In addition to efficiency-related features (e.g. efficiency), material-related features (e.g. stiffness) and connection-related features (e.g. connection type) are also specified. The technical features are in turn assigned to the

various life cycle phases at the level of life-phase oriented features. On this level the raw material extraction, processing, manufacture, use and end of use are described. The end of life is described using qualitatively estimated life-cycle oriented features in the form of circular economic potentials. The systematic aggregation of characteristics and features is pursued with the help of characteristic hierarchies. These combine the values of characteristics with a weighting factor and summarize them on the level of life-phase-oriented features. For example, the features manufacturing effort and assembly effort result in the production effort of a technical solution. The assembly effort is influenced by the characteristics contour complexity, dimensions and the selected connection type.

4.2. Systematic decomposition of ecological goals

Due to the increasing requirements regarding sustainability reporting, a consistent and systematic approach to corporate goals is essential. To link these with facets of the solution space to develop a product in line with the overarching sustainability goals, a process is presented below. The most important step in this process is goal decomposition which is carried out using an X-matrix shown in figure 4 and comprises five steps.



Content and relationships are entered in the X-matrix in a

Fig. 4: X-Matrix to systematically decompose sustainability goals

clockwise direction to derive effects on various aspects of sustainability. Firstly, the guiding corporate vision is recorded at the center. Afterwards, development goals are formulated, which must be specific, measurable, ambitious, realistic and time-bound [32]. Subsequent, the transfer to the sustainability categories takes place and indicators that serve to further specify the environmental categories are selected. The last step involves linking the selected indicators with the concept features from the introduced solution space.

In the third and fourth steps, the GRI Standards are used for the selection and description of the indicators to comply with the required reporting format. Within the structure, a distinction is made between universal standards and thematic standards, which includes an economic, environmental and social category [23]. This paper focuses on the categories of materials, energy, water, biodiversity, emissions and waste in the ecological dimension. Within the categories, the GRI

standards provide 29 different indicators. Each indicator and its measurable key figures are described precisely [23]. As not all indicators have the same relevance, they are categorized into two different classes in the present work, which enables better trade-off decisions regarding the solution selection. While primary indicators are directly influenced by the solution concept, secondary indicators only have a subliminal effect. The focus of the concept evaluation can be determined by the user through the selection of indicators as required.

The following example illustrates how the X-matrix is applied. A machine manufacturer's goal is to reduce water consumption. This goal primarily concerns the category of water, which is linked to the selected indicator "water consumption". This is primarily linked to the feature "production phase". A secondary way to reduce water consumption is to consider the material category. It can be linked to the indicator "materials used by weight or volume". This indicator is particularly relevant to the feature "raw material extraction". The example shows that the method enables a systematic transfer of the objectives to individual characteristics of the solution space.

4.3. Assessment of environmental impact

To select product concepts that meet the sustainability goals, limit values must first be defined for the technical solutions that fulfill the required functions. These can then be compared with the determined evaluation and the solutions that fall outside the limit values can be eliminated to specifically narrow down the solution space. For this purpose, the importance of the system's functions is determined in accordance with RUIZ-PASTOR ET AL. and then linked to the chosen sustainability indicators as shown in figure 5 [39].

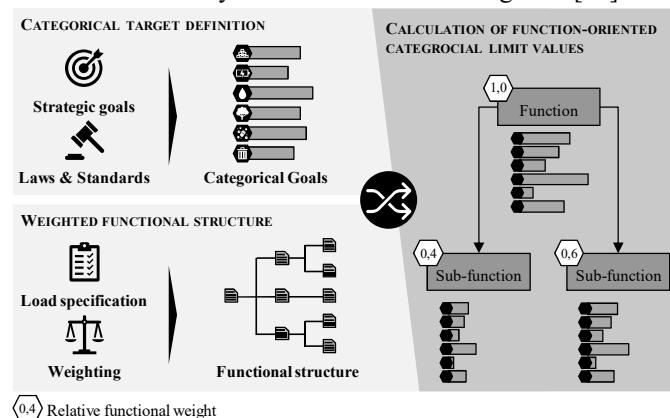


Fig. 5: Calculation of categorical limit values

As a result, technical solutions that fulfill critical functions may cause more environmental impacts than non-critical components. In contrast to the approach presented here, the functional importance is not derived on a component basis but based on the requirements or functionalities demanded by the market. Using the hierarchical representation of a functional structure, the functions can be weighted according to the relevance of the requirements to be fulfilled. The weighing process starts with the overall function and is carried out systematically. Additionally, a function-specific threshold for each indicator is set and thus the associated technical solutions

can be calculated. In combination with the weighted function structure, this forms a limit value for each technical solution, considering the environmental categories.

In the next step, the solution concepts are evaluated based on the features and properties introduced in the solution elements and compared with the limit values. The characteristics are specified with the help of data sheets, CAD data and qualitative estimates. The precise evaluation of the individual technical solutions, considering qualitative and quantitative values, is a complex problem. A starting point, for example, is the comparison of individual solutions with reference components that have been evaluated in detail. The specific evaluation of individual technical solutions will be addressed and detailed in later research projects. The characteristics are then aggregated at the feature level and finally linked to the indicators via the X-matrix. In this way, the environmental impacts in the different categories can be approximated and compared with the defined limit value as shown in figure 6. The figure shows the evaluation of the function-oriented technical solutions using one indicator out of the emissions category. The other categories are indicated in the foreground and background. If all solutions exceed the limit value, as is the case in the second row, the best solution should be selected after careful consideration of the alternatives.

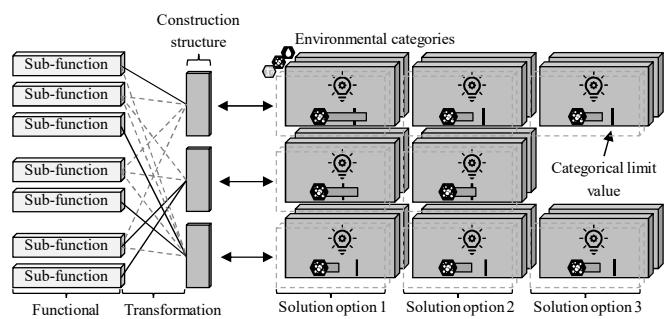


Fig. 6: The visualization of environmental impact in the solution space

The proposed approach allows a multifactorial comparison of technical solutions and highlights the respective strengths and weaknesses to be able to systematically narrow down the solution space and select the best possible product concept.

5. Summary and Conclusion

This paper presents a methodology that enables a comparison of product concepts with consideration of environmental sustainability. To this end, an approach is presented on how corporate goals can be systematically used to narrow down solution spaces in early phases of product development considering sustainability reporting.

Therefore, in step one, a solution space is presented that enables the classification of technical solutions. In addition, a model is presented that can be used to describe concepts in a standardized way, enabling the transfer of concept-specific environmental impacts. Step two shows a procedure that enables the systematic decomposition of strategic corporate objectives regarding sustainability. This allows objectives to be transferred to individual characteristics of technical solutions. In addition, environmental categories and indicators are defined that describe product concepts in different categories

of environmental impact. It also describes how solution-specific limit values can be defined and how these can be systematically applied to the solution space. The third step focuses on the evaluation of alternative solutions in the established environmental categories. It shows how evaluated solution alternatives can be represented in the solution space that can then be systematically narrowed down.

The proposed approach provides fundamental support for developers in manufacturing companies in early development phases. In comparison to existing methodologies for evaluating sustainability, conclusions regarding the environmental impact can already be drawn during early phases of product development. In the future, the derived content will need to be further detailed and validated using practical examples. Particularly data-based decision-making in early development phases is part of the authors' current research activities.

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