SUSTAINABLE DESIGN EVALUATION – INTEGRATION OF SUSTAINABILITY IN PRODUCT DEVELOPMENT PROCESSES

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ABSTRACT

To develop sustainable products, product developers must be able to incorporate sustainability into individual decision processes during product development. In doing so, they are faced with the conflicting demands of time and cost pressure and the growing complexity caused by the many requirements and (sustainability) criteria.

The Sustainable Design Evaluation, which is presented in this publication, is a method to enable product developers to estimate the impact of their product-related decisions along the three dimensions of sustainability across all phases of the product life cycle. The core of the Sustainable Design Evaluation is a two-stage assessment technique enabling a relative and comparable quantification of ecological, economic, and social criteria. Furthermore, an aggregation scheme for those criteria is introduced. Based on the two-stage assessment technique and the system of aggregation, the results of the Sustainable Design Evaluation can be displayed clearly and interpreted easily by product developers to assess the impacts of their product-related decisions.

Thus, in contrast to existing methods, the SDE combines ease of use and interpretation with a sufficiently holistic sustainability assessment.

Keywords: Sustainability, New product development, sustainability assessment, Decision making

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1 INTRODUCTION

Sustainability is one of the most current topics in business, politics, science and society. With Agenda 21 and Agenda 2030, two internationally recognized target agreements were made to come closer to the state of sustainability through concrete sustainable development goals (UN General Assembly, 2015). The 2030 Agenda is still in force today and calls on all social actors, including companies, to act.

Companies have a strong direct and indirect influence on the environment and the world around them (Grunwald and Kopfmüller, 2012). Therefore, the scope of companies' actions is large and extends beyond their company boundaries (Hochmann and Pfriem, 2018). To achieve the socially agreed sustainability goals, companies must also assume responsibility beyond legal requirements (Hanusch, 2010; Bras, 1997; Luttropp and Lagerstedt, 2006; O'Hare *et al.*, 2015; Loew *et al.*, 2004; Schreck, 2015; Carroll and Buchholtz, 2003; Suchanek, 2012).

For companies that develop and/or manufacture products, aiming for ecological, economic and social sustainability means that not only the company's structures, but also its products must be sustainable. To develop sustainable products, sustainability must be integrated into product development processes of companies (Birkhofer *et al.*, 2012; McAloone and Bey, 2009).

Product developers play a central role in the development of sustainable products. Decisions made or initiated by them within the product development process have great influence on the impact of the product on the environment in all three dimensions of sustainability and all product lifecycle phases. (McAloone and Bey, 2009; Herrmann, 2010; Birkhofer *et al.*, 2012).

In order to be able to evaluate the impact of a (future) product on the environment in decision-making processes during product development, suitable criteria are needed and must be made available to the product developer (Franz, 2021).

In this paper we follow the definition of Franz for sustainable products: a (future) product can be considered sustainable when the negative impacts of the product on the environment are below the maximum permissible and tolerable value (Franz, 2021). This definition is also consistent with Rockström's concept of Planetary Boundaries and Raworth's Doughnut Economy (Rockström *et al.*, 2009; Raworth, 2012).

A risk when considering the sustainability of a product is the "shift of burdens", that is, the effect of an optimization of a certain product criterion or life phase which leads to a deterioration in other, possibly not considered, criteria or life phases. This can lead to a situation where, despite the optimization of one sustainability criterion, the resulting product is overall less sustainable than the previous product version (Finnveden *et al.*, 2009; Markard *et al.*, 2014). Boks and Stevels also describes life phase thinking as a basic prerequisite for integrating sustainability into product development processes (Boks and Stevels, 2007).

Combining the results of Franz (2021), Finnveden *et al.* (2009), Markard *et al.* (2014), Boks and Stevels (2007), Raworth (2012) and Rockström *et al.* (2009) a sustainable product must therefore fulfil minimum requirements in a sufficiently large number of sustainability criteria from all three dimensions of sustainability in all phases of the product life cycle.

This places product developers in a field of tension between the growing cost, time and flexibility pressures (Trantow *et al.*, 2011) and the increasing technical and legal complexity of products, which grows even further through the inclusion of sustainability criteria (Eigner, 2021). Product developers are thus confronted with the multifaceted challenge of balancing a large number of factors and criteria against costs and time (Luttropp and Lagerstedt, 2006). They must weigh up a multitude of criteria in a complex situation, which have a massive influence on the characteristics of a product in all three dimensions of sustainability. Thus, to incorporate sustainability into product development processes, a method is needed to enable product developers to make decisions regarding the environmental impact of the product they develop.

Therefore, in this paper multidimensional requirements for such a method were extracted from the literature and discussed in three expert interviews and in a workshop with 19 scientific staff members from the Institute of Product Development at the Karlsruhe Institute of Technology (KIT). Based on the requirements identified, the approach "Sustainable Design Evaluation" has been developed.

The aim of this paper is to introduce the identified requirements (cf. section 2) and the theoretical basis of the Sustainable Design Evaluation (cf. section 4).

2 REQUIREMENTS FOR AN APPROACH TO INTEGRATE SUSTAINABILITY INTO PRODUCT DEVELOPMENT PROCESSES

To be able to make a quick prediction about the sustainability of a (future) product during the product development process and thus integrate sustainability into decision-making processes, the relevant information must be collected, structured, aggregated and evaluated, and the results must be presented intuitively and concisely to the product developers. Product developers must therefore be able to apply the method to their individual products themselves, but the collection and evaluation of the relevant data cannot be carried out by them because of the high complexity and time pressure and must be automated.

Furthermore, a sufficiently large number of criteria from all three dimensions of sustainability as well as all life phases of the product must be included.

In addition, the application of the approach should require few financial and human resources. No external expert knowledge should be necessary, and the approach should be easily and quickly applicable by product developers at any point of the product development process. Since every product development process is individual and unique (Albers, 2010), and most of the data needed is already stored in several locations in the company, such an approach should allow existing company knowledge to be incorporated and used as a priority.

The complexity of the sustainability assessment and the necessary data for relevant decision-making cannot be reduced at the expense of the completeness and relevance of the criteria. Rather, it must be transferred away from the product developer into an automatable process through good data structuring and a clear, universally applicable assessment system. It is not the method that must be simple, fast, and intuitive, but its application.

3 EXISTING METHODS FROM THE STATE OF RESEARCH

The state of research includes numerous methods, assessments, and tools for aspects of sustainability in the context of companies and products. For example, Mario Fargnoli *et al.* (2014) gives a detailed overview about existing tools.

Based on a systematic literature review, for this paper the relevant methods and tools were divided into two clusters. The first cluster contains generic and generalized methods based on guidelines. These methods are mainly used before or in early phases of development and are quick and easy to apply. The second cluster includes methods that perform a more elaborate and holistic assessment of sustainability criteria, but are mostly applied retrospectively to existing products due to their time- and cost-intensive application. All the methods investigated could be assigned to one of the two clusters on the basis of their basic principle. In the following, some examples are presented for each cluster.

3.1 Cluster 1: generalized methods based on guidelines

In the following, Design for X methods and Environmentally Conscious Design will be presented as examples of methods from Cluster 1.

Design for X methods are design guidelines that focus on a specific area of a product or its life cycle and seek to optimize it (Kuo *et al.*, 2001). To address ecological aspects in product development, there are, for example, Design for Disassembly, Design for Recyclability or Design for Source Reduction (Fiksel, 2009). These methods can be summarized under the term Design for Environment. They include environmental aspects in the development process, but are usually limited to one phase of the product life cycle (O'Hare, 2010).

Other design guidelines related to sustainability are eco-design, or eco-innovation, and environmentally conscious design. The term eco-design or eco-innovation is used to describe all guidelines that incorporate environmental influences and impacts into the product development process, taking into account all phases of the product life cycle. The aim is to minimize environmental impacts without compromising other criteria that are essential for the product, such as functionality or cost. (O'Hare, 2010; Pigosso *et al.*, 2013)

According to O'Hare, (2010), Environmentally Conscious Design (ECD) is an umbrella term for eco-design, eco-innovation and Design for Environment. In some cases, social and economic criteria can also be considered. However, these terms are defined differently and used inconsistently in different contexts in the literature.

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The application of Methods from Cluster 1 is possible with little time and financial effort and feasible for product developers after appropriate training. However, often not all three dimensions of sustainability are mapped and the methods are limited to a few criteria and/or only one life cycle phase of products. Company knowledge is not included and the information provided cannot be used for qualitative and/or quantitative assessment. As a result, no explicit provision of a broad information base for integrating the three dimensions of sustainability into decision-making processes is achieved with this methods (Kuo *et al.*, 2001; Fiksel, 2009; O'Hare, 2010; Pigosso *et al.*, 2013).

3.2 Cluster 2: sustainability assessments

In the following, the Life Cycle Assessment (LCA) and the Life Cycle Sustainability Assessment (LCSA) will be presented as examples of methods from Cluster 2.

The basic idea of LCA is to record all ecological environmental impacts of a product from raw materials to waste management (Klöpffer, 1997). According to the current state of research, about 15 environmental factors are mapped in the LCA (Hauschild *et al.*, 2018).

The LCSA expands the LCA based on all three dimensions of sustainability to include the social and economic dimension. For this purpose, in addition to the LCA which depicts the ecological approach, life cycle costing (LCC) for the economic and social life cycle assessment (sLCA) for the social dimension of sustainability are added (Ciroth *et al.*, 2011; Kloepffer, 2008).

Methods from Cluster 2 mostly cover all three dimensions of sustainability in all life cycle phases, taking into account a wide range of criteria. Corporate knowledge is used to create and interpret the assessment. In addition, a quantitative assessment of sustainability takes place. However, those methods require large financial, human and time resources as well as explicit knowledge from experts. Due to the exclusively retrospective analysis of existing products, the results can serve as input for a new product generation, but cannot be explicitly used for decision-making processes within the current product development process for product developers (Kloepffer, 2008; Hauschild *et al.*, 2018; Ciroth *et al.*, 2011).

Similarly, the methods not described in detail here, such as benchmarking, morphological matrix (Cluster 1), environmental effect analysis, or fast track LCA (Cluster 2) can be assigned to one of the Clusters and do not allow for both a holistic sustainability view and a quick and simple application by product developers.

Accordingly, the current state of research lacks an approach that meets the identified requirements for integrating sustainability (cf. section 2) into decision-making processes during the product development process.

4 SUSTAINABLE DESIGN EVALUATION (SDE)

To address the identified research gap, the theoretical bases of the Sustainable Design Evaluation (SDE) is presented below. The SDE is a method designed to support product developers in considering the three dimensions of sustainability in decision-making processes within the product development process.

To assess the impacts of a decision in the three dimensions of sustainability on all life phases of the subsequent product, the SDE contains an information structure that specifies which data and information are required for a quantitative assessment of the impacts.

However, to include the information in decision-making processes, it must be available in a form that can be used directly by product developers. For this the collected information must be structured and then evaluated, aggregated, and clearly presented. Due to the large number of criteria and great amount of data, a quantitative evaluation is needed, to give product developers a quick overview and allow them to assess the effects of their decision. This in turn creates the basis for taking these impacts into account in decision-making processes.

4.1 Integration of the SDE into company processes

To enable a holistic sustainability assessment and at the same time a simple application, the collection, structuring and evaluation of the relevant data must be automated as far as possible. Figure 1 shows how the SDE can be embedded in company structures. For the application of the SDE, a direct interface is needed between the decision-making object, in this case the product model, and the SDE.

Starting from a model of any level of detail, usually in the form of CAD data created by the product developer, it should be possible to carry out an evaluation at any point in the development process, which serves as the basis for decision-making processes (cf. section 2).
To do justice to the individuality of the company processes and structures as well as the uniqueness of each product development process, it cannot be sufficient to rely only on external knowledge; rather, the existing company knowledge must be included. This increases the quality of the data and thus also of the results and reduces uncertainties. For this purpose, the SDE must not only have access to an external, but also to the internal database, in order to store and link attributes that are already created in the product model, such as the material, directly and automatically with primarily internal information. In addition to material data sheets, this can also be information on suppliers, production systems or assembly and disassembly processes. If no internal information is available, the SDE can fall back on an external database with averaged material and process data.
The results of the company-specific analysis are then made available to the product developer in a clear and structured manner.
In the following, the evaluation and aggregation models required for the integration of the SDE into company processes and for an automation will be presented. The technical implementation will not be part of this paper.

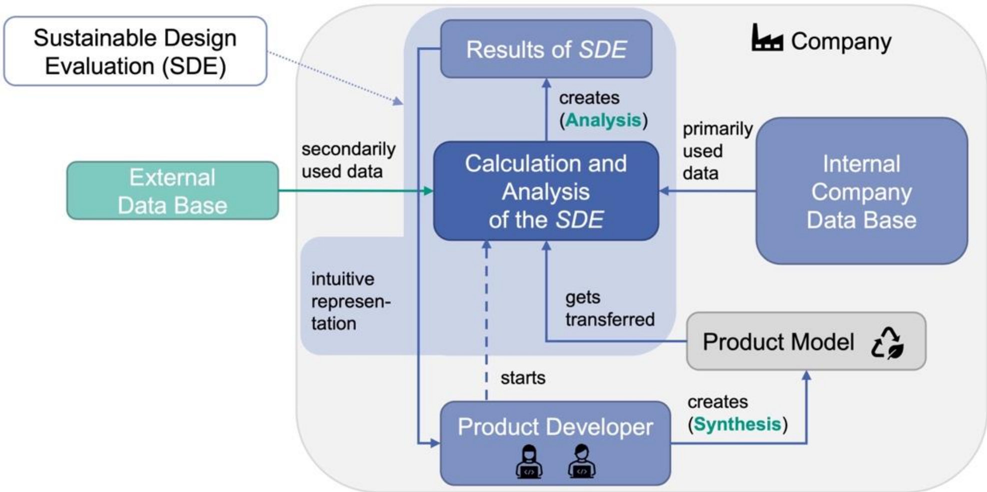

Figure 1: Schematic and simplified representation of the integration of the sustainable design evaluation into the company processes. A product developer creates a product model that is automatically transferred to the calculation tool when the SDE is started. This tool obtains data from an internal and external database and makes the results available to the product developer in an intuitive presentation.

4.2 Basics of the calculation framework

In order to make the collected data usable for decision-making processes of product developers, it has to be evaluated, aggregated and presented in an easily interpretable way (cf. section 2).

4.2.1 Relative quantification of individual criteria

The first step to quantitatively calculating the sustainability of any vague product model after collecting the necessary information is to evaluate the individual criteria in the respective life phases. Which criteria are relevant must be determined on a case-by-case basis by the company and developers. Extensive research for relevant criteria sets already exist for this, based on, for example, the Global Reporting Initiative (GRI) or the Sustainable Development Goals (SDGs). The selection of relevant criteria is therefore not part of this paper. The prerequisite is a sufficiently large variety of criteria to avoid a "shift of burdens" (cf. section 1).
However, the absolute values are often not intuitively interpretable and comparable for product developers. If we take the concentration of a hazardous substance in a material as an example, the absolute quantities determined do not contain any information whether a critical limit value has been exceeded and how this substance interacts with the environment. In addition, the absolute information cannot be aggregated with related criteria, such as other critical substances. The same applies to any

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other criteria, such as fair wages, water consumption or emissions. Therefore, the SDE includes a procedure for quantifying criteria in relative terms, which is shown in Figure 2 and Figure 3.
For the relative quantification of criteria from all three dimensions of sustainability, the SDE first distinguishes between two types of sustainability criteria, which are defined below as exclusion criteria and reference value criteria.

Exclusion criteria are criteria that must be ruled out for a product to be sustainable. Examples are child labour or forced labour, but also the use of certain non-permitted substances. A product in whose life cycle child labour takes place cannot be sustainable, regardless of the fulfilment of other criteria.
To quantify exclusion criteria, a two-stage procedure is proposed. Since processes in companies are dynamic, the first stage is to determine the inspection status of the criterion. The regularity of the check for correctness has a great influence on the quality and reliability of the information.
To determine the inspection status, three possible statuses are defined:
(a) The criterion is reviewed regularly. (b) The criterion has been reviewed once, for example when the contract was concluded. (c) The criterion has not been reviewed and/or no relevant information is available.
The second stage is the performance status. For this purpose, the criteria must first be positively formulated to enable a more intuitive interpretation of the results. In the example of child labour, the corresponding social sustainability criterion would be expressed as "child labour is ruled out".
Here three possible statuses are distinguished as well:
(a) The criterion is met. In the example of child labour, this would mean that child labour was actively ruled out in all processes in the life phase under consideration. (b) Non-fulfilment cannot be ruled out. If no or too little information is available to exclude a criterion such as child labour, a risk assessment must be provided. The level of risk - low, medium, high - for child labour in the location and industry of the processes relevant to the life stage must be determined on a three-point scale. (c) The criterion is not met. If child labour takes place in the life cycle stage, a product cannot be assessed as sustainable, even if it meets the criteria in other domains and life cycle stages.
The inspection status and the compliance status are now coupled with each other and underpinned with a scored scale from -3 to +4.

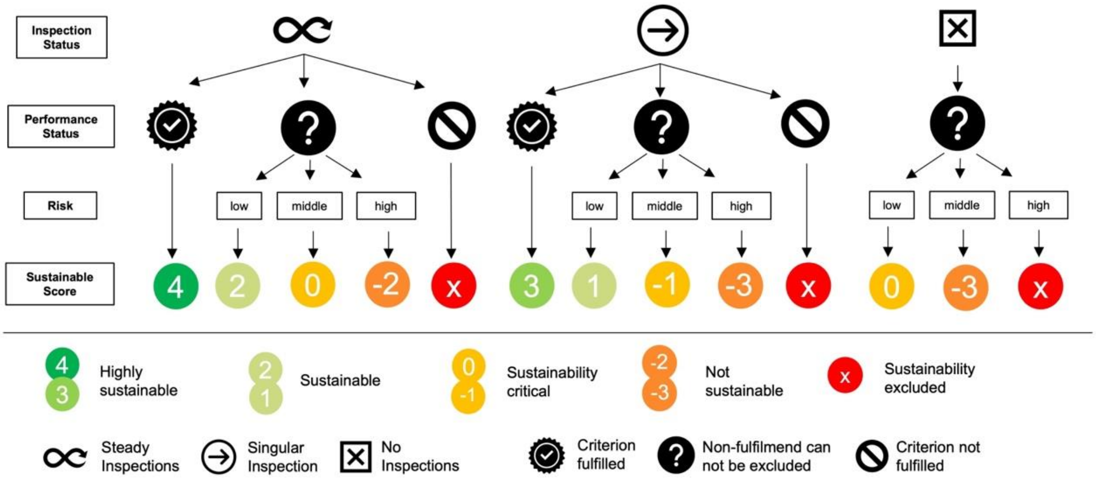

Figure 2: Quantification of exclusion criteria. A score is derived by linking the two levels of inspection status and performance status. For values greater than zero, the criterion is considered sustainable; for values less than or equal to zero, it is considered unsustainable. If sustainability is excluded (red x), this applies beyond the criterion to the entire product.

The second category of criteria, the reference value criteria, are criteria for which a reference value can be defined, above which the criterion is considered sustainable. The result can be derived from the deviation of the degree of fulfilment from the reference value. Examples are fair wages, occupational health and safety measures or water consumption. Reference values must be determined on a criterion- and company-specific basis. For the reference value of fair wages, for example, the maximum of the minimum wage, the living wage (Public Eye, 2019) and the industry-standard comparative wage could be used. If less is paid, the criterion "fair wages" cannot be considered sustainable. For a comparable

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quantified assessment of the reference value criteria, the two levels of inspection and performance status are also used. While the inspection status is the same as for the exclusion criteria, the performance status is described in four possible statuses:

(a) The reference value is significantly exceeded. (b) The reference value is met. In the case of fair wages, this would mean that all work directly or indirectly related to the product in the life phase under consideration is paid at least at the reference wage. (c) The reference value is undercut. In relation to the example given, this case occurs if at least one person is paid below the reference wage in direct or indirect product-related processes in the life phase under consideration. (d) Falling below the reference value cannot be ruled out. In this case, too, equivalent to the exclusion criteria, a three-stage risk assessment must be used.

For the quantification of the reference value criteria, inspection status and performance status are now also linked, and the relative scoring scale shown in Figure 3 is determined.

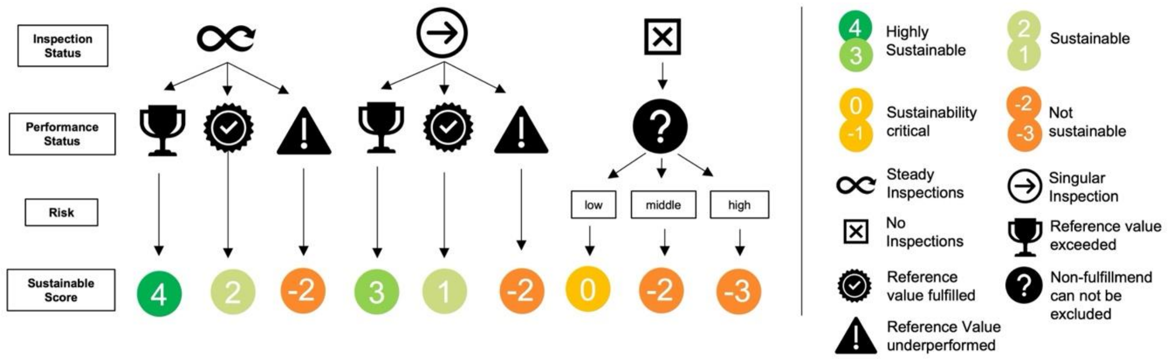

Figure 3: Quantification of reference value criteria. A score is derived by linking the two levels of inspection status and performance status. For values greater than zero, the criterion is considered sustainable; for values less than or equal to zero, it is considered unsustainable. The scale corresponds to the scale for exclusion criteria to enable comparability and aggregation, which is why not all possible values appear in the scale between -3 and +4.

With the evaluation scheme presented, a relative quantification of all social, ecological and economic criteria is possible for which an exclusion criterion or a reference value can be defined. For values greater than zero, a criterion can be described as sustainable; for values less than or equal to zero, it can be described as non-sustainable. The scale of the reference value criteria is compatible with that of the exclusion criteria, so that after evaluation the criteria considered can be intuitively compared, aggregated and interpreted.

4.2.2 Horizontal, vertical and lateral aggregation

Since a sufficiently large number of ecological, economic and social criteria must be considered for a valid evaluation, it is necessary to structure the evaluated criteria and present them in a way that the results can be interpreted quickly and intuitively by product developers and included in decision-making processes. For this purpose, it is necessary to aggregate the assessed individual criteria to reduce their number shown at the overview level because the product developer does not have time to interpret each criterion individually, but must focus on the most critical and relevant criteria.

At the end of the evaluation of the individual criteria, which is to be executed as automatically as possible in practice, results are available for each criterion in each phase of life. Figure 4 schematically shows the various criteria determined vertically and the individual life phases horizontally. Each criterion can be assigned a value in each life phase. Within the SDE, a distinction is made between two- and three-dimensional aggregation, which will be introduced below (see Fig. 4).

Two-dimensional aggregation can be divided into horizontal and vertical aggregation.

Vertical aggregation refers to the grouping of the results of different criteria in one life phase into criteria bundles. A criteria bundle can be, for example, biodiversity for ecological criteria, and human rights or working conditions for social criteria. Horizontal aggregation is the combination of the results of the different life phases of one criterion or criteria bundle into an activity bundle. After evaluation with the presented relative evaluation scheme, the results of a criterion or criteria bundle of all life phases can be summarized by means of weighted averaging, if necessary.

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Three-dimensional or lateral aggregation describes the combination of individual or vertically aggregated criteria in individual or horizontally aggregated life phases of different components and/or subassemblies. If a product model is to be evaluated that consists of several components or subassemblies, these must be aggregated laterally for this purpose. This can also be done by a weighted averaging, if necessary.

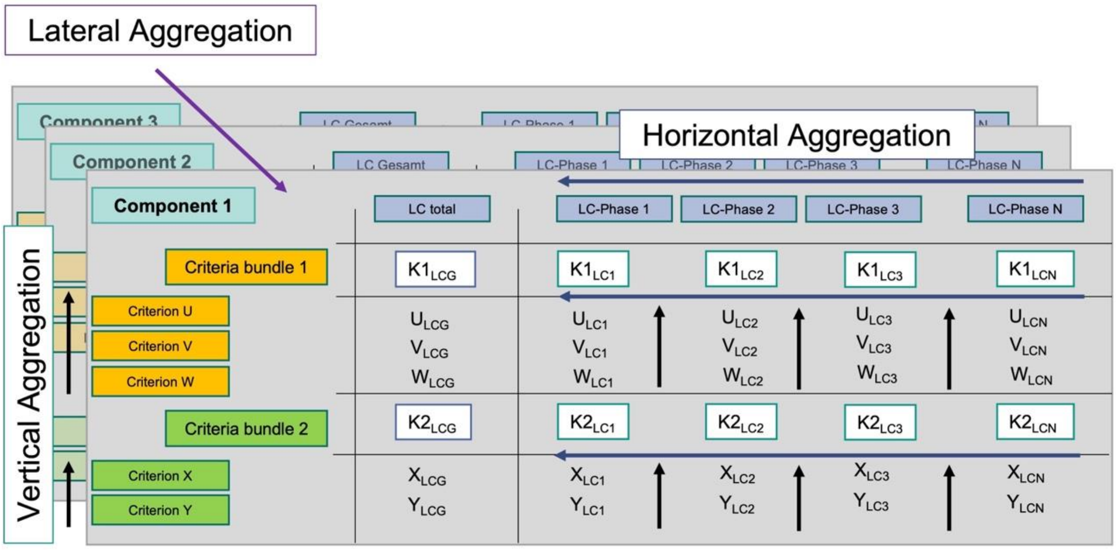

Figure 4: Two-dimensional aggregation can be divided into vertical and horizontal aggregation. Horizontal aggregation describes the summary of the results of the different life phases of one criterion (blue arrows), vertical aggregation the summary of the results of one life phase of different criteria (black arrows). Three-dimensional or lateral aggregation describes the aggregation of criteria or criteria bundles from one life cycle phase or from aggregated phases of different components or sub-assemblies. The order of aggregation depends on the weighting of criteria and life cycle phases.

4.3 Representation of the results against loss of information

The aggregation of criteria by averaging, which is necessary for the rapid interpretation of the results, always results in a loss of information. However, with Franz's assumption that a product can only be considered sustainable if the social, ecological and economic impacts of the product at all stages of its life meet at least the minimum sustainable standards (Franz, 2021) and the conclusion that this must also apply to all criteria, a substitution between different criteria in the area of non-sustainability is not permissible. When forming a bundle of criteria or activities through an average value, it must therefore be ensured that a non-sustainable result is not offset by many other sustainable results and disappears. Therefore, when presenting the results of an aggregation, it is proposed to show the lowest value of the aggregated individual results in addition to the average value. In the overall assessment, a bundle is only considered sustainable if the lowest value is also greater than zero (see Figure 5, left).

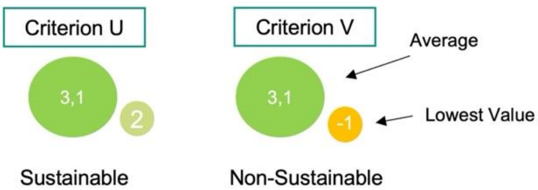

Figure 5: The average value of a criteria or activity bundle may only be interpreted in connection with the lowest value of the aggregated criteria. The fictitious example shows an average rating of 3.1 in both cases. In the example on the left, all values used to calculate the average are greater than zero, but on the right, at least one value used for the aggregation is -1 and thus less than zero. Hence, the example on the right cannot be classified as sustainable despite the high average value.

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By indicating the lowest value in the aggregation, it quickly becomes apparent which criteria or activity bundles contain non-sustainable criteria. In these bundles, it is worthwhile for product developers to take a close look at the individual criteria in order to identify where the non-sustainability arises.
The average value gives an indication of how the criteria bundles are to be classified within the process of a product that is as sustainable as possible. However, they may only be interpreted together with the lowest value, as shown in Figure 5.

5 CONCLUSION AND DISCUSSION

The strong presence of sustainable development in public discourse is leading companies to a growing awareness of the need to evaluate their actions in terms of sustainability. To develop sustainable products, product developers must be able to assess the impact of a decision during the product development process for a sufficient number of criteria from the three dimensions of sustainability and for all life cycle phases.
The Sustainable Design Evaluation presented in this publication aims to enable product developers to assess the impacts of their product-related decisions by collecting, structuring and evaluating relevant information and presenting the results in an intuitive way. This supports product developers to include ecological, economic and social criteria in decision-making processes within the product development process. In this way, the SDE addresses the gap between complex sustainability assessments and quickly applicable but less holistic and customizable sustainability guidelines by providing the ability to automate data management and sustainability calculations, while allowing the application and interpretation to be quickly and easily completed by the product developer.
The basis is the integration of the SDE into the corporate structure to make the existing knowledge available in the company usable for product developers. After the classification into reference value criteria and exclusion criteria, it is possible to evaluate criteria using the presented relative evaluation scheme and to aggregate them horizontally, vertically and/or laterally. In this way, the results can be made available to product developers easily and intuitively.
The SDE is not suitable for the certification of products, as it is applied individually and not reproducible across company boundaries. It serves as an individual decision-making aid for becoming aware of conflicting goals in sustainability within the company's own product development process. Therefore, the SDE does not suggest a decision in terms of a more or less sustainable solution. It merely makes the trade-offs and potential conflicts in sustainability visible and creates awareness of them, which is a prerequisite for product developers to integrate sustainability into decision-making processes during the product development process.
This paper presents only the basics of SDE, which provide much potential for further research. Applicable criteria sets need to be developed together with companies in an interdisciplinary team. In addition, the presented calculation and aggregation system needs to be validated in a case study. Here, questions of weighting in the aggregation of criteria and life phases are particularly challenging. The greatest challenge will be the meaningful integration of the SDE into the data management of companies, as it must be highly customizable. For this, the next step is to implement and test an initial prototype.

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