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Approach to Sustainability-Based Assessment of Solution Alternatives in Early Stages of Product Engineering

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Abstract

Sustainable product engineering is becoming increasingly important. This includes the development of environmentally friendly products and the design for recycling. In this paper a holistic method for the assessment of solution alternatives is presented, in which the stakeholder perspectives along the generic product lifecycle are taken into account. Finally, a new visualization is presented. By visualizing the results in the integrated sustainability triangle, decision-makers in product development can holistically assess the sustainability of the solution alternatives.

Keywords: sustainability, decision making, generic product lifecycle, design analysis, ecodesign

1. Introduction

In the engineering process, it happens several times that solution alternatives have to be assess and suitable ones have to be selected (Bender and Gericke, 2021). A continuous assessment of solution alternatives reduces the probability of erroneous developments, ensures a targeted product engineering and reduces costs through decision preparation (Lindemann, 2005). An assessment usually takes place when a conscious decision step is necessary to select one or more characteristics (Ponn and Lindemann, 2011). Product properties and characteristics are assessed on basis of selected criteria (VDI 2243, 2002). The assessment of solution alternatives is a crucial step in product engineering. In engineering of product design, compromises are made between requirements, guidelines and criteria (e. g., functional implementation, use of materials) in solution alternatives. The overall objective of an assessment is to identify the most sustainable solution alternative and by that the best compromises. Sustainable addresses the dimensions of social, ecological and economical. The social and ecological design of products is becoming increasingly important (Isaksson and Eckert, 2020). In the decision-making process, the perspectives of relevant stakeholders are necessary. Stakeholder refers to a person, group or institution that has some kind of relationship with or interest in the course or outcome of a process or project (Walden *et al.*, 2015). Stakeholders pursue distinguishable goals with a solution alternative developed for product. The prioritisation of criteria used differs according to objectives pursued. Choosing best possible solution alternative based on the prioritisation of one stakeholder therefore does not lead to the best possible decision for all stakeholders involved, such as relevant stakeholders like manufacturer, product users, waste collectors and recyclers (Ellen MacArthur Foundation, 2013). In order to find the most sustainable solution alternative, the solution alternative that has a balanced compromise between the dimensions of sustainability, represented by the relevant stakeholder objective, must be identified. Only the consideration of perspectives in the assessment of solution alternative enables sustainable product design and strengthens closed material cycles.

The publication at hand presents an approach for assessing the equally weighted sustainability of solution alternatives in early phases of product engineering by focusing on sustainability dimensions. The new visualisation enables the dimensions of illustrated without grouping them intransparently into overarching indicators. It is shown that the presented method enables product engineers to assess solution alternatives with regard to sustainability and to visualize them in the decoupled sustainability triangle.

2. Fundamentals

The following paragraph examines the decision-making process within engineering. Decision-making processes are located here in the selection of product concepts and the initial design. In this, sustainability is understood as the combination of the dimensions of social, ecological and economical aspects. Complete and utilitarian sustainability exists when the maximum concordance of the benefits of all stakeholders is achieved.

2.1. Solution Alternatives in Product Engineering

Product engineering is a process in which an idea for a solution for an identified problem is transformed into reality and manifests itself in a product (Pahl *et al.*, 2007). The product engineering process is structured by methodologies such as (VDI 2221, 2019) and (VDI 2206, 2021). An interdisciplinary approach with a special focus on mechatronic and cyber-physical products is the represented by (VDI 2206, 2021). In the VDI 2006 an essential feature is the dedicated break-down of complex tasks into functions. Afterwards, logical and physical structure including partioned sub-systems and system elements are derived. VDI 2206 provides the engineer with control points and thus matches the decision-making process to the product engineering process.
In the early phases of product engineering, stakeholder requirements are implemented through the overall function of the product to be developed. To reduce the complexity of the development task, the overall function can be detailed by sub-functions. Subsequently, operating principles are defined by which the sub-functions can be implemented in reality. There are several operating principles for the realisation of a function. Therefore, there are also several different possibilities to realise the partial functions and thus the overall functions. The different possibilities to realise the final product are known as solution alternatives. The solution alternative to be chosen is decisive for the sustainable success of the product. In the checkpoints of VDI 2206, criteria are established to select the best possible solution alternatives for further engineering. The criteria are specific to the product class of the solution alternatives developed. Classically, the solution alternatives are differentiated according to functional and economical criteria (Ehrlenspiel and Meerkamm, 2013; Bender and Gericke, 2021). The criteria do not influence the decision to select a solution alternative equally and are differentiated by weighting factors. The weighting factors are subjectively determined by the stakeholders and integrated into the assessment. For sustainable product success, it is therefore crucial to consider all stakeholders across the product life phases.
For the success of the product and the fundamental product engineering, stakeholders acrosst the whole product lifecycle need to be considered (Walden et al., 2015). If the design of a specific product characteristic is not secured holistically via criteria, unforeseen disadvantages will occur in later product life phases. Soo et al. refer to such adverse characteristics as "fixed that fail" (Soo et al., 2018). Thereby, Soo et al. describe the design of connections between two elements in terms of production and lightweight design in product use. Thus, the use of riveted and glued joints leads to low-cost and weight-reducing properties. However, mechanical shredding at the end of the product's life results in material contamination, as the fragments are larger in mass than the joints that are not separated. An assessment of solution alternatives in early stages of product engineering ensures that the needs in the different life phases are met. It thus lays the foundation for business models implementing Circular Economy.

2.2. Sustainability Assessment

Sustainability as a paradigm is divided into several dimensions (Ellen MacArthur Foundation, 2013). The social, ecological and economical dimensions combine different perspectives that pursue different goals and strategies to secure and improve performance (Enquiry Commission, 1998). The achievement of objectives becomes verifiable through cause-effect relationships as well as quantifiable and measurable assessment criteria (Fiksel, 1996). There are various procedures for the criteria-based sustainability assessment of alternatives in product development, which are explained below. (Deutsches Institut für Normung, 2021).

To identify methods for assessment and visualisation of the sustainability of products, literature research is conducted according to Briner and Denyer (Briner and Denyer, 2012). There is a large number of procedural models that use development to assess solution alternatives and the sustainability of products. The methods found in the literature enable to assess products in the late stages of product development and to select them for further production (Hassan *et al.*, 2017). Existing methods for assessing aspects of the sustainability dimensions are provided by lifecycle assessment (LCA), lifecycle costing (LCC) and GaBi software (Göhlich *et al.*, 2022; *Gabi Solutions*, 2022). LCA methods according to (Ness *et al.*, 2007) and according to (Singh *et al.*, 2009) enable an assessment of product life.

Furthermore, criteria are mentioned in the literature that make it possible to quantitatively and qualitatively assess the sustainability of products in the phases of production and product use. From the literature review, there are 239 quantitative and qualitative criteria that can be used in a sustainability assessment (Amrina and Yusof, 2011; Heng *et al.*, 2012; Bocken. Nancy *et al.*, 2013; Hede *et al.*, 2015; Rodrigues *et al.*, 2017; Bertoni *et al.*, 2018). From the criteria identified in the literature for the assessment of solution alternatives, a catalogue has been compiled that classifies the criteria according to the product life phase, stakeholders and sustainability dimension. These criteria are used for the following validation.

Bringing together the many and varied criteria is a crucial activity in order to reduce complexity and make it accessible to the cognitive abilities of the observer. Accordingly, visualisation methods play an important role in the assessment of alternative solutions. Hauff (2014) presents the integrated sustainability triangle for this purpose and combines the three dimensions as a mixing ratio (Hauff, 2014). The integrated sustainability triangle enables a central statement to be made about the combination of the three dimensions. A special feature is that the continuum within the triangle visually supports the expression of a dimension. In doing so, detailed statement about one of the three dimensions and its criteria is lost. Kwok (2020) et al. present an visualisation of the assessment results through various diagrams from which no overall statement on sustainability is possible and which are more difficult to interpret the more criteria are included in the assessment (Kwok *et al.*, 2020).

In order for product engineers to be able to assess developed product concepts and initial designs against each other and individually, this paper presents a procedure and a new visualisation method to identify the need for change in sustainability dimensions. It is essential for the assessment of sustainability that the dimensions social, ecological and economical remain independent of each other in order to avoid ethical challenges. In addition, the developed procedure and the visualisation methods must be independent of the product type and the disciplines involved in order to enable a broad application.

3. Assessment in early Product Engineering Phases

The procedure for assessing solution alternatives is embedded into the product lifecycle for a generic view of the product life phases. Product lifecyle models are named in the literature. One model that is particularly suitable due to its transferability to different types of product is the generic product lifecycle (gPLC) according to (Gräßler and Pottebaum, 2021). The gPLC places the product life phases "strategic planning", "engineering", "realisation", "operation/service delivery" and "decommissioning" in an upward sequence and relates them to each other. The decisive features for embedding the assessment in the gPLC are a) Circular Economy compatibility and b) uptake of the benefits of intrinsic engineering methodologies (Gräßler and Pottebaum, 2021). Circular Economy is represented by the return flow of information and materials. With the gPLC, Gräßler and Pottebaum succeeded in developing a model that combines the advantages of the intrinsic product lifecycle from the engineering and project perspective and the requirements of the Circular Economy with regard to material and information circularity.

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Within the product lifecycle phases, there are distinguishable stakeholders (e.g. manager, designer, product user, maintenance engineer, salesperson, etc.) with their specific perspectives (see Figure 1 on the left). The stakeholders pursue different goals with the product, which is reflected in the different weighting of the criteria. The product-specific criteria are classified and weighted depending on stakeholders. The solution alternatives are to be examined according to the life-phase weighted criteria so that the product is designed in the best possible way. In this paper, the product in which the materials are included is considered. The material lifecycle is therefore only considered in context of recycling.

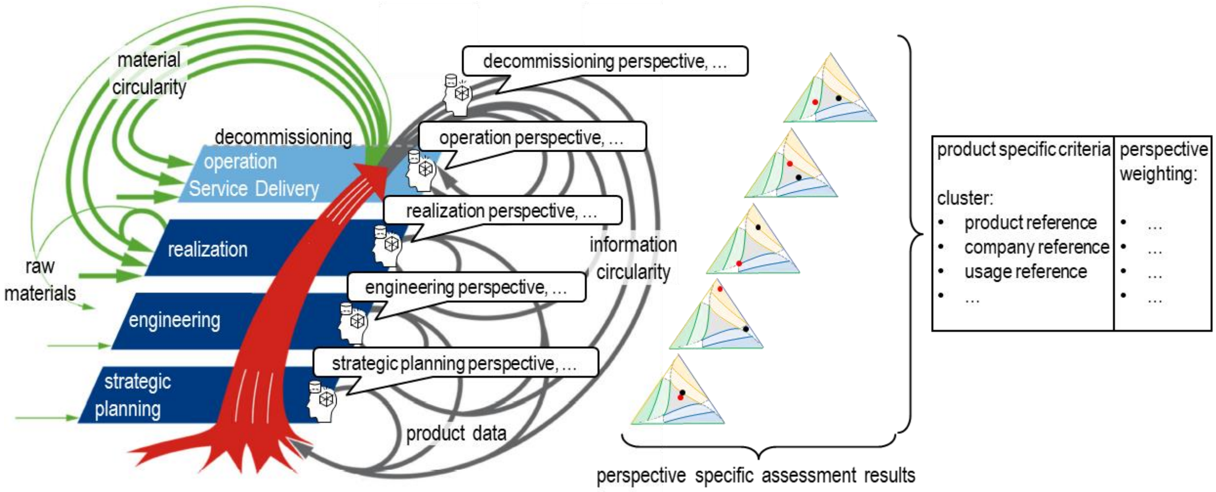

Figure 1. Integration of stakeholder perspectives into generic Product Lifecycle, based on (Gräßler and Pottebaum, 2021)

Taking these criteria into account in engineering has an influence on the costs of future recyclates. A product can be designed in such a way that it can be recycled without much effort using low-cost technologies. The lower the effort, the lower the price of the recyclate. The prices of materials can thus be better determined and their availability ensured. By integrating actors from recycling companies, business models emerge to create synergies between companies (Ellen MacArthur Foundation, 2013).

3.1. Approach for Sustainability Assessment in Engineering

The approach presented here describes the process for creating the decoupled sustainability triangle. This is shown in Figure 2 and is embedded in the V-Model of VDI 2206. Within the gPLC, the procedure is to be classified in the engineering phase. The solution alternatives of the product concepts are transferred to the initial design. The engineer is the user of the approach and the visual representation. The engineer derives criteria from given specifications of the requirements and the properties.

The assessment of solution alternatives is part of the development methodology VDI 2206 (VDI 2206, 2021). Within the V-model of VDI 2206, the assessment of solution alternatives is located in the phases "system architecture" and "implementation of system elements". The assessment of solution alternatives can take place once or several times in a product engineering process. As solution alternatives become more concrete, the number of included criteria increases, as more properties and characteristics can be addressed. Accordingly, the criteria are to be selected on a product-specific basis. From the interactions of characteristics and properties with the individuals, the product environment, system elements, sub-systems and/or other independent systems, criteria from the created criteria catalogue can be assigned to the characteristics.

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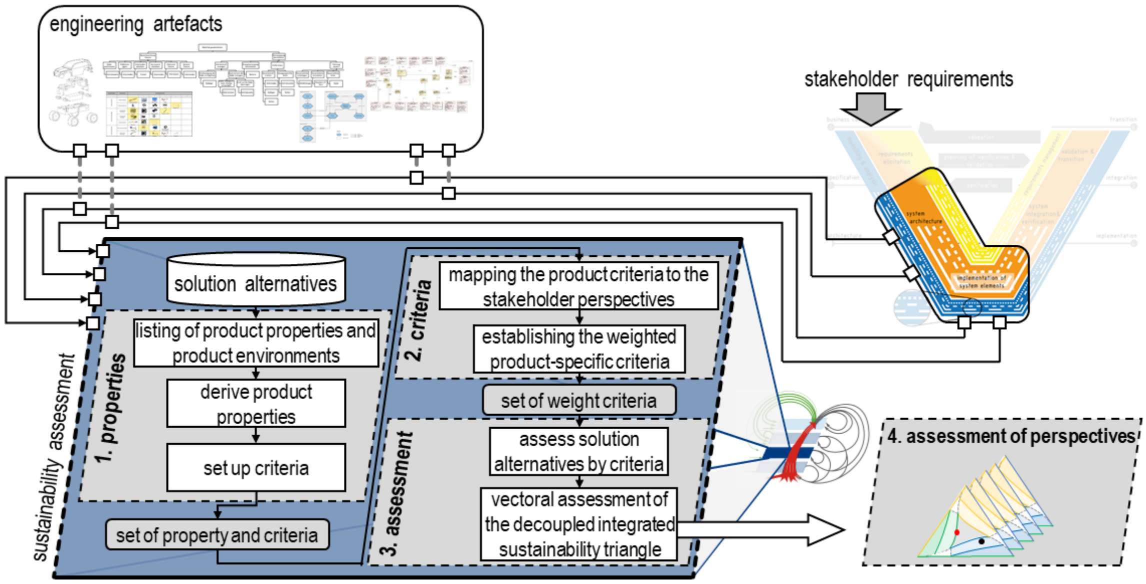

Figure 2. Method for sustainability assessment in early phases of product engineering

The product concepts and the initial design are used in the process and are oriented towards the "architecture" checkpoint. A checkpoint describes the system engineering progress and provides control questions that help the engineer to plan and execute the associated engineering in a structured way (VDI 2206, 2021). The following artefacts are available in these phases: product requirements, product variants, production processes, modules available. The approach is divided into the four steps "properties", "criteria", "assessment" and "assessment of perspectives". In the step "properties", the product properties are collected and analysed, which serve as a basis for the criteria determination. Product engineering has access to various engineering artefacts such as stakeholder analysis, environment model, functional structure, functional hierarchy, sketches, morphological boxes, bill of material and CAD models (Gräßler *et al.*, 2021). In addition to the internal information, external information (e. g. recycling technologies, environmental conditions, material data, other stakeholders) must be available for the assessment. From the artefacts as well as from the internal and external information, the product properties in the future product life phases are predicted.
The product properties result in criteria that can be assigned to the dimensions of sustainability according to which the solution alternatives are assessed.
In the second step criteria, the product characteristics and criteria are compared with the stakeholder perspectives. The stakeholder perspectives differ according to the product life phase, see Figure 1. According to the product life phase, the stakeholders pursue different goals with the product. To take this into account, the criteria are weighted for each product life phase and the relevant stakeholders. At the end of step two, the criteria set for the assessment is finalised. After the definition of the basis for the decoupled sustainability triangle with the weighted criteria, the assessment of the solution alternatives is carried in step three. The result are decoupled sustainability triangles for each product life phase, each of which contrasts the existing solution alternatives (Figure 2, right). Finally, the five decoupled sustainability triangles are evaluated by the product engineers. Dimensions as well as criteria can be identified that are underrepresented in several or in one solution alternative. If a dimension is underrepresented, the solution alternative must be optimised with the aim to better fulfil the criteria applied. The most promising solution alternatives can now be selected through the product engineers.

3.2. Vectoral Visualisation of the Decoupled Sustainability Triangle

As a result, the decoupled sustainability triangle, explained in the following paragraph, reflects the relationship of the three dimensions social, ecological and economical without bringing them together in just one indicator. To ensure that these conflicts are not at the expense of one dimension, the decoupled sustainability approach is presented. Through the presented procedure, the dimensions remain independent of each other. This avoids a conflict between economical and social criteria

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without having holistic competences in both dimensions. The objective of the assessment, i.e. the desired position of the centroid (ratio), must be determined in advance. The focal point provides information about the relationship of the dimensions and thus the criteria to each other. Compromise solutions that disadvantage one or two dimensions are identified and can be optimised accordingly.
The calculation approach presented here for visualisation of sustainability is based on the integrated sustainability triangle (Hauff, 2014). Characteristic for the visualisation of sustainability according to Hauff is, that the percentage shares of the dimensions are entered in a mixing ratio. Due to the mixing ratio, the dimensions are interdependent. Furthermore, the continuum within the triangle is not clearly defined mathematically. Thus, an area is defined that is described by the point ratio, for example the central area is defined by: social = 33,3 %, ecological = 33,3 % and economical = 33,3 %. Accordingly, there is a here to decouple the dimensions from each other and to describe the continuum mathematically. The calculation method of the decoupled sustainability triangle is presented below.
The criteria assigned to the dimensions are transferred to the integrated sustainability triangle with a metric scale. The criteria are summarised via the weighting in the dimensions, whereby 100 % means that all criteria are completely fulfilled. The three sides of the equilateral triangle represent the dimensions of sustainability (social, ecological, economical) and have an edge length of 100 $units$. Each side of the triangle is provided with a metric scale from 0 % to 100 % and thus enables the description of the extent of a dimension. The metric scale requires quantifiable criteria. The triangle is implemented in a cartesian coordinate system. The origin of the coordinate system is located in the lower left corner of the triangle, see Figure 3.
To keep the equations clear, the dimensions are distinguished by numbering in the indices: social := 1, ecological := 2, economical := 3. Each dimension is represented by a vector located within the continuum. The vectors are shown on the left side of Figure 3. Each direction-vector $\overrightarrow{Dim_1\Delta_{Dim_1}}$, $\overrightarrow{Dim_2\Delta_{Dim_2}}$, $\overrightarrow{Dim_3\Delta_{Dim_3}}$. of a dimension is described by the position-vector $\overrightarrow{Dim_1}$, $\overrightarrow{Dim_2}$, $\overrightarrow{Dim_3}$ and the destination-vector $\overrightarrow{\Delta_{Dim_1}}$, $\overrightarrow{\Delta_{Dim_2}}$, $\overrightarrow{\Delta_{Dim_3}}$.

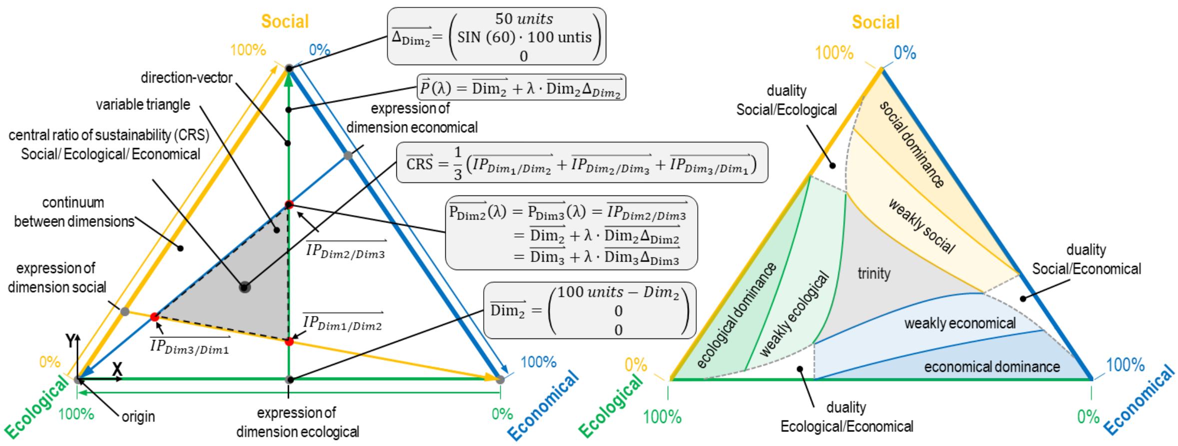

Figure 3. Calculation of the ratios in the decoupled sustainability triangle

For the explanation, the dimension ecological is used as a basis to describe the calculation more clearly. Any point (P) on the direction-vector ecological is calculated by the equation (1). In equation (2), the direction-vector and the destination-vector are inserted into equation (1) to illustrate the linear system of equations.

$$\overrightarrow{P_{Dim\,2}}(\lambda) = \overrightarrow{Dim_2} + \lambda \cdot \overrightarrow{Dim_2\Delta_{Dim\,2}} \tag{1}$$

$$\overrightarrow{P_{Dim\,2}}(\lambda) = \begin{pmatrix} 100\ units - Dim_2 \\ 0 \\ 0 \end{pmatrix} + \lambda \cdot \left[\begin{pmatrix} 100\ {}^{units}/_{2} \\ SIN\ (60) \cdot 100\ units \\ 0 \end{pmatrix} - \begin{pmatrix} 100\ units - Dim_2 \\ 0 \\ 0 \end{pmatrix} \right] \tag{2}$$

The direction-vectors of the ecological and economical dimensions intersect within the continuum at the intersection point (IP) $\overrightarrow{IP_{Dim_2/Dim_3}}$. The equations for the intersection point can be found in Figure 3. For

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the calculation of the intersection point, the point-vector $\overrightarrow{P_{Dim_2}}$ is equal to the point-vector $\overrightarrow{P_{Dim_3}}$. The resulting system of linear equations is to be rearranged according to the factor λ. For the factor λ the equation (3) results in. X and Y represent the axes of the Cartesian coordinate system.

$$\lambda_{Dim_1/Dim_2} = \frac{\left[\frac{Dim_{2\_x}-Dim_{1\_x}}{Dim_{1\_x}\Delta_{1\_x}}+\frac{(Dim_{1\_y}-Dim_{2\_y})\cdot Dim_{2\_x}\Delta_{2\_x}}{Dim_{2\_y}\Delta_{2\_y}\cdot Dim_{1\_x}\Delta_{1\_x}}\right]}{\left[1-\frac{Dim_{1\_y}\Delta_{1\_y}\cdot Dim_{2\_x}\Delta_{2\_x}}{Dim_{2\_y}\Delta_{2\_y}\cdot Dim_{1\_x}\Delta_{1\_x}}\right]} \tag{3}$$

The intersection of two direction-vectors within the continuum describes the relationship of the two dimensions to each other. With the new calculation it is also possible to graphically assess the relationship between two dimensions within the continuum. Using the intersection points of the vectors, the following ratios can be graphically represented:

- social/ ecological → Dim_1/Dim_2
- ecological/ economical → Dim_2/Dim_3
- economical/ social → Dim_3/Dim_1

The calculation of the intersections resulting from the vectors social/ecological and economical/social is based on equations (1) to (3) with correspondingly adjusted indices. Within the continuum, there are always the intersections social/ecological, ecological/economical and economical/social, irrespective of the value of dimensions. There are therefore three points of intersection within the continuum, which graphically form the corners of a variable triangle. The geometric centroid of the variable triangle visually represents the overall relationship of all three dimensions to each other. Mathematically, the geometric centroid represents the averaging of all points within a figure (variable triangle) and is therefore suitable for describing the relationship of the three dimensions to each other. The central ratio of sustainability (CRS) is not calculated with vectors. The point coordinates of the intersection points ($\overrightarrow{IP_{Dim_1/Dim_2}}$, $\overrightarrow{IP_{Dim_2/Dim_3}}$, $\overrightarrow{IP_{Dim_3/Dim_1}}$) in the cartesian coordinate system are used to calculate the centroid. The coordinates of the centre of the triangle are calculated using equations (4).

$$\overrightarrow{CRS} = \frac{1}{3} \cdot \left(\overrightarrow{IP_{Dim_1/Dim_2}} + \overrightarrow{IP_{Dim_2/Dim_3}} + \overrightarrow{IP_{Dim_3/Dim_1}}\right) \tag{4}$$

For the graphical assessment of the intersections and the central ratio of sustainability (CRS), the continuum is divided into areas that allow a statement about the dominance of dimensions. The areas that divide the continuum are visualised on the right in Figure 3. The continuum of the decoupled sustainability triangle divides the areas into: dominance, weak dominance, duality and trinity.

The area dominance (5) describes the ratio in which the percentage value of a dimension is greater than the sum of the other two dimensions. The special characteristic of dominance is that the dimension that dominates is fulfilled to 100 %. Weak dominance also results from the fact that one dimension is greater than the sum of the other two, with the difference that the predominant dimension is only 50 % fulfilled. Duality (6) describes the area in which two dimensions have a similar percentage value and decisively dominate the third value. Trinity (7) as the central area results when the percentage values of the three dimensions converge. In this case, the dimensions are equally represented in the product.

$$Dominance: \qquad social \geq \text{ecological} + \text{economical} \tag{5}$$

$$Duality: \qquad social \approx \text{ecological} > \text{economical} \tag{6}$$

$$Trinity: \qquad social \approx \text{ecological} \approx \text{economical} \tag{7}$$

4. Validation

The validation of the developed assessment and the visualisation method of the decoupled sustainability triangle is carried out using the case study of fully automatic coffee machines. Two solution alternatives for the brewing unit of a fully automatic coffee machine are considered. The brewing unit holds the ground coffee powder and compresses it. Then 100 °C warm water flows through the compressed coffee powder. Finally, the coffee powder is dispensed. The two solution alternatives are based on brewing units already realised, see Figure 4 on the left. Information about the material, components, operating noise can be assessed via the existing brewing units.

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Table 1. Criteria across the social, environmental and economical dimensions

		weight	flexible brewing chamber	fixed brewing chamber
Social	sum:		90 %	96,5 %
- coverage of performance indicators for different stakeholders		0,1	60 %	80 %
- generation of irreversible waste		0,2	100 %	100 %
- number of chemicals, hazardous materials used		0,3	100 %	100 %
- number of injuries, risk of exposure, leakages		0,3	80 %	95 %
- fulfilment of the requirements		0,1	100 %	100 %
Ecological	sum:		66 %	84,67 %
- energy utilization		0,13	70 %	90 %
- solid waste		0,2	80 %	100 %
- materials (e.g. percentage recycled)		0,2	50 %	90 %
- environmental requirements in product target specifications		0,2	20 %	40 %
- noise and vibrations		0	73 %	100 %
- critical materials: SCI score for alloys		0,27	100 %	100 %
Economical	sum:		62 %	82 %
- material cost		0,1	70 %	70 %
- unit cost		0,2	40 %	90 %
- number of elements		0,2	70 %	80 %
- number of materials		0,3	70 %	90 %
- hidden and external cost		0,2	60 %	70 %

The weighting and application of the criteria result in the values for the three dimensions shown in the scales (Figure 4). For the assessment of the sustainability of the solution alternatives presented in Figure 4, the criteria related to the product properties are collected and weighted according to the perspectives. The criteria are determined in the first step, "properties", of the procedure in Figure 2. The aim of the assessment in the validation is to identify the solution alternative that takes equal account of the three dimensions. Considering the dimensions equally ensures that the design trade-offs are made equally and that the product is designed for the life phases. The engineering perspective (stakeholder: engineer) is used for the validation and weighting of the criteria. The weightings are collected from three product engineers by using the pairwise comparison method.

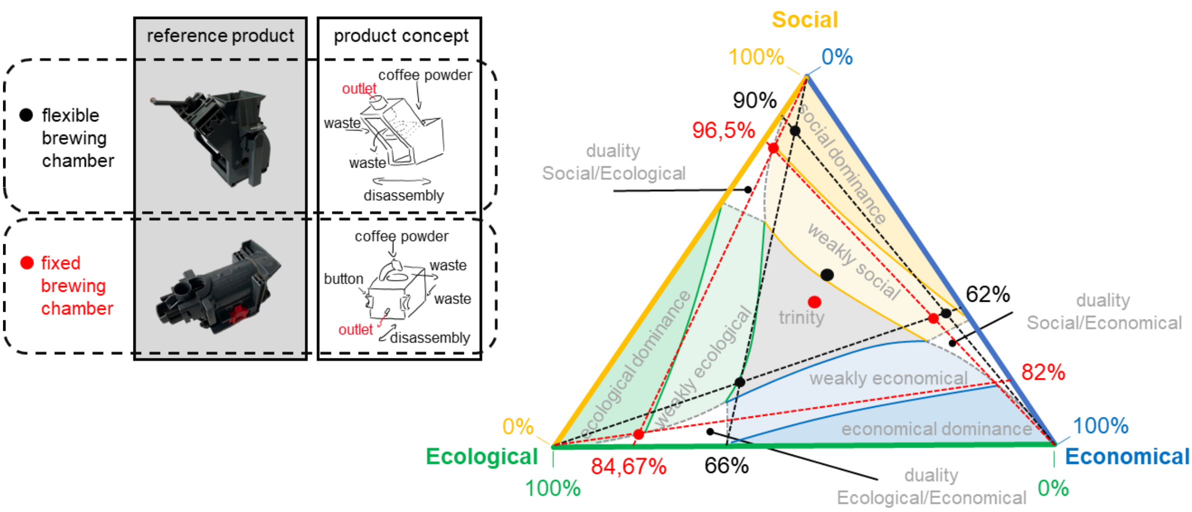

Figure 4. Assessment of two solution alternatives one brewing unit

The criteria collected in Table 1 are taken from the catalogue compiled from the literature. The result Table 1 shows that the solution alternative with the fixed brewing chamber covers all three dimensions better than the solution alternative with the flexible brewing chamber. The solution alternative with the

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flexible brewing chamber that does not cover the dimensions equally. The entry in the decoupled sustainability triangle in Figure 4 shows that the solution alternative with the fixed brewing chamber is closer to the centre. This means that the solution alternative with the fixed brewing chamber considers the dimensions of sustainability more evenly than the alternative with the flexible brewing chamber. This leads to the recommendation that the brewing unit with the fixed brewing chamber should be chosen for further elaboration. Alternatively, the flexible brewing unit should be redesigned so that the compromise solution covers the dimensions evenly.

The values of the dimensions in Table 1 are congruent with the statement of the decoupled sustainability triangle. The social dimension of the flexible brewing unit is greater than the ecological and economical dimension. This picture is confirmed in the decoupled sustainability triangle. In direct comparison with the alternative solution with a fixed brewing unit, it becomes clear that the compromises in the design were made more inconsistently. The brewing unit with the fixed part also shows an orientation towards the social dimension. Accordingly, the visualisation of the decoupled sustainability triangle is a suitable option to compare several solution alternatives.

5. Conclusion and Outlook

In product engineering, several solution alternatives are created from which the best possible ones must be selected (product concepts and initial design). The created solution alternatives are differently suitable for further development. Therefore, this paper presents an approach and assessment that enables product engineers to differentiate and select solution alternatives. In order to avoid an imbalance in the choice of compromises, the decoupled sustainability triangle that has been developed relates the sustainability dimensions social, ecological and economical to each other without combining them in a single indicator. Conflicts between the prioritisation of economical and social dimensions are avoided, as this is done in each of the dimensions.

In the developed assessment approach and the visualisation via the decoupled sustainability triangle, product engineers are enabled to compare solution alternatives. The model of the decoupled sustainability triangle classifies the solution alternatives according to the dimensions of sustainability. The new visualisation method allows two or all three dimensions to be compared with each other. The continuum within the decoupled sustainability triangle is mathematically determined. This enables to assess the relationship of the dimensions to each other In the graphical assessment, suitable solution alternatives can be determined and then further elaborated. Alternatively, the need for rework in one dimension can be identified for a solution alternative. According to the need for rework, product developers can specifically improve the properties via the product properties. The basis for the assessment is the product concept and the initial design. It is essential that the product properties form the basis for the selection of the criteria. The product-specific compilation of the criteria in combination with the stakeholder-specific weightings per product life phase ensures a sustainable assessment of the product properties for each product life phase. The calculation method presented is thus a fundamental component of product engineering in context of the Circular Economy.

Further research is needed on the implementation of variable areas within the continuum. In addition to the relationship of the dimensions to each other, this also considers the properties of the dimensions within the continuum. Finally, consideration should be given to integration of the extraction of data from existing digital twins of previous product instances. Digital twin data obtained in this way enables a targeted analysis of the product characteristics and selection of the product-specific criteria within a dimension. Furthermore, it is conceivable that previous product instances are evaluated by digital twin and criteria are weighted on the basis of the knowledge gained. This further reduces subjectivity of the stakeholders who weight the craters.

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