Potential of Common Methods to Integrate Sustainability Requirements in the Product Development Process: A Case Study

Maike Kosiol, Dominik Weidmann, Daniel Kammerl, and Udo Lindemann

Abstract Sustainability is a process of change, which ensures present generations to meet their needs without preventing future generations from meeting their necessities. Products have a huge impact on sustainable development since product properties determine the product's environmental impact. This contribution analyzes the potential of commonly known and established methods to support developers in designing sustainable products. Possibilities to integrate sustainability requirements, as well as thereby arising difficulties, are considered. The development of an ice crusher is the use case for the analysis.

Keywords Sustainability • Development process • Case study • Methods • Sustainability requirements

1 Introduction

The core ideas of sustainability are saving the climate, saving our standards of living, and creating a livelihood for future generations [1]. These topics are influenced by the lifestyle of the human population. The population expands rapidly and interacts with its environment by consuming products and services. This is inseparably linked to an increased energy demand, resource exploitation, and environmental pollution including exhaust gases [2]. In the long run, these impacts affect societies by diseases or climate change [3]. The development and mass production of technical everyday products once enabled the so-called consumer society. Decisive product properties affecting all phases of a product's life are already defined in the product development process [4]. The product life cycle covers all stages from the first idea over the development, production, distribution, usage, and finally to the disposal or even beyond [5]. To meet the demand of designing sustainable products along the entire life cycle, the focus is to be set on the product development phase.

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In literature numberless methods are available, which support developers to achieve specific objectives in context of sustainability. A number of authors analyzed the applicability of such methodologies. They figured out that many tools are not used in industrial development processes. Tools which might be predestined to integrate sustainability aspects are not immediately applicable, due to their complexity, the required time to apply them, budget, personnel, or the lack of knowledge about how to use them [6].

This paper focuses on methods which are already commonly known and established in product development. The goal is to analyze how these methods can, in addition to their primary application background, support developers in designing products that meet the requirements of sustainability at the best possible rate.

This paper has the following content:

The second chapter is about sustainability in literature, especially in the content of the product development process. The third chapter describes the research methodology. The fourth chapter analyzes the potential to integrate sustainability aspects to methods, which were applied within the scope of a use case. Chapter 5 draws a conclusion and gives a brief outlook.

2 Sustainability in Product Development

For our current understanding, 1987 is said to be the birth year of sustainability. In this year, the Brundtland Commission took place, which published a definition of sustainability that is still valid today: “Humanity has the ability to take development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs” [7]. The commission describes sustainability as a continuing process of change which reaches for harmony and enhancement in the interaction of resource utilization, technological development, institutions, and investments [7]. The Brundtland report describes sustainability as a broad field, and consequently, many discussions about sustainability focus on particular aspects.

Sustainability is commonly subdivided into three dimensions: economy, ecology, and society. They represent the multitude of sustainability requirements [8]. A product is torn between these three dimensions, which have partly conflicting claims. Figure 1 shows the interdependencies: economy, ecology, and society demand requirements for the product. Additionally, interactions between the dimensions exist; e.g., economy provides workplaces for society; the environment is the basis of life for the society and provides raw materials which are used in the economy.

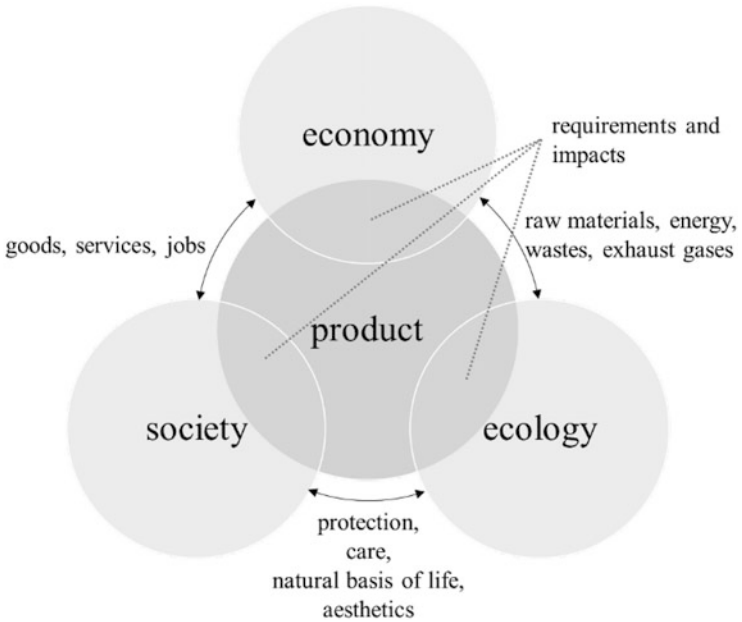

Fig. 1 A product in the area of conflict of sustainability dimensions (Modeled after Ref. [8])

2.1 Development of Economically Sustainable Products

Literature with a focus on the economical sustainability of products isn't widely spread, because this is a self-motivated goal for companies with a long-range plan [8].

2.1.1 Objectives

The development of economically sustainable products means to create successful products which are in line with the market and the customer. Further goals are reducing the amount of goods, such as costs and time, and increasing quality and efficiency.

2.1.2 Methodological Tools

Using methods can lead to better quality, efficiency, and saving of time. Directives and standards serve to design products that are in line with the market. Checklists support the identification of sustainability requirements [9]. Another useful tool is based on value analysis (VA) with the goal to design or redesign a product at low cost. Therefore it is analyzed which functions the consumer is willing to pay for.

Only these functions are implemented in the product, and in doing so, environmental benefits are obtained. Based on the acceptance of the product by consumers, this method was enhanced through the application of life cycle costing (LCC). From a life cycle perspective, product costs are analyzed by integrating environmental cost with the internal cost. The continuous evolution of this method toward sustainability led to the Eco-VA (assesses each product function from the customer, environmental, and cost perspective) and to the LCECA (mathematical model that enables an isolated calculation of environmental cost independent of the product component). Life cycle planning is a recent method, which combines quality function deployment (QFD), life cycle assessment (LCA), and TRIZ. It aims to integrate quality, cost, and environmental aspects in a systematic way into the early stages of a product's life cycle [6].

2.2 Development of Ecologically Sustainable Products

Currently products are produced and disposed at an alarming rate. As much as 75 % of material resources used in products and their manufacture are disposed back to the environment as waste within a year [10]. The statistic speaks about so-called throwaway products, which cause challenges toward resource extraction, waste collection, growing landfills, and the arising environmental influences.

2.2.1 Objectives

Ecologically sustainable product development focuses on products that cause less influence on the environment throughout their entire product life cycle compared to previous or competing products [11]. Approaches to achieve this objective are, for example, the usage of regenerative energies [12] and assuring the emission-free usage [13]. Another approach is the consideration of the products' end of life already in the early design process by taking decomposition, material separation, and reuse into account [9]. However, it is important to maintain, or better, to increase the product incentive for the customer. Therefore an additional ecological value is a core issue [14].

2.2.2 Methodological Tools

Most approaches in connection with sustainable development are searching possible solutions concerning the environment. Numerous tools and methods exist to support ecological goals. A multitude of laws and quasi-statutory texts and directives as the VDI 2243 [4], the 2005/32/EC [15], or the 2002/96/EG [16] give practical advice and contain goals and limiting values. Integrated product policy (IPP) aims for constant improvement of products with a focus on their impact on mankind and environment over the entire life cycle [17, 18]. Methods like environmental accounting or life cycle assessment (LCA) deal with the evaluation of the product's ecological performance [19]. A wide range of tools allows quality function deployment (QFD) to be applied in order to consider environmental requirements during the early stages of product development [20]. The purpose is to check if the product corresponds to the customer's requirements, including environmental requirements. Further methods often combine the House of Quality (HoQ) of the QFD with LCA-based techniques: e.g., House of Ecology (HoE) deals with environmental requirements instead of quality requirements, E-QFD combines LCA and HoQ in order to evaluate alternative design proposals, and Readiness Assessments for Implementing Design for the Environment Strategies (RAILS) focuses on supplying tools for selecting environmental improvement options that could be carried out [6].

2.3 Development of Socially Sustainable Products

The product development's role in designing socially sustainable products was already formulated in the 1970s. Products which were aligned to the actual human needs should be developed. They should generate positive social aspects instead of contributing to the erroneous trend of society, which means every deviation from the environmentally optimal behavior with minimal impacts on the environment [14]. In literature judgmental terms are often used in the context of products with a social focus. Expressions like "socially acceptable" assume inherently a damage [8].

2.3.1 Objectives

In the design process, social aspects can especially be included in the requirement analysis. It is within the responsibility of the product development to gather information about the society's needs or about personal preferences. Further areas in connection with the social dimension are work and product safety [8].

2.3.2 Methodological Tools

For the social dimension, far less comprehensive methodical support is available in contrast to both previous dimensions. The few existing approaches often focus on one specific issue, like "design for the third world"; "design for teaching and training devices for the retarded, the handicapped, and the disabled"; or "design for elderly people" [8]. Evaluating approaches like the social life cycle assessment often use indicators defined by the United Nations Environment Program [21]. Indicators can be obtained by a listing of the Committee on Sustainable Development

[22], the standard SA 8000 of the Social Accountability International [23], the norm DIN ISO 26000 [24, 25], or [26].

Failure mode and effect analysis (FMEA) is primarily used to identify, assess, and prevent failures related with product safety. The adapted environmental impact and factor analysis (EIFA) considers environmental issues related to reducing, reusing, and recycling [6]. E-FMEA identifies and assesses potential environmental impacts rather than potential failure and its influence on inventory data life cycle and human-related causes [6, 20, 27].

2.4 Sustainability Relevant Design-for-X Approaches

The three previously considered sections can be completed by Design-for-X strategies. These strategies are listed separately in this section because of their huge number and importance. Many Design-for-X strategies cannot be assigned to one specific sustainability dimension although every approach addresses a particular issue that is caused by properties of a product or affects others. Each approach gives practical advice in guidelines and has a particular objective, which is represented by X [28, 29]. Figure 2 shows some particularly crucial approaches in connection with sustainability. They are structured according to the dimension they can mostly affect.

Design for Sustainability serves as a melting pot for more detailed approaches of the three dimensions of sustainability. Especially Design for Upgradability and

Fig. 2 Overview on central design-for-X approaches with focus on sustainability

Design for Maintainability target at life extension of technical products which affects all three dimensions:

- Design for Upgradability: foreseeing of further use phases by enabling the addition of new functions [3]
- Design for Maintainability: taking measures to preserve and recover a product's initial state [30]

Design for Environment is about minimizing the impacts on the environment during the product life cycle as much as possible, e.g., by considering a realistic mix of recovery and disposal [31]. For example:

- Ecodesign: includes the integration of ecological and economical aspects into product development by considering the entire life cycle [11]
- Design for Recycling: economically restoring material and energy to production processes that accrue by producing and consuming products [19]
- Design for Disassembly: simplifying the process of dismounting [30]
- Design for Remanufacturing: functional or withdrawn products can be renewed through a series of industrial operations [32]

Design for Economy is used as an umbrella term for strategies that try to optimize products with a focus on the economic dimension. For example:

- Design for Reliability: reduction of unplanned interferences and component failures and thus increasing of reliability [8]
- Design to Cost: contains approaches to reduce costs [33]
- Design to Manufacturing: designing suitable for production [33]
- Design for Assembly: suitability for mounting a product [3]

Design for Society develops products that support the improvement of social difficulties [8]. For example:

- Design for Safety: minimization of risk potential by the work with products and machines [8]
- Design for Ergonomics: adaption of technical systems to humans in order to avoid health impairment by using the product as planned [30]
- Universal Design: designing products that can be used by as many users as possible, including people with disabilities [8]
- User-Centered Design: designing interactive products fit for purpose [8]

3 Research Methodology

The product development process contains all steps from the product idea to the generation of manufacturing documents [34]. Procedure models help to deal with the complexity of design processes. Such models in combination with methods can support sustainability studies and hand out advice for decision-makers [35]. The

Association of German Engineers (VDI) provides an established procedure model to develop and design technical systems and products by following seven steps in the directive VDI 2221 [36]. We chose this model because it is commonly known and refers to specific resulting documents like requirement specification. This paper analyzes one method representative for each of the first four process steps to determine the potential of the methods to integrate sustainability requirements in the early design phase.

The first step clarifies the problem definition. Identified requirements are documented in the requirement specification. In the second step, functions and their structure are determined and illustrated in the function modeling. In the third step, solution principles for the functions are identified. Reverse engineering is a method which provides possible effective structures that need to be analyzed in this step. The fourth step structures the solution principles based on various criteria. The weighted points rating evaluates solution possibilities in a quantitative and qualitative manner. More methods have been analyzed within the framework of this project, but would go beyond the scope of this paper.

The presented methods were integrated in a real development project, whose focus was not especially on sustainability aspects, but on cost, time, and effort. Consequently, the selection of the methods was based on close to reality conditions and to cover an as large as possible part of the development process.

Analysis and evaluation of the methods are carried out in the framework of a student project in cooperation with a manufacturer. This development project followed the steps of the briefly introduced procedure model and especially analyzed the creation of conclusion documents. The focus of this paper is not on the detailed description of the methods themselves but on their possibilities to integrate sustainability requirements. The theoretical findings have been evaluated within an interdisciplinary team of five students by practical application of the methods in a use case: the goal was to design an ice crusher add-on for a fully automated home coffee machine with a special focus on sustainability (Fig. 3). The ice crusher has to be integrated in an existing coffee machine in order to produce a frappé with just a single push of a button.

4 Case Study: Ice Crusher

4.1 Analysis and Discussion of Applied Methods

4.1.1 Requirement Specification

The requirement list basically structures requirements systematically. It helps to comprehend responsibilities and changes within the entire development process.

The method serves as a structured documentation of all kinds of requirements that have to be considered during the development process. Each line contains one requirement which is specified by the following columns entering information as an

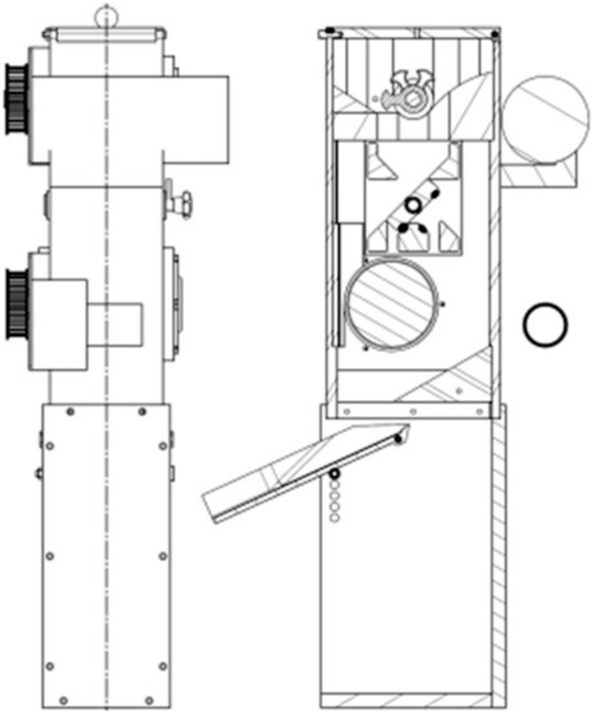

Fig. 3 Use case: the development of an ice crusher add-on for a fully automated home coffee machine

identification number, characteristic, characteristic value, origin, explanatory note, responsible person, and information concerning the revision tracking in the list (Fig. 4).

The requirement list can integrate relevant sustainability issues. It is possible to divide the list into different phases of the product life cycle. In the use case, the requirement list was structured into the phases: product development process, manufacturing, use phase, application, and after use phase. Developers' thoughts are guided to often forgotten phases like disposal. Within these main phases, we created further subgroups, e.g., in the phase manufacturing: material choice, production, and quality.

As shown, sustainability criteria can be easily integrated into a requirement list. However, it is challenging that requirements are not yet defined or known in the early stages of the development process. At least limiting values for sustainability requirements might not be available. Other requirements are not yet evident, which leads to another challenge: the requirement specification does not principally prevent forgetting key aspects of sustainability. Finally, a high number of laws, standards, guidelines, and directives exist, which provide requirements with relevance for sustainability, but this flood of information could overcharge developers. Because of the scale and the complexity of this topic, it is not possible to take every thinkable sustainability requirement into account. Iteration loops with a specific

			Characteristic Values							Revision Tracking		
No.	**Description/ Name of Requirement**	**Short Form**	**min.**	**exakt**	**max.**	**Unit (phys.)**	**Origin**	**Date**	**Responsible Person**	**What? Why?**	**Who?**	**Date**
…	…	…	…	…	…	…	…	…	…	…	…	…
End-of-life Stage												
15	**Disassembly**											
15.1	guarantee accessability for removal tools	-					VDI 2243	28.10.14	MK			
15.2	standardize connection elements	-					VDI Report No. 1570	29.10.14	MK			
…	…	…	…	…	…	…	…	…	…	…	…	…
16	**Recycling**											
16.1	recycling rate for small household appliances	R		80		weight-%	Directive002/96/EG of the European Parliament & Council	13.02.03	JL			
16.2	place reusable modules easily separable	-					Product Design Suitable for Recycling of Kahmeyer & Rupprecht	18.06.05	MV			
…	…	…	…	…	…	…	…	…	…	…	…	…

Fig. 4 Requirement specification

focus, respectively, could support developers. However, developers have to focus on some core sustainability requirements.

4.1.2 Relation-Oriented Function Modeling

Functional models reduce the complexity of a system and thus increase the understanding of developers.

At the beginning of the modeling, it is important to define a clear objective and a suitable level of abstraction. A system boundary has to be set to separate the considered system from its environment. Technical functions are described by the combination of a substantive with a verb. The relation-oriented modeling differs between harmful and beneficial functions. The causalities between those functions are relations. Based on the main function of the system, further beneficial and harmful functions are identified, which are required to realize the main function.

Focusing on sustainability, this method offers the possibility to especially analyze harmful functions. Solution-neutral functions can be added in order to prevent harmful functions or at least to weaken them, and specific problem formulations can be derived. Harmful functions are unwanted functions, which influence the system negatively. In the context of functions, the focus can be set on the numerous aspects of sustainability, e.g., created emissions, corrosion of materials, used energy, and further more. The harmful functions can address various life cycle phases. It is also possible to derive problem formulations in the background of socially sustainability by considering noise pollution, the handling of hazardous substances, or of heavy objects. By marking harmful functions, the developer can

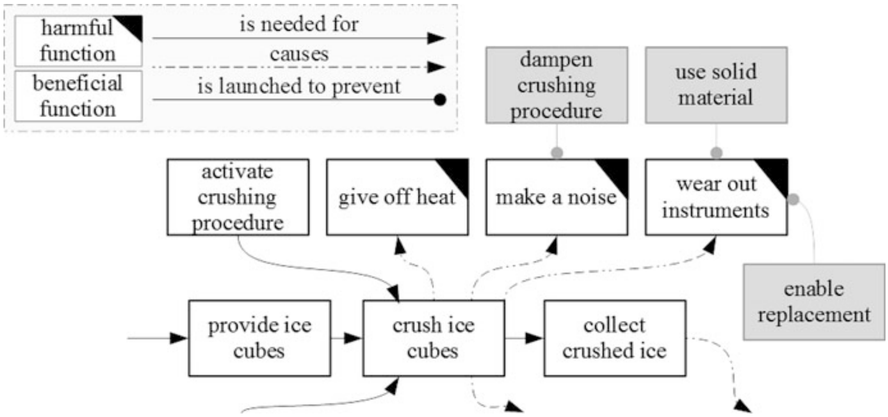

Fig. 5 Extract from the relation-oriented function modeling

concentrate on them. Their setting in the model enables analyses to avoid them, as they can be considered immediately in the appropriate context of their interactions. Possible consequences of modifying harmful functions can directly be noted.

Figure 5 shows an extract of the model which was developed in the framework of the ice crusher project. In this context all functions, which are functionally unwanted or against the principles of sustainability, were named harmful. We explicitly integrated functions to avoid harmful functions, e.g.,"enable replacement" in favor of "wear out instruments."

In our opinion this method offers a great potential to assimilate sustainability criteria into the early stages of the product development process. However, the results of this method still have to be questioned critically. Models always display a reflection of the reality. Several assumptions support the abstraction of the reality. Models and their outcome are always limited in their significance, and they should not be the sole basis for decisions. Another handicap of the relation-oriented function modeling is that it usually considers only few phases of the product life cycle. Primarily it considers functions of the use phase of the product. However, there are other types of function models that look at material flows and flow of energy that occur during all phases of the product's life. Consequently, they are predestined to be used in the context of ecological aspects of sustainability.

4.1.3 Reverse Engineering

Reverse engineering generates ideas for the current design process by analyzing existing products. This method allows developers to gain an extensive insight into the state of the art. They get new impulses for requirements [37] and data about the product that can be used to quantify the characteristic values.

Typically, products with an outstanding position in a certain area are chosen. The purchased product is analyzed in detail, so the developer could create a copy of the product by himself. Therefore the product is fully disassembled – intellectually or physically.

The disassembling of the product is a central aspect in the context of sustainability because it is the basis for recycling, remanufacturing, maintenance, etc. Thereby the following questions can be considered:

- Which and how many tools are required?
- Is it easy to find connection points?
- Is it possible to separate different materials?

In the framework of the development project, two different ice crushers were purchased, which cover the price segments cheap household appliance and professional gastronomic business. The ice crushers were analyzed with the focus on sustainable product design. The disassembling without detailed knowledge about the appliance made us aware of essential sustainability aspects. This is exactly the starting situation in recycling processes. It was hard to detect connection elements that protracted the disassembly process. Another identified deficit was the usage of different connection elements, so different tools and frequent tool changes were necessary. We noted positively that almost every used material could be separated without any damage.

Reverse engineering is a cost-intensive method, because of the purchase of the product, and the analysis can take a lot of time and expert knowledge. A critical aspect of reverse engineering is the developer's fixation on the seen solution. This might prevent innovative and creative solutions.

4.1.4 Weighted Points Rating

If different solution concepts are generated, they have to be evaluated. The weighted points rating can be the basis for the decision-making. This method can consider a huge number of aspects, while the comparability between the different solution alternatives is guaranteed. Developers deal with the specific characteristics of each possible solution and finally present a ranking.

But first of all, evaluation criteria have to be defined. This should be a well-balanced system of criteria in order to not overestimate specific aspects. Sustainability requirements can be easily integrated in this method. The list of requirements can be an orientation for choosing criteria. Fiksel et al. [38] provide, e.g., criteria that aim at sustainability. They provide indicators to evaluate a product, structured into the three dimensions of sustainability (e.g., recycling revenue (economic), life cycle energy (environmental), or illness avoided (societal)). In the development project, we considered aspects of all three dimensions, e.g., costs (economic), noise emission (societal), or resource requirements (environmental). The evaluation of different concepts is based on the degree of fulfillment of the evaluation criteria. A value function or the relation to the remaining alternatives helps to transfer the degree of fulfillment of each criterion into point values. Besides each evaluation criterion can be weighted (e.g., 1, lower importance; 3, average

Evaluation Criteria:	Cost		Safety		Noise Level		Energy Con-sumption		…	**Sum**		**Ranking**	
Weighting	-	*3*	-	*9*	-	*3*	-	*9*	...	unweighted	weighted	unweighted	weighted
Solution 1	2	6	1	9	2	3	1	9	…	6	27	2	3
Solution 2	2	6	2	18	1	3	1	9	…	6	36	2	2
Solution 3	3	9	3	27	3	9	3	27	…	12	72	**1**	**1**
…	…	…	…	…	…	…	…	…	…	…	…	…	…

Fig. 6 Weighted points rating

importance; 9, high importance compared with the other criteria). At this point the focus can be set on sustainability criteria. Both the choice of criteria and the weighting should be done in an interdisciplinary team to minimize subjective influence on the evaluation. The point values are multiplied with the weighting and finally added line-by-line (Fig. 6, every line contains one solution alternative and its evaluation of the several criteria). The ranking is the result of the added point values, whereas the solution with the highest point values is the best evaluated solution regarding the present task.

Various sustainability requirements can be easily integrated into the weighted points rating. Due to intercultural differences, the specification of sustainability aspects might be challenging, and interdependencies between the evaluating criteria can cause overestimations of specific criteria.

4.2 *Final Discussion*

The analyzed methods offer potential to integrate aspects of sustainability. However, none of the presented methods consider every aspect of sustainability. Consequently, a set of methods, which integrate sustainability aspects into the product development process, is necessary, and they are already available.

However, resources such as budget, time, available employees, and manufacturing possibilities limit the application of sustainability into product design. Furthermore, those available resources are often fully used up to realize the basic functions of the product which has priority in terms of products that are in line with the market.

The use case showed the complexity of the thematic, but also pointed out that sustainability criteria can be easily integrated in common methods. If background knowledge can be provided and if one just spares a thought to the thematic, the more sustainability requirements are considered, the more complex and time lasting is the process. Developers deal with interdependencies, which can't be met all concurrently. In the context of the use case, we need several iterations to get over the narrowness of thinking and working capacity, which restrict the simultaneous integration of all interacting functions.

5 Conclusion and Outlook

In the context of product design, many methods exist to integrate sustainability requirements. Those tools vary widely in their complexity, quality, and the time which is required to apply them [6]. Methods that necessitate high-application effort are often not used in companies. Therefore it makes sense to integrate sustainability criteria in such methods that are already widely applied in the product development process.

Case studies integrating sustainability aspects are mostly theoretical examples, without the backing of a product design company [6]. This use case was executed in cooperation with a world-leading company specialized in domestic appliances. However, as it was an academic-based research, the exchange was not as intensive as it could have been within a company. We recommend further use cases in the framework of a company.

This contribution analyzes four established product development methods concerning their potential to integrate sustainability aspects. All four, requirement specification, relation-oriented function modeling, reverse engineering, and weighted points rating, are highly interesting in context of sustainability integration.

Many other methods exist, which are predestined to integrate sustainability aspects to the product development process, such as scenarios [39, 40] and portfolios [35, 41, 42]. As the thematic is so extensive, a product in the context of sustainability will always remain a compromise capable of improvement [29].

As a further step toward sustainable products, we recommend to measure their sustainability objectively. It is not sufficient to integrate as many sustainability requirements as possible without knowledge about their effects.

In conclusion, the spreading and application of sustainability requirements in the product development process will only take place in the long term if it promises personal, financial, or scientifically success [8].

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