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Enabling Product Development Engineers to Select and Combine Methods for Sustainable Design

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Abstract

A broad range of engineering methods, from simple checklists to sophisticated analytical tools, has been introduced to support the development of more sustainable products. Nevertheless, a lack of holistic approaches, which support the entire product creation process, can be observed. Combining the advantages of different existing methods could enable a rather continuous decision support. This paper presents an analysis and a categorization of current tools. On this foundation a process-based approach for method selection and combination is derived. By determining the concrete output of a method it becomes possible to use this information for defining sustainability milestones in project management. Hence, the allocation of design methods to different phases of the product creation process can be performed more intuitively and a combination of methods is encouraged. In order to test this approach, an exemplary redesign of a turbocharger has been conducted. From a pool of 50 methods nine are systematically selected and applied in order to check whether the selection was successful or not.

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Keywords: Design methods; Sustainability; Product development; Method selection; Decision support; Sustainable engineering

1. Introduction

The principle of Sustainable Development encompasses the environmental, the social and the economic dimension as it has been defined by the Brundtland commission in 1987. Ever since, sustainability is of growing importance within the development and production of goods for all areas of human living. Especially, the engineering design of technical products shows an inherent complexity both in the assessment of sustainability criteria and the proper integration within traditional product creation approaches. Consequently, the number of methods and tools that promise to create sustainable products is evolving. This includes both, prescriptive (e.g. guidelines) and descriptive (e.g. Life Cycle Assessment) approaches. Performing most of the methods and tools basically requires information about the product's (future) lifecycle perspective. Engineering design departments in companies face the challenge of gathering and allocating lifecycle information. Additionally, due to more complex products and decreasing product lifecycles the method and tool support during the design process becomes intangible. Therefore, a framework that covers engineering design processes, methods, tools and information is needed.

2. State of the art in design methodology for sustainable product development

The field of sustainable product development is established for decades [1], and is gaining more and more attention due to the stricter legal framework and a growing consumer demand for green products [2].

One research focus is the methodological support of participating actors in product design. Bovea & Pérez-Belis speak of a wide range of techniques that have been developed

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to analyze the environmental requirements for products and to facilitate the integration into the product creation process (PCP). Furthermore, they notice significant differences in the complexity, quality and time needed to apply the methods [3]. Bovea & Pérez-Belis also distinguish between methods that were designed for environmental and sustainability assessment and methods, which are supposed to integrate environmental requirements into the design process [3]. Ness et al. are criticizing in that context that many methods are solely focused on the environmental dimension of sustainability, while economic and especially social factors are often neglected [9].

The developed methods range from simple checklists to complex methodologies and frameworks [2]. Due to the described long-term research in this area, the mass of publications can be confusing. In addition to the variety of methods, their nomenclature is ambiguous and inconsistent in some cases and thus can lead to misunderstandings. Terms such as Design for Environment, Eco- or Lifecycle Design are used interchangeably in some publications, while other authors distinguish between them [8].

Several surveys have been conducted to classify the approaches that have been developed over the last twenty years. Baumann et al. group the different tools according to their basic structure into frameworks, checklists and guidelines, rating and ranking tools, analytical tools, software and expert systems as well as organizational tools. They criticize that many researchers are rather interested in developing new methods than to improve and test those, which already exist. Additionally they observed a lack of integration of product development in higher corporate levels and processes, such as in strategy development. As a result, there are too many immature methods, which are based on normative recommendations and were only validated by a few case studies [1].

Knight & Jenkins state that the compatibility of methods with the company-specific PCP is a further important factor for diffusion. Many methods are not generic in the original version and have to be adjusted first. This additional expense is a barrier for many companies [10]. Unger et al. point out, that the use-case-specific method selection is of particular importance for the success of the result. Thus, the effect of improperly selected methods can have the opposite effect and may be misleading for the user [11].

Since most of the methods only aim for certain phases of the PCP, a combination of several methods for the continuous support of the designer seems reasonable. Kaebernick et al. address this aspect by applying four different groups of methods in one PCP [12].

In recent years, several integrated approaches have been developed to merge the different methods. Examples include Product Sustainability Assessment (PROSA) [13], Design for Sustainability [14] and the Integrated Approach for Sustainable Product Development [15]. These approaches however appear static in their application. Included methods are usually combined in a fixed order, which prevents a dynamic selection and combination of methods that can be adapted to different types of products.

3. Theoretical concept

As shown, there is a multitude of different approaches available for sustainable product development. Hence, a significant amount of time and effort is necessary in order to scan literature for methods, which suit the respective user-requirements. When it comes to the combinations of methods it is even more difficult, since it is also required to check for the correct application phases as well as for compatibility of the tools. Existing method combinations are mostly designed rigid and are therefore not suitable for use-case specific method selection as pointed out by Unger et al. [11].

Therefore, streamlining the process of method selection and combination was seen as necessary. The underlying assumption for the proposed approach is that the engineer is more interested in the results, which can be achieved by using a method rather to learn about the method itself. It is also assumed that he has little knowledge about sustainable design methodology but is interested in learning more about his product. Hence, it would be more important to supply the engineer with the purpose of a method rather than its name. Following this idea, it becomes apparent to describe the outcomes of the existing design methods in a way that they can be easily understood without oversimplifying them. Quickly navigating through the different method purposes allows the use of a collection of methods as a toolbox where every tool helps to solve a certain problem. This principle can also be applied to allow a more intuitive integration of different design methods in the PCP. By defining which results shall be reached in different phases of the PCP a planning perspective can be enabled.

Figure 1 shows how the approach could be realized by the integration in an IT system. At first the PCP needs to be

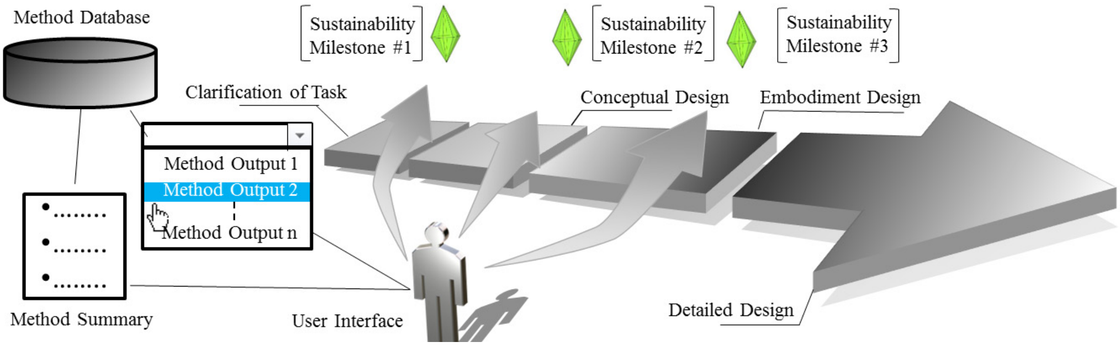

Figure 1. Proposed concept for method selection and combination.

customized according to company standards. After that the user selects an output that is relevant for the current application and opens a summary sheet containing the methods' characteristics (derived from a database). If the user is satisfied with the selected tool he can directly allocate it to a specific phase of the PCP as a sustainability milestone. This procedure can lead to a sequential or parallel combination of tools. Following the steps provided in the respective literature source, the user could then apply the selected methods.

4. Approach

In the scope of this research a collection of 50 methods and tools for sustainable product design has been assembled. In order to achieve a better overview, the systematization of Baumann et al. has been used as a basis for grouping the methods [1]. The group organizing tools has not been considered, since these methods only focus organizational measures and thus do not match the scope of this research.

Seven key properties have been identified for each method. Different categories, which can be allocated to the respective properties, are presented in Table 1. This categorization scheme forms the basis for the method-summary sheets, which are used to support the method selection process by providing the user with information about respective tools.

Table 1. Properties and categories of the method database.

Property	Category
Focus of the method	New product design, Improvement of product/process
Addressed life-cycle phases	Manufacturing, Distribution, Use, End of life
Point of application	Clarification of the task, Conceptual design, Embodiment design, Detailed design, Production planning
Dimension of sustainability	Economic, Environmental, Social
Type of processed data	Qualitative, Quantitative, Semi-quantitative
User of the method	Product manager, Product designer, Sustainability evaluator, Production planner
Layer of abstraction	Product, Process, Requirement, Component, Service

As a next step the researched 50 methods were filtered according to their scientific relevance (number of publications/ citation index) and applicability (availability of procedural information). The barriers for scientific relevance were kept low (at least two publications and more than five citations) in order to maintain the diversity of approaches. Missing information regarding the method-procedure was seen as a direct criterion for exclusion. After this process, 20 tools formed the basis for further analysis.

In order to allow a quick selection of the methods the actual purpose of the method needed to be described (as discussed above). The formulation of these method-outputs proved as challenging because of the required compromise between simplicity and loosing distinctive information. In case of doubt simplicity was preferred since the summary sheets of the methods provide all the necessary details. The full list of all 20 method outputs can be seen in Appendix A. To evaluate the derived concept for method selection, it was tested in a case study.

5. Case study – Redesign of a turbocharger

In the course of this research a PCP has been simulated to test the developed methodology. In order to do so, a Garrett GT2860R turbocharger (for application in passenger cars) has been redesigned. As a first step, the PCP was defined according to the generic VDI 2221 (Association of German Engineers (VDI) reference. The development project primarily focused on the phases: clarification of the task, conceptual design and embodiment design [16]. Three different sequential and parallel method combinations (from now on referred to as method bundles) were selected from the method database (see Figure 2). The method outputs were assigned to three sustainability milestones, each after completing a design phase. The parallelly and sequentially applied methods were compared with each other in order to evaluate whether the choice was beneficial and where difficulties arise.

A physical turbocharger as well as its computer aided design (CAD) assembly served as a basis for the research project. If information could not be derived from one of the models, literature-based assumptions were made. An application scenario has been defined around a downsizing approach for gasoline powered passenger cars. The purpose of downsizing is increasing fuel efficiency through a scaling down of the drivetrain while maintaining comparable performance data [17].

5.1. Clarification of the task

In a redesign process, this phase typically targets the gathering of information regarding the reference product as well as the derivation of improvement measures in the form of requirements for future products [16]. For this case study the Simplified Life Cycle Assessment (LCA) was selected to identify quantitative benchmarks for the product redesign, e.g. greenhouse gas emissions over the product life cycle. Through the Ten Golden Rules it was intended to derive qualitative

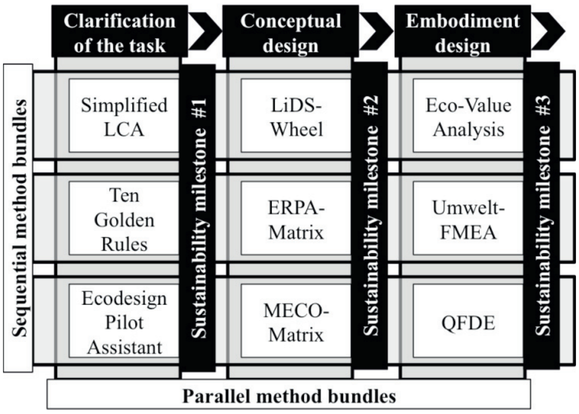

Figure 2. Selection of methods for the case study.

improvement potentials. With the Ecodesign Pilot Assistant the turbocharger has been characterized with respect to its main environmental impacts.

Within clarification of the task, the applied methods complemented well. It was possible to derive a broad set of quantitative (Simplified LCA) and qualitative (Ten Golden Rules, Ecodesign Pilot) requirements. The Simplified LCA was executed for the greenhouse gas emissions impact category using the Solidworks Sustainability tool. The influence of the turbocharger on fuel consumption in the usage phase has been pointed out as main lever for further improvement measures. Through a set of predefined input forms the Ecodesign Pilot Assistant as well pointed out the relative environmental importance of the usage phase. The Ten Golden Rules revealed various starting points for further research of the reference product, like the reduction of component weights. Modifications of the product structure regarding reparability, a key element of the method, showed very little improvement potential.

5.2. Conceptual design

The main tasks for the conceptual design stage of the reference PCP are the generation of product concepts and the selection of the most promising approaches for further development [16]. The outputs of the selected methods in this phase (see Appendix A) promise assistance in decision support for selecting product concepts. Different methods use deviating criteria sets for supporting this selection process. A parallel method bundle can therefore be used to validate decision recommendations. The LiDS-Wheel is evaluating concepts based on a qualitative and predefined criteria set. The ERPA-Matrix is providing a semi-quantitative scoring approach whereas the MECO-Matrix is based on a simplified quantitative LCA.

Based on literature research and the previously identified environmental requirements, different concepts for improving the turbocharger were defined. Two addressed efficiency increases through a redesign of components relevant for the flow paths; the last one was focusing material selection and manufacturing improvements.

Through testing the selected methods with the three concepts, a discrepancy in decision-support has been identified. The scoring approach of the ERPA-Matrix has been applied with respect to the previously researched lifecycle impacts of the reference product and thus clearly favored the concept with the highest potential fuel savings. This advice was confirmed by the quantitative MECO-Matrix. The LiDS-wheel focused on tradeoffs between the concepts, e.g. concerning an increased material input and lowered maintainability of the most fuel saving concept. Because of the pure graphical results representation that does not encompass a cumulative scoring, the isolated application of the LiDS-wheel could have led to an alternative decision.

Nonetheless, all approaches provided unique perspectives on the product concepts. Thus, the selection and parallel application of approaches from the method database was beneficial for the sample case.

5.3. Embodiment design

For the third stage of the reference PCP methods with outputs on a component or functional level were selected. With the application of methods on a more detailed level compared to the previous stage, it was intended to address the iterative and corrective character of embodiment design [16] to elaborate the previously selected product concept. Whereas the Eco-Value-Analysis focuses on dispensable product functions, the Umwelt-FMEA identifies potential environmental weak points while the QFDE compares improvement measures with environmental and customer requirements.

All applied methods showed highly diverse architectures and strategies to generate their outputs. A parallel combination of methods in this phase therefore enabled a more holistic understanding of the product features and of potential improvement measures.

QFDE provides the user with a detailed effects analysis of possible design changes. For example, the effects of geometry changes to environmental requirements out of the manufacturing or usage phase can be shown. This qualifies QFDE as a controlling tool for the PCP. However, the case study indicated a time and resource consuming application effort with covering 20 environmental requirements. Furthermore, QFDE is designed to support a broader part of the PCP. The method starts with defining requirements to the product and is also covering the evaluation of different concepts. For a useful application the method should have been applied earlier in the PCP. Therefore the proposed method selection concept should also reflect the starting point of the method in order to derive useful method combinations.

During the application of the Umwelt-FMEA another drawback could be observed. Potential environmental harms, e.g. possibly toxic materials, were identified on a qualitative component level. Since the method does not include any validation of these risks with quantifiable data, the outputs remained on an imprecise level.

The application of the Eco-Value Analysis did not lead to significant results. The main purpose of the method is an identification of product functions which do not contribute to customer requirements, have a high cost and are a strain for the environment. As part of an internal combustion engine the reference product follows a highly functional design. Therefore, neither of the proposed measures by the Eco-Value Analysis to leave out certain functions would be realizable without losing the product functionality.

Overall, the outputs from embodiment design contributed to the PCP. Nevertheless, some methodological weak points were discovered. While the Eco-Value Analysis has not been appropriate for the reference product, the other approaches showed a clear tradeoff between easy application (Umwelt-FMEA) and comprehensible outputs as a basis for a more detailed design (QFDE). At the same time approaches like or QFDE cover several phases of the PCP. This means that an application in later phases resulted in additional work.

5.4. Case study summary and reflection

All applied methods and tools could be executed properly with the available procedural information. As well, all methods showed to be applicable within the reference PCP requiring an acceptable amount of time and resources. However, weak spots of the method selection as well as starting points for further research have been identified.

- Both the sequential and the parallel execution of methods were proven to be beneficial for a multilateral view on the reference product. However, the parallel execution tends to cause the duplication of work efforts.
- The greatest benefit of method-combinations concerning information generation arose due to a joint application of quantitative and qualitative-oriented methods.
- The procedures, which are necessary for method application, may conflict with the own definition of the PCP. Customization of the methods contradicts the idea of an intuitive method selection for users with less experience regarding design methods.
- Some tools are assisting more than one phase in the PCP (as in the example of the QFDE). The concept for method-selection needs to be adapted for these cases.
- Methods in conceptual design may lead to different concept decisions. A parallel combination of tools can be used for the validation of the derived decisions.
- In embodiment design the availability of tools is limited. Compared to other phases, the applied approaches are either not allocable to a single phase or require extensive resources.
- Not all approaches are suitable for all kinds of products. Learning about these limitations often requires a sample application.
- As already discussed in the literature review, the environmental perspective of current methods for sustainable design is predominant over the economic and social perspectives of sustainability.

6. Conclusion

Starting from a broad range of engineering methods to support the design and engineering of more sustainable products, this paper stresses the need for a holistic approach by utilizing existing tools. The proposed methodology is based on a categorization of existing methods. It can be used to provide development engineers with the necessary knowledge for method selection by limiting effort for information search and enabling comparison between methods at the same time. Within a case study it has been shown that despite of the identified obstacles, the combined elements of the framework have the potential to enable design engineers to select and combine methods for sustainable design and thus for sustainable decision making.

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Appendix A. Method collection

Table 2. Overview of design methods and their respective outputs.

Group	Method	Reference	Output
Rating and Ranking Tools	Cumulated Energy Demand (CED)	[18]	Indicator for the primary energy demand of a product or process over its lifecycle
	Eco-Efficiency	[19]	Proportion between monetary product value and environmental performance
	Eco-Value Analysis	[20]	Analysis of product or concept functions regarding environmental and economic value as well as importance for the customer
	ERPA-Matrix	[21]	Analysis of environmental hotspots and comparison of products or concepts regarding environmental performance
	LiDS Wheel	[22]	Comparison of products or concepts on environmental impacts by predefined criteria
	MECO-Matrix	[23]	Analysis regarding environmental hotspots and comparison of products or concepts regarding environmental performance
	MIPS	[24]	Proportion between resource utilization and product value
	Sustainability Radar (STAR*)	[25]	Comparison of products or concepts regarding economic, environmental and social impact
Analytical Tools	DfE-Matrix	[26]	Comparison of products or concepts regarding environment, health and security
	E-FMEA/EEA	[27]	Analysis of a product or concept regarding environmentally critical product features, product functions and manufacturing processes and derivation of optimization measures
	Eco-indicator ‘99	[28]	Assessment of a product or concept regarding health, eco-system quality and resource utilization
	ECQFD/ QFDE	[29]	Analysis of environmental hotspots of a product and comparison of product concepts to that reference product regarding environmental requirements fulfilment
	House of Ecology	[30]	Identification and ranking of product optimization measures for environmental impact reduction
	Life Cycle Costing	[31]	Cost caused by a product or concept from development till End-of Life
	(Simplified) Life Cycle Assessment (LCA)	[32]	Different Indicators for assessing the environmental performance of a product
	Umwelt-FMEA	[33]	Analysis of product or concept-components regarding environmental weaknesses and derivation of improvement measures
Checklists	ECODESIGN Pilot	[34]	Classification of a reference product and its lifecycle concerning environmental improvement potentials for redesign purposes
	The Ten Golden Rules	[35]	Analysis of a product or concept regarding predefined environmental criteria and derivation of improvement measures
	UNEP Ecodesign Checklist	[22]	Analysis of a product or concept regarding environmental impacts by predefined criteria
	Volvos Black, Grey and White Lists	[36]	Analysis of a product or concept regarding materials or substances which should be excluded or limited regarding health and environmental considerations

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