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Multi-criteria decision making as a tool for sustainable product development – Benefits and obstacles

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Abstract

For developing sustainable products design engineers need to foresee diverse interrelations between a product's characteristics and its economic, social and environmental impacts. In order to support this complex task a wide range of design methods has been developed. Retrospective analytical methods like Life Cycle Sustainability Assessment (LCSA) require a large amount of information and are thus utilized when important design decisions are already made. Prospective methods are rather generic (e.g. checklists) and too broad to be helpful in concrete design decisions. In this paper, the integration of discrete decision trees with LCSA is proposed for shifting multi-criterial quantitative analysis to earlier development. On the basis of sustainability indicators Pareto-optimal decision-paths for given material- and process alternatives along the product lifecycle can be compared up-front. Resulting benefits and obstacles are illustrated by evaluating value creation options of a bicycle frame.

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*Keywords:*Decision support;Life Cycle Sustainability Assessment; Multi-criteria decision making; Sustainable Product Development

1. Introduction

The principles of sustainable development, as they were defined by the Brundtland commission in 1987 [1], are widely seen as one of the major pillars for future human development. Producing companies can contribute to sustainability targets by offering products with minimal negative economic, environmental and social impacts.
The process on how decisions regarding sustainability issues are made is based on multiple factors mentioning solely the following examples:

- Humans (e.g. competencies, team behavior),
- Quality and availability of sustainability information and
- Company capabilities (e.g. resources, funds).

Within value creation conceptual design has the most significant influence on the product's impact on surrounding systems, since a large extent of the product's-properties are defined in this phase [2]. In terms of the environmental dimension, energy and resource consumption as well as the emission of pollutants are influenced. The social dimension is reflected by working conditions or further implication of usage (e.g. through an increase in safety). Economic effects are for example caused by the product price or customer experience.

By the definition of products characteristics (like materials or geometry) design engineers determine product properties like weight or durability to a large extent [3]. For example the selection of a component-material limits possible processes for production and end of life treatment automatically. The product structure determines whether a product can be disassembled and therefore influences maintenance and remanufacturability [4]. Hence, it would be beneficial if the product lifecycle could be optimized in early design phases.

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2. Problem Statement

The integration of sustainability aspects into product design requires continuous quantitative assessment of the product along its creation process [5]. Current assessment approaches like Life Cycle Sustainability Assessment (LCSA) demand detailed information about the product which is usually not available in early design phases [6]. Therefore, quantitative-oriented methods are currently used retrospectively when design activities are nearly finished. Approaches like Simplified Life Cycle Assessment (LCA) try to deal with this problem by offering more lean decision support, but only covering the environmental dimension of sustainability [7]. However, they also do not provide a real prospective support. An up-front simulation model for different configurations of value creation networks may enable "planning" of sustainable products.

Furthermore, the various interrelations between lifecycle and product related factors are very complex and a wide variety of criteria is used [8-9]. This includes the functions a product has to fulfill (according to customer wishes and needs) and the product's lifecycle behavior on environmental, social and economic issues.

Research for solving these kinds of problems has been performed in several scientific fields including operational research, environmental science and engineering design research (e.g. [10-11]).

Therefore, it is seen as vital to develop a coherent approach between the following three subjects:

- Engineering design methodology (1),
- Lifecycle evaluation (2) and
- Multi-criteria assessment (3).

(1) The engineering design methodology provides the approach on how to perform a design project; basically a systematic approach for developing sustainable products (e.g. which design decisions have to be made, what are the crucial product properties and characteristics).

(2) The lifecycle evaluation provides the methodology on how to perform a lifecycle assessment considering the three sustainability dimensions (e.g. which assessment methods have to be considered, which sustainability information is available).

(3) The multi-criteria assessment provides a methodology on how to find the most promising lifecycle decision amongst the solution space (e.g. which design decision is more sustainable considering its manufacturing processes, what are the different local optima in the supply chain).

Nowadays, a combined approach is missing. Nonetheless, it is essential for the development of genuine sustainable products.

3. State of the art

3.1. Sustainable Product Development

The principle of sustainable development inspired a whole generation of scholars and lead to a multitude of publications in design research from various fields like environmental sciences and mechanical or electrical engineering. As a result different frameworks emerged, which are broad concepts representing certain design ideologies (e.g. Ecodesign, Design for Sustainability, etc.) [11]. The different approaches likewise focus on broadening the scope from a cost-centric perspective to a more integrated view and are sometimes used interchangeably [12]. Sustainable Product Development is a framework which aims at the integration of economic, environmental and social considerations into product development [13]. One of the major challenges on this field of research is the holistic analysis and improvement of products regarding their impact on surrounding systems. For a valid assessment the product needs to be analyzed along its complete lifecycle [14]. Furthermore, the principle of sustainable development requires the consideration of multiple design targets at the same time (e.g. reduction of hazardous waste against higher material cost). In this context conflicting requirements can lead to an over constrained design space where trade-off decisions are necessary [7]. The resulting complexity challenges traditional design approaches and leads to the development of a wide range of design methods with varying simplicity, required application-time and quality [8,15]. Baumann et al. categorize the available approaches into six groups from checklists and guidelines to quantitative assessment methods [11].

In previous research projects more than 50 design methods were analyzed and systematized according to different criteria (e.g. point of application in the product development process or addressed type of users of the method). One key finding was the strong focus on environmental sustainability of existing approaches [16]. Ness et al. are coming to similar results [17]. A further objection regarding currently available forms of design methods is the unsatisfying support of multi-criterial decision situations. Byggeth & Hochschorner state that six of their 15 evaluated methods did not address trade-off decisions. The remaining approaches were missing forms of evaluation. The authors therefore recommend including all three sustainability dimensions from a lifecycle perspective as a basis for evaluation [7].

3.2. Life Cycle Sustainability Assessment

Addressing the three dimensions of sustainability the LCSA method has been suggested. It aims at the integration of Life Cycle Assessment (LCA) [18-20], Life Cycle Costing (LCC) [21-22] and Social Life Cycle Assessment (SLCA) [23].

LCSA can be formally expressed in the symbolic equation [14]:

$$LCSA = LCA + LCC + SLCA \qquad (1)$$

The measurement of impacts concerning the environmental dimension of sustainability is the most advanced methodology within the LCSA framework. The life cycle approach avoids shifting burden from one phase to another and enables the identification of trade-offs between life cycle steps and sustainability dimensions. Life Cycle Assessment (LCA) is a standardized method [18] widely used to investigate the potential environmental impacts of products throughout the complete life cycle from cradle to grave [20].

Environmental Life Cycle Costing (LCC) is proposed for the assessment of the economic dimension of sustainability, by including relevant costs for different perspectives, like consumer or producer, into assessment practice. It builds further on the older Life Cycle Costing which has been used since the 1930s. However, it is relatively new within the sustainability assessment [21].

Social Life Cycle Assessment (SLCA) is a method to assess the potential social impacts of products and their consumption throughout their life cycle. SLCA pays great attention to measure the impacts on workers, local communities, consumers, value-chain actors and societies affected by the production and consumption of products [23].

In connection with Sustainable Product Development, LCSA helps to identify hotspots along the products life cycle. Suggestions for more sustainable product alternatives seem possible especially in connection with the multi-criteria decision making (see section 3.3)

3.3. Multi-criteria decision making

Multi-criteria decision making problems comprise of an underlying space of feasible solutions and several objectives that can be evaluated with regard to the feasible solutions. In general, for this kind of problem there does not exist a generic solution approach and unambiguous concept of optimality, but different approaches depending on the viewpoint of the decision maker towards the underlying problem. Lexicographic optimization assumes that the given objectives can be ranked a priori and that the decision maker is interested in an optimal solution with respect to this ranking. Goal programming transforms the given objectives into goals specifying certain values that a solution is supposed to achieve. Reference point methods assume that the decision maker is interested in a solution that minimizes a certain distance function to a given reference point. If the objectives are considered to be equally important and cannot be ranked a priori, a decision maker might also be interested in the entire set of solutions which cannot be improved with respect to one objective without worsening the value of another objective leading to the concept of non-dominance and efficient solutions. These different premises and notions of optimality will generally lead to different (desired) solutions. For a more extensive review of multi-criteria optimization the reader is referred to [24].

In Sustainable Product Development problems the objective cannot be ranked a priori since the economic, environmental and social dimension is considered to be equally important.

4. Approach

In order to improve decision making an integrated methodology for sustainable product design is proposed. As a major target the chosen approach shall bridge the gap between prospective and retrospective decision support by offering quantitative analysis in early design phases already. Furthermore, the user of the method shall be enabled to consider multiple design objectives in order to identify efficient solutions.

As a starting point, properties of value creation networks (e.g. aggregated CO2 emissions) are seen as the result of subsequent decisions of different stakeholders along the product lifecycle. Design engineers determine the product characteristics (design parameters like materials or geometry) by choosing from a pool of alternatives, which potentially fulfil given requirements. Process engineers select manufacturing alternatives which are capable for the implementation of given requirements by design. Remanufacturers and recycling companies decide whether components and materials will be recovered according to cost-benefit considerations etc.

Since decisions of design engineers have a large influence on all downstream activities it would be beneficial to identify optimal paths through value creation networks from a sustainability perspective. If, for example the designer knows that remanufacturing is more beneficial than recycling, he could implement a modular product structure which simplifies disassembly. Therefore, he indirectly influences the solution space of the remanufacturer to some extent. In addition he could foresee the long-term consequences of his decision. For example cost savings by choosing a cheap material could be overcompensated by a high scrap rate during the production.

In order to visualize and calculate the different dependencies and options for designing a value creation network, a consistent way of modeling is needed. Approaches coming from engineering design, lifecycle evaluation and multi-criteria assessment shall be combined for that purpose.

Common ways for representing the structure of the described situations are *decision trees*. They show hierarchical interrelations and can therefore be used to model process alternatives for every phase in the product lifecycle. Every time a design parameter is set, the solution space is limited, leading to different decision pathways, e.g. if a complex part-geometry is chosen, but selected manufacturing processes are possible. These processes may be only available in some of the company's production sites. Moreover, the decision for the location of manufacturing requires commitments for transport and logistics, etc.

As an additional element the decision tree can be enriched with attributes to characterize the impacts of the alternatives. In this work quantitative sustainability indicators coming from LCSA will be used for that purpose.

In Figure 1 this approach is visualized. Different *Tiers* characterize the sequence of decisions made. Since the method is used by designers a Tier 1 decision could be the definition of a design parameter (e.g. material, tolerances, technology etc.). The following Tiers reflect all value creation decisions along the product lifecycle associated with economic, environmental and social indicators.

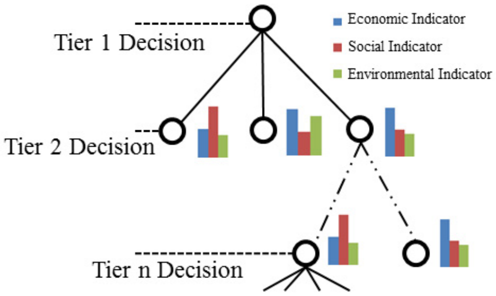


Figure 1: Decision Tree for Sustainable Product Development

When all value creation options are defined and assigned with indicators they provide the basis for multi-criterial mathematical algorithms, which allow the calculation of efficient solutions.

Those solutions are superior from a pareto-perspective (see 5.2). However, there are still multiple solutions which are at least in one dimension preferable. The final selection of the decision path out of the remaining alternatives therefore needs to be based on individual (and company's) preferences. The process of method application consists of four steps which are described and demonstrated on the example of designing a bicycle frame in the following paragraphs.

5. Exemplary method application

5.1 Definition of research target, scope & decision options

In analogy to the LCA procedure the method user defines the target and scope of the analysis [18,19]. First design parameters to be included in the analysis need to be defined. Since the method can only handle discrete variables some design parameters (e.g. specific geometry decisions) are excluded automatically. Furthermore, specification of considered lifecycle stages is necessary. For a holistic analysis the scope should be as wide as possible. However, if it is clear that a process only contributes to a small extent to sustainability impact, simplifications might be justified. If required information about a process step is missing it may also be necessary to narrow down the analysis.

As a next step, given alternatives and their relation to each other need to be researched for the defined scope. A pre-selection of options is the result of comparing existing solutions with the product's requirements and company's capabilities (e.g. existing manufacturing processes).

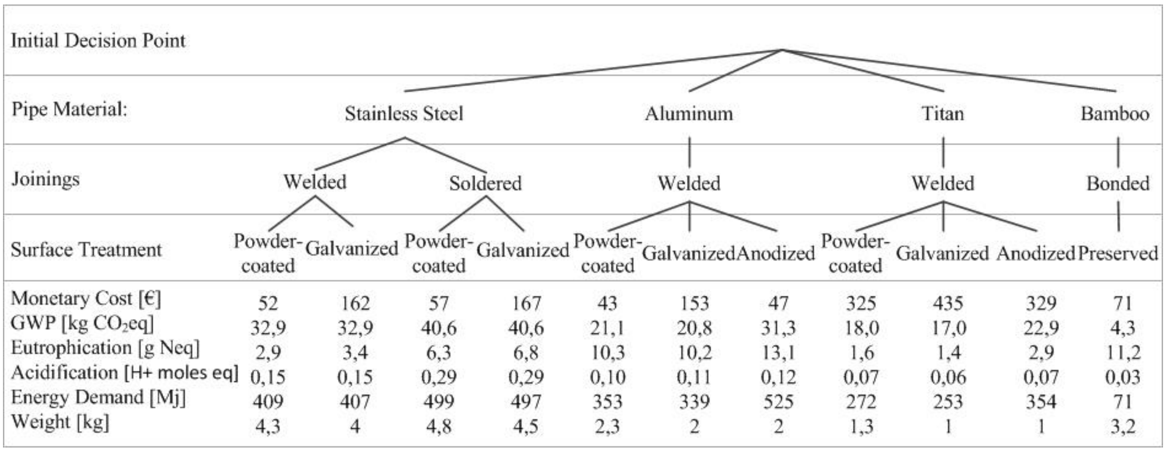
The target for the analysis of the bicycle value creation network is the evaluation of different options for frame-materials as well as for the follow-up processes joining of the pipes and surface treatment (see Figure 2). The use phase was seen as less relevant, as the bicycle frame is supposed to last for the complete life time of the bike. Durability and maintenance; the most significant factors in this context, were assumed as requirements on the frame, which are the basis for a first selection of design options. Due to missing data regarding take-back systems for bicycle frames the end of life phase was not considered.

As the first set of options, established materials of bicycle frames (Stainless Steel, Aluminum and Titanium) are considered. Bamboo was also included as a promising alternative. For joining the tubes welding is the most common process. For steel tubes soldering is possible as well, whereas bamboo frames are bonded via epoxy and hemp fibers. The surface of the tube can be treated with powdercoating or galvanization for all metals. Aluminum and Titanium frames can also be anodized. Bamboo tubes are painted with a special coating for conservation.

5.2. Indicator selection and data sources

One of the main characteristics of the proposed decision-tree method is its focus on quantitative analysis. Qualitative requirements like aesthetics or ease of disassembly can only be considered by the mathematical algorithm when they are quantified. Nevertheless, in many cases semi-quanitative scores are more subjective since they leave room for interpretation. Therefore, they are excluded from the analysis.

In order to measure the social dimension, the weight of the product has been chosen as a reference. It was seen as significant since it implies social, economic and environmental aspects. A lighter frame is beneficial for improving handling in production processes. Therefore, it directly contributes to the ergonomics for the worker. In addition it provides further benefit to the customer in the use phase since he can drive faster with less effort and therefore requires less energy. To adequately address the environmental dimension, indicators which are found to be relevant by several institutions are included. Good indications can be taken from the ILCD handbook or the UNEP/SETAC Life Cycle Initiative [25-26]. Climate change is of high relevance for production processes, especially in connection with fossil fuels. For agricultural processes, eutrophication is also of importance due to fertilizer use and related phosphorus and nitrogen emissions [27-28]. Both indicators are included in this study due to the fossil fuel based metal production, along with the production of the bamboo cultivation. In addition acidification and primary energy demand are included to indicate more environmental impacts but also to show the challenges in decision making due to contradictory results. The environmental indicators could be calculated by utilizing the GaBi-database. Some processes needed to be modeled since they were not included (e.g. cultivation of bamboo) Economic aspects were measured in process- and material costs. For an assessment purchasing prices for products (pipes) and services (welding the frame) were used as a reference. In some cases data was not available (e.g. soldering of a steel frame). Assumptions were made by estimating wages and material cost. Therefore, the validity of the calculated costs is limited.



Pipe Material:	Stainless Steel				Aluminum			Titan			Bamboo
Joinings	Welded		Soldered		Welded			Welded			Bonded
Surface Treatment	Powder-coated	Galvanized	Powder-coated	Galvanized	Powder-coated	Galvanized	Anodized	Powder-coated	Galvanized	Anodized	Preserved
Monetary Cost [€]	52	162	57	167	43	153	47	325	435	329	71
GWP [kg CO_2eq]	32,9	32,9	40,6	40,6	21,1	20,8	31,3	18,0	17,0	22,9	4,3
Eutrophication [g Neq]	2,9	3,4	6,3	6,8	10,3	10,2	13,1	1,6	1,4	2,9	11,2
Acidification [H+ moles eq]	0,15	0,15	0,29	0,29	0,10	0,11	0,12	0,07	0,06	0,07	0,03
Energy Demand [Mj]	409	407	499	497	353	339	525	272	253	354	71
Weight [kg]	4,3	4	4,8	4,5	2,3	2	2	1,3	1	1	3,2

Figure 2: Decision Tree for the selection of material for a bicycle frame

5.3. Enumeration of efficient solutions

In general, considering several objectives, one cannot expect to find a (unique) solution that optimizes all objectives simultaneously. Instead, one has to deal with trade-offs. Letting $X=\{x_1,\dots,x_n\}$ be the set of feasible solutions and $f_1,\dots,f_k$ be the different objectives a solution $x \in X$ is called efficient (for a minimization problem) if there exist no $y \in X$ such that $f_i(y) \leqslant f_i(x)$ for all $i \in \{1,\dots,k\}$ with a strict inequality for at least one of the objectives. In other words, a solution is efficient if any improvement in any of the objectives will result in a worsening in at least another one. Furthermore, only an efficient solution is considered to be a solution a decision maker is willing to base his final decision on. Hence, in the following it is assumed that the decision maker is interested in the whole set of efficient solutions.

If all six indicators are considered simultaneously two inefficient solutions could be identified for the bicycle frame. Both variants of the soldered steel frame (powdercoated or galbvanized) are inferior to the nine other product-designs. The high number of efficient solutions is not surprising since the set of feasible solutions is relatively small compared to the number of focused objectives. Since the solution space is still large indicators can be excluded from the analysis. Using this approach can be considered as an indirect weighing according to the preferences of the design engineer.
If eutrophication is neglected for example, galvanized steel is also inefficient. When weight is excluded instead of eutrophication, soldered steel as well as anodized aluminium and titan are not efficient anymore.

6. Discussion and further approach

As the presented example has shown, multi-criteria analysis of decision trees has the potential to contribute to Sustainable Product Development. By up-front comparison of different combinations of design choices and manufacturing processes a real planning perspective can be enabled. Nevertheless, there are some restrictions connected to the approach:

One of the main problems of mathematical trade-off analysis via decision trees is the definition of the regarded scope. In the case of a bicycle frame only few manufacturing processes are necessary. More complex products require additional effort in modelling. Furthermore, the alternatives for combination grow with every further system element. Leaving out certain phases in the product lifecycle automatically results in imprecisions and may result in including inferior points or missing efficient solutions. In the bicycle example a company would need to build a model for all available decision alternatives (e.g. different alloys of steel) which fulfill the given requirements. Nevertheless, due to the multitude of available options and combinations only selected alternatives can be considered. Therefore, further research is necessary for automatized generation of decision trees.

Another important factor is process granularity. A node of the decision tree could for example either represent the process “welding” or it could be the sub process “preparation of the components”. The user needs to choose the adequate level of detail by keeping in mind that the effort for data-provision rises with process granularity.

Further limitations can be found in the selection of indicators. The method is only capable of computing quantitative results. Qualitative indicators are therefore neglected. Furthermore, research about social sustainability is still in its infancy. As long as no quantitative product-related indicators are available the proposed method cannot contribute to implementation of all sustainability dimensions.

Acquisition of data is another point. The six indicators, which were used as a basis for the analysis of the bicycle frame required a complete GaBi-model for all considered production processes. Further research was necessary to calculate the cost of the processes and the resulting weight of the frame. Within a company context information availability should be less critical. Cost information can be acquired through the companies ERP system. Design-related information like component-weight can be determined within CAD.

Furthermore, knowledge acquired in previous projects can be utilized for estimation of indicator values.

The proportion between feasible solutions and considered objectives needs to be chosen well. Many objectives in contrast to a small amount of paths through the value creation network will lead to a high amount of efficient solutions and therefore in limited use for the design engineer.

If the model is designed one time it can be reused for any similar decision situation as a prospective analysis method. Furthermore, it needs to be researched in further works how the decision tree could possibly be integrated with other system models (e.g. as a form of ontological knowledge representation)

7. Conclusion

For developing sustainable products design engineers could benefit from multi-criterial quantitative sustainability information which is available in the early phases of product design already. Therefore, an integrated methodology was developed which implies research activities of different scientific fields (environmental sciences, product design and mathematics). The resulting decision tree was tested for the case of material selection for a bicycle frame. The application process delivered promising results and gives an idea of how value creation chains can be planned and influenced by design engineers for including sustainability principles. The resulting complexity of the addressed decision situations leads to a number of obstacles like the missing consideration of qualitative indicators or the difficulty of data acquisition. Nevertheless, by embedding the proposed approach into the companies IT landscape, and continuous coupling with other models (e.g. by ontologies), the design engineer's workplace can be improved.

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