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ANALYZING THE PROJECT-SPECIFIC RELEVANCE OF ENERGY EFFICIENCY AS A DESIGN OBJECTIVE

A. Albers, P. Martin and S. Geiger

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1. Introduction

Energy efficiency (EE) generally describes the degree of usage of energy in order to generate a beneficial output. Thus it describes the trade-off between functionality and performance on the one hand and a corresponding energetic effort on the other. Such a trade-off and thereby affected decisions are virtually exemplary for almost all important decisions in the product development process.
In the overall societal context, the efficient usage of energy is perceived and with increasing sensitivity. This is mainly caused by a rising ecological awareness and higher energy costs. Additionally an increasing importance of energy efficient products is caused by a rising number of mobile applications, i.e. energy related products that draw energy from a limited mobile storage as well as by more severe energy saving regulations and specifications.
The combination of this variety of facts leads to two major impacts on product development and design: On the one hand companies that design ‘energy-related products’ and even products where there is no evident energy use, try to clearly highlight the energy efficiency of their products at alleged unaffected effectiveness. On the other hand the actual requirements regarding the development of energy efficient products are really increasing due to numerous reasons, which are discussed in this paper. Due to the rising demand and market potential for in-use energy-efficient products, EE is seen as a rapidly growing sales segment for innovative products. According to Ziegler [2011] a quadrupling of the revenue is expected in the global market for energy-efficient products. However, formulation and communication of objectives and requirements regarding EE often are undifferentiated. This leads to a lack of common and consistent understanding and corresponding handling or use. However, as for every objective in product development the definition, communication and quantification of the objectives are a major requisite for its successful implementation or fulfillment. Additionally for industrial companies an early assessment of the value creation potential of considering Design to Energy Efficiency (DtEE) aspects is necessary. Methods that are meant to support the design of energy efficient products, at the same time have to promote the efficiency of design processes and the quality of the product, in order to be accepted and applied in industry.

2. Fundamentals and state of the art

In 2.1 different definitions, perspectives and understanding of EE are discussed. In 2.2 methods and corresponding groups of methods within DtEE are distinguished and their contribution is discussed. In 2.3 the relevant state of the art is presented regarding general understanding of objectives and requirements.

2.1 Energy efficiency

Originally, efficiency is almost synonym to effectiveness (from Latin efficere = to effect, to bring about, to execute). The actual and common meaning of efficiency, however, is the description of a relation between effectiveness and effort. Thus, by the ratio of a desired generated effect to an input effort, which is required to generate the corresponding effect, it describes the adequacy of the effort with respect to the benefit or utility value.

According to this rather broad definition of efficiency, there are various possibilities of interpretation or corresponding definition of energy efficiency. The most established ones are thermodynamic, physical or economic points of view and combinations thereof [Patterson 1996]. Additionally there are different definitions according to the dimension in time that is considered, e.g. holistic or product lifecycle phase specific, and according to the level of abstraction [Patterson 1996], [Pehnt 2010].

The most common description of in-use EE of technical systems is the 'efficiency ratio', i.e. the ratio of energetic output to energetic input. This allegedly simple approach offers maximal comparability; the meaningfulness however, can be questioned for most products, which are not primarily designed for a transmission of energy, which is exemplarily described by Mitsos et al. [2007]. Different perspectives on EE of technical systems can be mainly assigned to different considerations, for example of what counts for the energetic effort, for the desired output or what is the considered time range [Mudgal et al. 2012].

As described in Martin et al. [2013] the authors propose to bound the desired output of a system very tightly to the fulfillment of customers' requirements, which are translated into the utility profile of a future product. This has to be considered already during the definition and communication of initial objectives regarding EE, and even more during deduction of more concrete design objectives. It still lacks of corresponding definitions and systematic approaches in order to support such a target oriented understanding and its differentiated and task-specific application.

2.2 Design to energy efficiency

In the past, general research on EE and corresponding approaches that support the identification of suitable objective's meaning and formulation has mainly been discussed in context of policy, economy or, very occasionally in product-specific EE improvements. However, those aspects and especially a differentiated understanding of EE are of increasing importance for engineering design, also in order to choose appropriate methods for increasing the EE in a following step.

Depending on the motivation, that causes the EE to be a relevant objective for a specific design task, the methodical approaches being suitable to support the designer differ considerably.

If the motivation is dominated by ecological reasons, appropriate methods are to be of holistic character in order to cover all influences and interrelations that are ecologically relevant. Those methods are extensively discussed for example in Abele et al. [2005]. Within that field, EE is only one single aspect considered in terms of the general efficiency of resource usage and thus is not studied in depth or in a differentiated way.

If EE is motivated by an economic perspective, EE is sometimes even described solely by financial parameters so that the desired output as well as the energetic effort is measured in terms of economic value [Patterson 1996]. If the economic motivation for EE is caused by operational costs due to operational energy demand, there are methods available for focusing the increase of in-use energy efficiency by means of guidelines [Bonvoisin et al. 2010] and product-type-specific approaches [e.g. Simunic 2001], [Rünger et al. 2011]. The method developed by Rath et al. [2011] allows the identification of suitable measures depending on the actual design phase. [Elias et al. 2009] differentiate between in-use energy losses caused by the design of the product, its technology or materials and the losses caused by the user and his way of product application.

If EE is motivated by legal conditions the specific constraints are usually described within the corresponding law and limit the suitable guiding methodical approaches. Legal conditions and labeling obligations for EE mostly are defined for in-use EE, for instance by the EU [2010].

EE motivated by technical and functional requirements is characterized by a limited possibility to abstract those matters in order to transfer corresponding solution approaches in an appropriate manner. In such cases product-specific research is usually necessary in order to improve EE. Nevertheless there

are many approaches aiming to provide product-independent support to improve product-specific EE. One sub-reason of technical motive is the mobile application, i.e. the limited availability of mobile energy [Simunic 2001], [Diehl et al. 2006].
These different perspectives and corresponding methodical approaches do not include any systematic procedures of how to identify or differentiate between specific motivations for EE. There are approaches that are independent of the motivation, especially for analysis of energy flow and deduction of EE potential. The potential of an increase in EE, however, is only described as the gap between theoretical or technical optima and current characteristics, usually in % or by the height of energy use [Elias et al. 2007]. Unfortunately, the relevance of an improvement in EE from the different motivational perspectives has been neglected so far. The relevance describes the potential benefit from different motivational perspectives in case of an EE improvement, instead of a quantified theoretical gap. By considering both, EE relevance and EE potential, it should be possible to estimate the resulting value creation potential (Figure 3).

2.3 Understanding of design objectives and requirements

According to Lohmeyer [2013] objectives can be described as a conscious mental anticipation of a future target state that is commonly agreed upon. And it is the objectives that found the objects' future function and embodiment. Furthermore they are perceived information units for mental guidance [Albers et al. 2012]. It is known that especially in interdisciplinary development projects the common understanding of the objectives as well as their explication and objectivation is essential for a successful development [Albers et al. 2011]. Due to the individual state of knowledge and experience [Ahmed et al. 2007], the perceived information is interpreted differently.
By bringing together customer requirements and corporate goals, the initial system of objectives is set up. The technical requirements for the design task are then to be deduced from those objectives.

3. Research target and approach

Within our research on differentiated understanding and handling in DtEE we propose an extension of the existing, rather solution-oriented DtEE by a more target-oriented view in the first step. The superior research question that is dealt with in this paper is: "How can EE as a design objective be considered systematically?" This includes sub-questions, such as: "What aspects of EE are to be considered for further developing the objective?", "How can the relevance of EE be evaluated?", "How can the motivation for a consideration of EE as a design objective be identified?" as well as "How can suitable system borders be early defined for a consideration of EE?". A methodical approach is developed that implements the answers by covering two different levels:
The first is to support the management of design projects dealing with EE as a major objective. This can be realized by supporting the definition of EE objectives in a more differentiated and case-specific way. This is expected to lead to better communication and thus to a better common understanding of the objective, which in turn is essential for successful product development. Furthermore early differentiated understanding of the objectives enables a better assessment of the objective's value creation potential.
The second level is meant to support the designer in handling the objective in a more differentiated, predictable and thus more efficient way. This is possible by means of a systematic identification and evaluation of the underlying project-specific motivations and their relevance for the task, by recommending adequate scopes to be considered, as well as by operationalizing the EE as a design objective including its representation by means of suitable indicators [Martin et al. 2013].
Our research is neither aimed to directly support technical improvement of the EE nor to decrease the lifetime energy consumption. Those important topics have already been dealt with in numerous other research publications (cp. 2.2). Rather, we intend to support the earlier fundamental steps of the design process in order to enable a more consistent and target-oriented basis for the application of those methods that are meant to directly support an increased EE of technical systems.
Generally, it is the EE of the product itself what is studied. Lower energetic effort for the manufacturing process for example is not part of the products EE, except in case of ecologic motivation where EE has to be understood and treated more holistically.

4. A differentiated view on energy efficiency as a design objective

In addition to the findings in theory of objectives (cp. 2.), analyses of design projects centrally aiming at energy efficient product solutions have shown that an individual and rather undifferentiated approach often leads to different understandings and corresponding handling of EE as a design objective. It can be seen that different intensions and motivations underlying this particularly imprecise objective aim at different aspects of EE and consequently lead to very different design problems, foci and corresponding solutions.

During the definition of the product profile, objectives are defined and complement the system of objectives, which is extended and adapted during the entire product engineering process. Definition and changes of those objectives considerably affect the following product engineering activities.

This shows the importance not only of an adequate understanding of the objectives, but even more of their differentiated and target-oriented definition. In case of EE this is particularly critical due to its variety of strong interrelations with other objectives and requirements regarding the utility value of the product as well as its energetic properties.

By transferring the objectives into objects it is mainly the engineering designer who puts into effect the utility value as well as the energetic properties over every life cycle phase of a product, thus this step also determines the energy efficiency. The designer's decisions primarily are based on his understanding of the desired product properties, which in turn are based on his personal experience and knowledge. However, those properties and the underlying motivations, especially regarding the energy efficiency objectives, are not always clear and the evaluation of their meaning or relevance is not intuitive.

The actual meaning of EE as an objective depends on the underlying intensions and motivations, as well as on the respective combination of their project-specific manifestations. The presented approach is based on the assumption that it is possible to find most of the relevant information for a suitable understanding and handling in the more or less extensive description of the product's utility profile and the defined boundary conditions. Especially in case of the commonly occurring product generation development this should be possible by knowing the underlying motivations causing the objective EE. Additional information regarding future product properties based on the predecessor versions or competitor solutions enables an early increase of the objective‘s maturity without an inadequate increase in rigidity.

Hence, the methodical approach presented in the following sections aims to systematically clarify the underlying motivation, as well as their motivation-specific relevance for the further design process. Additionally, the developed method gives guidance and recommendation regarding possible foci in order to reduce the scope (with respect to time and space) to be considered, as well as it points out chances and risks. In order to enable a systematized way towards a differentiated understanding of EE as a design objective, the different dimension of EE are to be distinguished.

4.1 Different underlying intensions and motives for DtEE

There are basically two groups of intensions and motives for designing energy efficient products (cp. Table 1): endogenous and exogenous. For endogenous motives the major influence on the definition of the objective is from within the company. Those are economic, ecologic and technical/functional aspects. Exogenous motives are marked by major external influence on the objective's definition. They mainly consist of legal aspects and motives linked with external representation and marketing.

Table 1. Classification of motives for EE as design objective

Type of motivation	*Dimensions*	*Main influencing factors*
endogenous	**Economic (E)**	Energetic operational costs; Public funding; Purchase costs; …
	Ecologic (O)	Energetic effort; Emissions; …
	Technical/functional (T)	limit of energy flow regarding material (thermal,…) or user (ergonomics,…); Power availability; Power sources; Thermal load; Mobility (Capacity / application range; transportability); …
exogenous	**Legal (L)**	Limits power consumption; limits of emissions; binding labels
	External presentation (I)	Binding and non-binding labels; Marketing/PR; …

For a differentiated and target-oriented understanding of EE it is necessary to clarify the specific manifestations of existing and potential motives. This is done by analyzing five basic motives (Table 1, middle column). With those basic motives it is possible to describe any possible motivation.
By analyzing the project- or utility-profile-specific manifestation of these motives the actual potential of EE for the parties involved (manufacturer, user, environment) can be analyzed. It is possible to gain additional knowledge by uncovering implicit information and non-obvious interrelations and effects in order to get a differentiated understanding of the EE with an adequate maturity for target-oriented formulation and communication.
The respective manifestation and combination of the basic motives determines, among others, the lifecycle phase, which is most important to focus with respect to the EE objective (cp. Figure 1). If the motivation is, for example, dominated by ecological matters, corresponding understanding and applied methods are to be of holistic character in order to cover all interrelations, that are ecologically relevant. In such a case all lifecycle phases would have to be considered and suitable methods and tools could be chosen correspondingly.

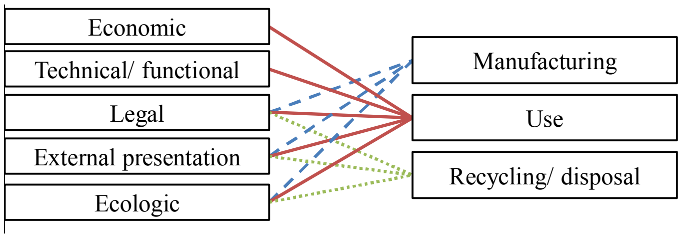

Figure 1. General relations between different motives for EE as a design objective and the corresponding life cycle phases to be considered

All motivations that usually play major roles in practical product design context do affect the use-phase of the product. That was already mentioned by Abele et al. [2005] who identified the product's use phase as crucial for energy using products. Hence the use-phase is recommended to be focussed in most of the application cases. Manufacturing and recycling/disposal phase of the product are only recommended to be considered if the motivation specifically reveals its relevance during evaluation.

4.2 A method for differentiated understanding and evaluation of the relevance of EE

In order to enable a differentiated understanding of EE as a design objective a method is developed. It is based on a differentiated knowledge about the task-specific manifestation of the motives and their relevance. This knowledge on the one hand is used to get an idea of the overall relevance of EE for the task or project. On the other hand it leads to the possibility of focussing decisive areas (in space and time) to be considered.

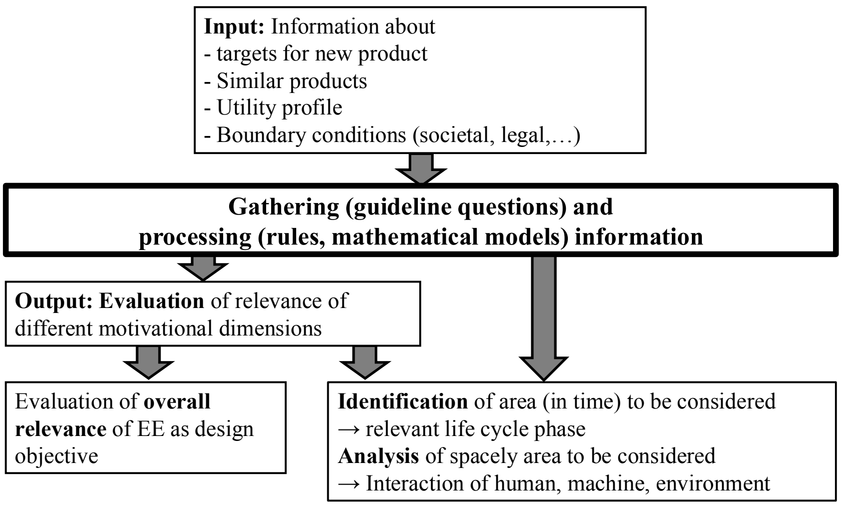

Figure 2. Schematic illustration of methodical approach

Hence, in the first step the method is supposed to support the analysis of the information available about the utility profile, the targets for the system of interest and relevant boundary conditions.
Based on the result of this analysis the method interprets and complements this information with general data (e.g.energy costs), interrelations of context and eventually with assumptions. These assumptions for example are based on experience and knowledge from predecessor solutions of the same or similar utility profiles. For identification and evaluation of the interrelations cross-impact-matrices are used to include project independent logical and experience-based knowledge.
By crosslinking the information and comparison with reference patterns, the method recommends system foci, and potentially decisive product engineering activities and critical project interfaces, depending on the respective product utility profile and the corresponding manifestation of the motives. It aims to guide deciders and designers step-by-step in order to clarify the actual meaning, relevance and characteristic of EE in the specific project context and to point out potential beneficial and critical aspects for the further design process. The principle procedure of the method is schematically illustrated in Figure 2.
The relevance of EE for a specific development task can be evaluated by means of the developed methodical approach. The 'η-potential' (Figure 3) means the potential of improving the efficiency ratio in relation to a technical optimum or a market's benchmark and has to be evaluated regarding suitable established solutions. By considering both, EE relevance and technical potential, it is possible to estimate the value creation potential (Figure 3) for in-use energy efficiency. This way, corresponding measures can be deduced, such as adapting or questioning the exploitation effort and shifting resources. In case of high relevance and low technical potential of improving EE, an alternative solution technology might be interesting. At this point established methodical approaches (cp. 2.2) can be helpful for finding appropriate alternative product solutions.

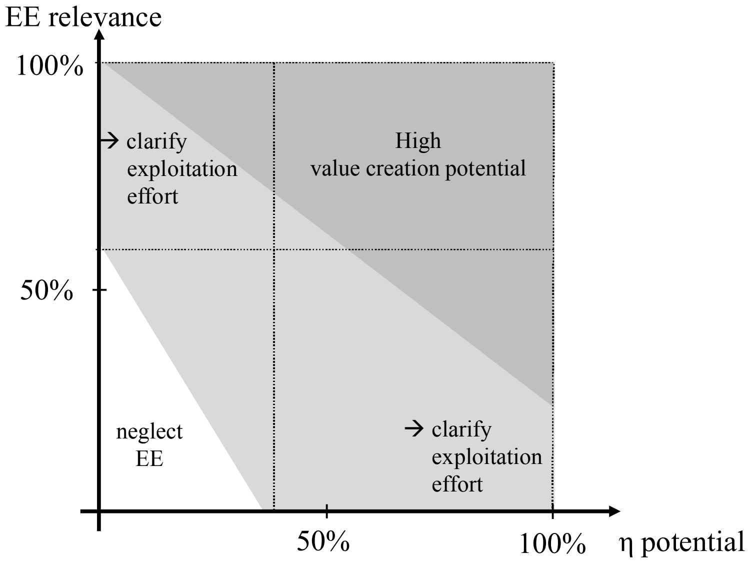

Figure 3. Qualitative illustration of value creation potential of in-use EE, depending on EE relevance and EE potential

4.3 Implementation of the Method

The method consists of a generic and an adaptive part. The generic part describes the approach of an interactive guideline consisting of several classified sequences of questions regarding the different motivational dimensions in order to clarify their specific manifestation, and thus, their relevance. Every answer contributes to a qualitative and quantitative evaluation of the relevance of EE as a design objective, as well as to logical and experience-based recommendations for further understanding and handling of EE. The latter also has major effects on the setup of suitable EE indicators according to Utiliy based Energy Efficiency Indicators (UBEEI) [Martin et al. 2013].

For the setup of product utility-specific indicators suitably representing EE targets, it is essential to have clarified adequate scopes to be considered, as well as the product properties derived from the utility profile that are decisive with respect to the EE of the object.

The motivational aspects (cp. Table 1) which contribute to the relevance of EE for the specific task are analyzed each by a sequence of questions and the interrelations of the corresponding answers. The questions are to be answered by choosing from a set of answer-options. The answers are linked to certain relevance-values that are summed up for each sequence to build the quantitative evaluation of the relevance of this motivational aspect. By the value and distribution of the overall relevance evaluations suitable recommendations can be given (e.g. regarding the scope). Additionally some of the answers cause indirect consequences in relation with other answers depending on the cross-impact-analysis. Furthermore, the answers lead to a qualitative evaluation in terms of logical interpretation and when inidcated in terms of a link to potential recommendations. There are also questions that can be answered quantitatively leading to a calculation of parameters and ratios indicating direct and indirect consequences as well as to a refinement of the subsequent questions. Certain sequences of answers can also lead to direct consequences, which can be statements or recommendations.

There are different questions, varying in the type of possible answeres:

1. Binary decisions (Yes/No)
2. Quantitative values (given dimension)
3. Alternative decisions choosing different options
4. Alternative decisions choosing a quantized degree of manifestation
5. No answer (not specified) due to lack of information or conscious solution neutrality

The order and length of the sequence of questions for each motive depends on the context and the incremental level of concretization during one sequence and is not bound to any superior structure.

A classification used for numbering the questions enables short and clear description and assignment. Additionally the scheme of classification gives orientation to the user regarding the motives (letter for motive group see Table 1) and its current question level (number).

The principle setup of the generic part of the method is illustrated in Figure 4.

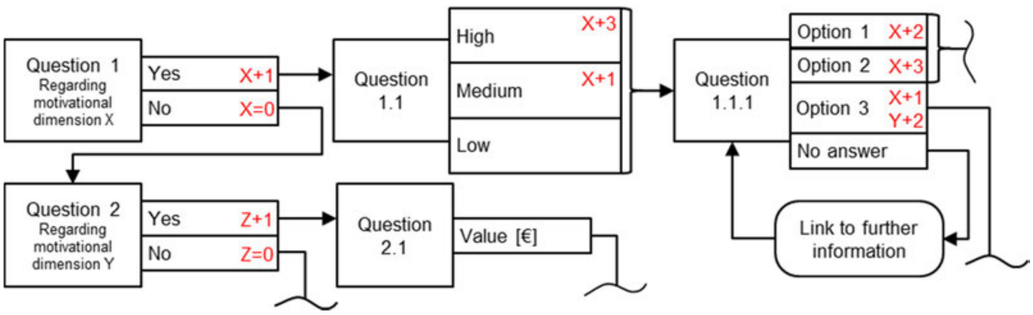

Figure 4. Schematic illustration of the generic methodical approach: Exemplary sequence of questions evaluating specific motives x and y

Let's take the development of an electric vehicle as an example: From the product profile, the requirement to use a mobile energy storage is deduced. If the weight of the product is evaluated to have a medium or high impact on its energy demand (what usually would be the case in our example), this combination of answers would increase the specific relevance of EE in this case. Since the weight of the energy storage usually makes a considerable fraction of the vehicle's weight, the potential advantage of a bigger storage as the easiest solution is no longer given. Contrariwise, if the answer indicates a low impact of the products weight on its energy demand, a bigger storage might be an interesting solution, and the relevance from a technical/functional point of view would be much lower. However, a bigger energy storgare usually causes higher costs, what increases the EE relevance from the economic point of view. Hence, for this example the overall relevance would depend on the relative weighting of the motives economy and techincal/functional as well as on answers discussed. If there already are intensions or requirements regarding the energy form to be used, the discussed interrelations are additionally intensified or diminished, as the correlations of storage size and weight

or costs very depend on the energy form. A storage increase in case of a battery has much higher impact on the vehicles weight and costs, as in case of a conventional fuel tank.
Within the adaptive part of the method there are default settings that intend to cover most practical applications but are designed to be adaptable in order to increase domain-, company- or project-specific significance. These are for example the number and type of existing motives, the arrangement and sequence of questions, the number and range of answering options, the relevance values linked with the respective answering options as well as the logical links between different answers and given recommendations.
Addtionally, there are some elements of the method that are explicitly designed to be adapted for the company- or domain-specific application, or even complemented during the project-specific application due to their dynamic nature. One example for these is the cost of different energy forms since they depend on their source and current prices.

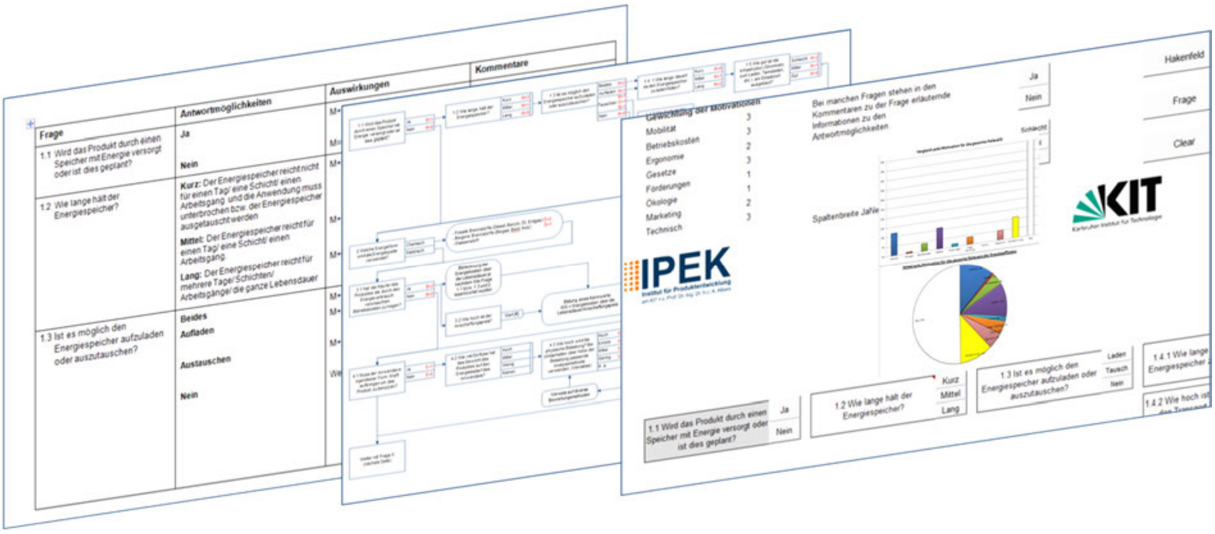

Figure 5. Three levels of representation of the methodical approach

There are three main levels of representation of the methodical approach (Figure 5). One is the complete guideline in a list-form with the complete set of questions, all interrelations, explaining comments for the answering options and possible recommendations and potential risks and chances.
The second is a graphical representation illustrating the structural dimension of the classification as well as the interrelations.
The third representation is a graphical user interface (GUI), implementing the method in a simple software tool. Here the questions appear either one after another or all of one sequence, until the next answer leading to different answer branches. The explaining comments are only shown for the last unanswered question and for other questions or answering options by a "mouse-over" function. The interrelations are not visible and are only reported if identified as relevant due to the answers given or chosen. Also the quantitative evaluation is only shown in its fuzzy form of answering options (e.g. low, medium, high). The current relevances (overall and motive-specific) is shown in a live-chart.

5. Validation by practical design tasks

The methodical approach was applied during development and design of two different products in real development projects. In the following, only the major effects of the method's application are presented:
High current connector: The application of the method led to an unconventional formulation of the design objective EE, also highlighting the energetic effort applied by the user. This caused a different perspective on the initial design task and thus an innovative solution. As a result of the new mechanism principle, the ratio of contact force and actuating force was increased by a factor of eight. The main recommendations that were deduced from the method's application were a focus on the in-use EE and the special system borders including the user. By choosing the operational current as the

reference characteristic for a quantification of the EE target, it is much more flexible with respect to the application range, than it would have been in case of a simple energetic efficiency ratio. Although the technical η-potential was estimated with less than 5%, a considerable value creation potential was identified due to the high relevance of EE for the utility profile. A reduction of the electrical resistance of ca. 10% was achieved. The main improvement was realized in a reduction of the user's energy effort.

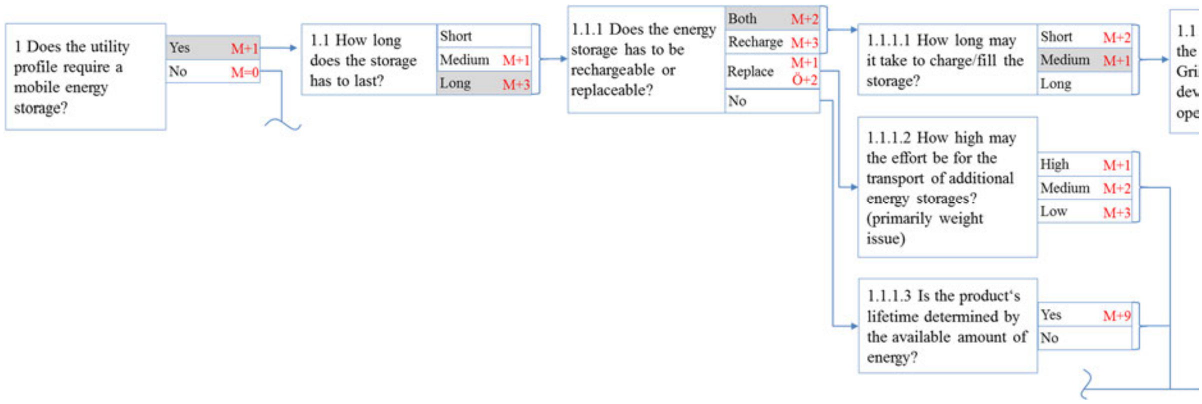

Figure 6. Excerpt of evaluation of relevance of mobility for the energy efficiency of a battery driven hammer drill

Battery driven hammer drill: The method was applied for further development of a drive cylinder hammering mechanism of a professional hammer drill. It supported a more differentiated and practical understanding of EE for the design task. An excerpt of the evaluated sequence for the mobility aspect is shown in Figure 6. Although one initial focus was set on increasing the EE by reducing thermal losses, the method uncovered a rather moderate value creation potential at a relevance of ca. 45% and less than 10% technical EE potential for this specific design task (compare Figure 3.). A high relevance of EE was limited to the technical/functional motive, due to mobility and ergonomics. Thus, the design effort with respect to EE could be reduced, the focus and corresponding resources were shifted on reducing costs and the solution space was adapted consequently. This way, the method helped to avoid not-target oriented efforts on increasing the EE by enabling an early evaluation of its actual relevance and thus enabling an estimation of the value creation potential with respect to EE. Early shifting of resources is expected to be one reason for the successful reduction of manufacturing costs by 50%.

6. Summary and outlook

A method is developed to systematically analyze and scrutinize different motivations of using the EE as a design objective. It consists of a generic and an adaptive part and is implemented by means of an interactive guideline. The method helps to consider the relevance of EE extending the commonly focused technical EE potential towards an estimation of the value creation potential with respect to EE. The main benefits of the method's application are recommendations regarding suitable foci of system and design activity, and regarding beneficial or critical design aspects.

Additional practical application of the method has to be studied in different product categories, primarily to investigate how the initial state of knowledge affects the quality and benefit of applicability. In order to strengthen the experience base for the recommendations given by the guideline, additional input from expert-surveys and interviews is strived for.

The tool (see Figure 5) has to be further developed so that the non-generic part can be adapted easily in order to consider company-specific or even task-specific conditions.

Finally the transferability of the approach to other difficult objectives could be studied.

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Dipl.-Ing. Paul Martin, Doctoral Assistant
Karlsruhe Institute of Technology, IPEK – Institute of Product Engineering
Kaiserstrasse 10, 76131 Karlsruhe, Germany
Telephone: +49 721 608 45234
Email: paul.martin@kit.edu
URL: http://www.ipek.kit.edu/english/index.php