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Lightweight creativity methods for idea generation and evaluation in the conceptual phase of lightweight and sustainable design

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Abstract

Regarding the implementation of lightweight design in products, there are various guidelines, principles and methods that support the developers methodically throughout the entire design process. Such methods often pursue the goal of optimizing an existing product by reducing the amount of consumed material (e.g., topology optimization). A more effective way to apply lightweight design lies in fostering the creativity and intuitiveness of engineers to develop miscellaneous concepts with the capability to provide far greater mass reductions in contrast to smaller efficiency enhancements. Supported through the breakdown of assemblies via thinking in terms of functions along the paradigm of systems engineering, existing creativity techniques (e.g., “brainstorming” or “6-hats-method”) and evaluation methods (e.g., “point scoring”) for idea generation and evaluation have been analyzed and rethought from a lightweight and sustainable design perspective resulting in so called lightweight creativity methods (LWCM). The methods were tested on a use case from the field of robotics, which enabled the identification of the potential of LWCM for a lightweight and sustainable design.

Keywords: lightweight design; sustainable design; idea generation; idea evaluation; creativity method

1. Introduction and Motivation

Lightweight design can be an effective tool for achieving resource efficiency in terms of material and energy consumption, which is why lightweight design can increase the sustainability of products while decreasing the costs of their manufacture. Viewed across the entire product development process (PDP), the phase of conceptual design is outstanding for the application of lightweight design strategies on products. The systems engineering approach [1] assists at this stage by first abstracting the problem and, subsequently, by creating a wide area of possible solutions. As one part of this, the idea generation and detailing into clear design principles and their following often multi-criteria evaluation are decisive for the future success of any product. To generate new solutions offering true innovations, the creativity, expert knowledge as well as intuitiveness of developers can be powerful drivers. However, the difficulty arises from the various boundary conditions on the realization of product functions, such as ensuring function fulfillment, intense cost and time pressure, and responsibility regarding sustainability, limiting the developers in their scope and resulting in a lack of innovation. It is, therefore, necessary to methodically support developers in their inspiration for a lightweight and sustainable design as well as to make innovations evaluable as quickly as possible in a diversified way [2]. Long-term existing exemplary approaches, such as in Liu et al. [3], no longer meet today's demands, which is why for this purpose traditional creativity and evaluation methods are firstly discussed to identify their characteristics (section 2) and secondly both logically combined and

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complemented by lightweight design and sustainability criteria (section 3). Having stated the methodical background, the lightweight creativity process (LWCP) was tested on a use case from the field of robotics (section 4) before resulting in a short conclusion and discussion of further research in section 5.

2. State of the Art in Literature

In a systemic development process to exploit lightweight potentials, as exemplarily the SyProLei framework by Kaspar et al. [4] has been realized using the model-based systems engineering (MBSE) paradigm, the transition from the functional ("F") to the logical ("L") view is driven by the search for operating principles on the way to realize solution-neutrally described product functions. Irrespective of the lightweight design or sustainability aspect of this contribution, well-established PDPs, e.g. Pahl and Beitz [5], adapt this procedure likewise. Throughout this procedure, numerous conceptual alternatives for the realization of subfunctions are initially generated, then integrated into a comprehensive overall system, leading to a logical model that describes the system-in-development by operating principles. Afterwards, an evaluation of the concepts follows, whereby a reduced number of most favorable principles results, which are then further detailed. This procedure is iterative, indicating that operating principles may have a retrospective influence on the initially functional modeled structure, potentially causing adjustments to peripheral components in the system. This solution-finding process is deficient regarding a specific synthesis method for the concept generation within a lightweight and sustainability-oriented product development and which will hence be developed in the following sections.

2.1. Creativity in Idea Generation

Along the problem-solving process, creativity techniques support the generation of solution ideas. For this purpose, numerous individual methods exist, whereby a summary of 172 creativity techniques can be found in [6]. To filter out the most suitable methods for the intended application in lightweight and sustainable design, the following points should be considered:

- *Classification.* Creativity methods can generally be classified into intuitive, logical as well as systematic methods [7].
- *Choice and combination.* Since each creativity technique embodies different properties, they are also characterized by different strengths and weaknesses. Thus, the choice of the appropriate method directly affects the creativity and general properties of the results [8]. Therefore, creativity techniques should preferably be performed in combination, whereby several methods of different categories and strengths should be linked to each other to mitigate their weaknesses [9].
- *Involvement of the human being.* As it is argued in [5], the human being is creative, hence it should be a central part of any creativity technique.
- *Team composition.* When carrying out creativity methods, a large number of people as interdisciplinary as possible should be chosen [10].
- *Temporal approach.* At the start of the creative process, the focus should first be on the quantitative idea generation, followed by a quality-oriented concentration on individual solutions for a successive idea detailing [10].

Based on these aspects, Fig. 1 lists a total of 17 selected creativity techniques for idea generation and evaluates them with regard to the specified aspects (*quantity of results*, *quality of results*, *combination possibility*). The criteria for evaluation are extended to include the following relevant factors for a lightweight and sustainable design:

- *Intuitiveness and popularity.* Since lightweight and sustainable design is a highly complex field with many dependencies and often multidimensional implications, the underlying methods of traditional product development should be as widely known and as simple as possible before they are adopted for a lightweight and sustainable design. The criteria of intuitiveness and popularity provide a remedy for this.
- *Multidisciplinarity.* As both lightweight design with its various strategies (material, production, joining technology, product shape) and sustainable design regarding the three pillars of sustainability (ecological, social, and economic effects) are highly interdisciplinary, a creativity technique must also match this nature.
- *Digital implementability.* Alternative forms of work (e.g., mobile working) as well as increasing globalization often require the enhanced implementation of product development methods via digital platforms, which is why creativity techniques in lightweight design shall essentially be digitally implementable.
- *Controllability of focus.* Since this research aims to adapt existing methods in the field of idea generation by the integration of lightweight design and sustainability principles, the degree of focus controllability is used to evaluate the possibilities to introduce these aspects into the various methods.

○ not/low
◔ rather low
◑ intermediate
◕ rather high
● high

Creativity technique for idea generation	Characteristics of each method									
	Classification	Quantity of results	Quality of results	Combination possibility	Intuitiveness	Popularity	Mult-disciplinarity	Digital implementability	Controllability of focus	Potential for innovation
Brainstorming	I	●	◔	●	●	●	◔	●	○	◑
Delphi method	I	◔	◕	◔	◑	●	●	◔	●	◑
Gallery method	I	●	◑	◕	●	◑	◕	●	○	◑
Method 635	I	◔	◑	◑	◕	◑	◕	◕	◔	◑
Phillips 66	I	◕	◔	◑	◑	○	◑	◑	◑	◑
Stop-and-go-method	I	◕	◑	◕	◕	◔	◑	◑	◔	◔
6-hats-method by De Bono	L	◔	●	◔	◑	◔	●	●	●	◑
Bionics	L	◔	◕	◕	◕	●	◑	◔	◑	●
Emotive word analysis	L	◑	◔	◕	◕	◔	◑	●	●	◕
Look for opposites	L	◕	◑	◑	◕	◑	◑	●	◕	◕
Osborn's checklist	L	◑	◕	◔	◕	○	◑	●	●	◑
SCAMPER	L	◔	◕	◑	◕	◔	◔	●	●	◑
Stimulus picture analysis	L	◑	◔	◕	◕	◑	◑	◕	●	◕
Synectics	L	◑	◑	○	◔	◕	◑	◑	◑	◑
Design catalogue	S	◔	●	◔	●	◕	○	●	◕	○
Morphological box	S	◑	◑	●	◕	●	◑	●	◑	◔
TRIZ	S	◔	◕	◑	◑	◕	◔	◕	◑	○

Fig. 1. In product development applied creativity techniques for idea generation and their characteristics
(Classification: "I" = intuitive, "L" = logical and "S" = systematic method).

- *Potential of innovation.* This criterion refers directly to the degree of innovation of the solution resulting from the application of each creativity method. This parameter should be as high as possible achieving a strong decoupling from existing solutions.

The evaluation of the creativity methods indicates that a large number of methods are appropriate for a wide variety of aspects, which means in summary that there is not one creativity method for lightweight design. Nevertheless, given the necessity to start at a certain point, the following parts of the publication will first focus on intuitive and logical methods.

2.2. Evaluation Techniques in Conceptual Design

The search for solution ideas by using creativity techniques generates numerous concept alternatives, which then have to be analyzed in an often multi-criteria way (e.g., development costs and times, manufacturability, etc.) while ensuring the conformity to predefined boundary conditions, e.g., the requirements list or other company specifications. Regarding the PDP, this design activity follows the process of opening up the solution space, aiming to shrink it again by excluding disadvantageous solutions, allowing the available development resources to be used only for detailing of the promising ones [11]. The therefore used evaluation procedure is mainly characterized by the two principles of eliminating unsuitable solutions and preferring the better alternatives [5].
An analysis of these frequently used evaluation methods, extended by the idea evaluation technique "how-now-wow" matrix with regard to relevant characteristics for a lightweight and sustainable design is performed in Fig. 2. Similar to the analysis of creativity methods in the previous section, the following criteria can be defined as essential for the use of evaluation methods in the context of lightweight and sustainable design:

- *Evaluation type*. For a method adaptation to lightweight and sustainable product development, the evaluation criteria must be freely definable and multi-criteria. Ideally, the criteria can be grouped into the categories of lightweight design, sustainability and costs, but must be free of contradictions and redundancies [12].
- *Effort and sharpness*. The acceptance threshold for the required effort to evaluate ideas depends on the number of ideas [12]. Thus, the more ideas that need to be evaluated, the simpler and faster the evaluation procedure itself must be. Vice versa, the fewer ideas remaining, the more comprehensive the evaluation should be. Likewise, for the sharpness: the fewer ideas are available, the sharper the evaluation method should be. Furthermore, to minimize subjective individual decisions, an evaluator group should be composed of a large number of diversified participants from different perspectives meaning interdisciplinary backgrounds [12].
- *Digital implementability.* Analogous to the idea generation methods, the following evaluation procedures preferably also have to be digitally implementable, so that a lean process can arise.

○ not/low
◔ rather low
◑ intermediate
◕ rather high
● high

Evaluation technique	Characteristics of each method: Evaluation type – Degree of freedom of criteria	Evaluation type – Multicriticality	Evaluation type – Possibility for criteria grouping	Evaluation type – Number of concurrent ideas	Complexity and requried effort	Sharpness of the results	Digital implementability
Argumentative balance sheet	●	◑	○	◔	○	○	◔
Meaning profiles	◕	◕	○	◔	◑	◑	◕
Comparison of couples	●	◔	○	○	◔	◑	◕
Point scoring	●	●	◔	●	○	◑	●
How-now-wow matrix	●	◕	◑	●	○	◔	●
Utility analysis	●	●	◕	◑	◕	◕	●
Ranking process method	●	◑	◑	◔	◔	◑	◑
Preference matrix	●	◕	◔	◑	◔	◑	◑
Techno-economic evaluation	◔	◕	◔	◔	◕	●	◕
Distance calculation by Bauer	◕	◕	◕	◑	●	●	●
AHP-method	●	●	◕	◔	◑	●	◕
Method by Breiing	●	◑	●	◑	◕	◕	●
Method by Knosala	●	◕	●	◔	◕	◑	◑

Fig. 2. Overview of well-established idea evaluation methods and their classification for a lightweight and sustainable design.

Similar to the creativity techniques, the analysis of the evaluation methods suggests as well that various methods have different advantages and disadvantages. Based on these findings, individual methods are selected in the following section.

3. The Process of Lightweight Creativity Methods

Given the fundamental background for the use of idea generation and evaluation methods, this chapter synthesizes a methodical framework that creates ideal conditions for a lightweight- and sustainability-oriented concept generation process, which is fully realized via digital tools. The presented method is mainly directed at product developers to assist them in finding solutions.

Starting with the "F" view, the developed procedure shown in Fig. 3 initially requires the definition of a function for which a lightweight or sustainable design solution is to be sought via LWCM. Therefore, relevant boundary conditions (e.g., target system) and interfaces (e.g., connecting functions and ensuing constraints) in the overall system must be known and defined. Based on these necessary constraints, the LWCP envisages two creative and two evaluation phases, whereby a creative session begins and is followed by the other phases in alternation. The aim is to generate many lightweight solutions, which are preselected to reduce their number for the second creative session, wherein the ideas are qualitatively detailed. These detailed ideas get a final selection in the second evaluation phase according to their then precise known properties, enabling a subsequent integration into the overall system for the technical concept selection as well as the cross-company management of the generated knowledge. As Fig. 3 shows, the phases are implemented by applying individual lightweight- and sustainability-oriented methods that require inputs and generate valuable outputs, with each method aiming for specific outcomes (goals & results). The application of the methods is initially designed in sequence to ensure the attainment of the indicated goals. In some places, however, the various methods can certainly be either skipped or replaced. Therefore, depending on the varying goals of the method application, alternative solutions can be examined regarding Figs. 1 and 2. To give an idea of how methods can be built on top of each other for a lightweight and sustainable design, in the following sections, the individual phases are discussed in more detail, whereby their contents can be obtained from Fig. 3.

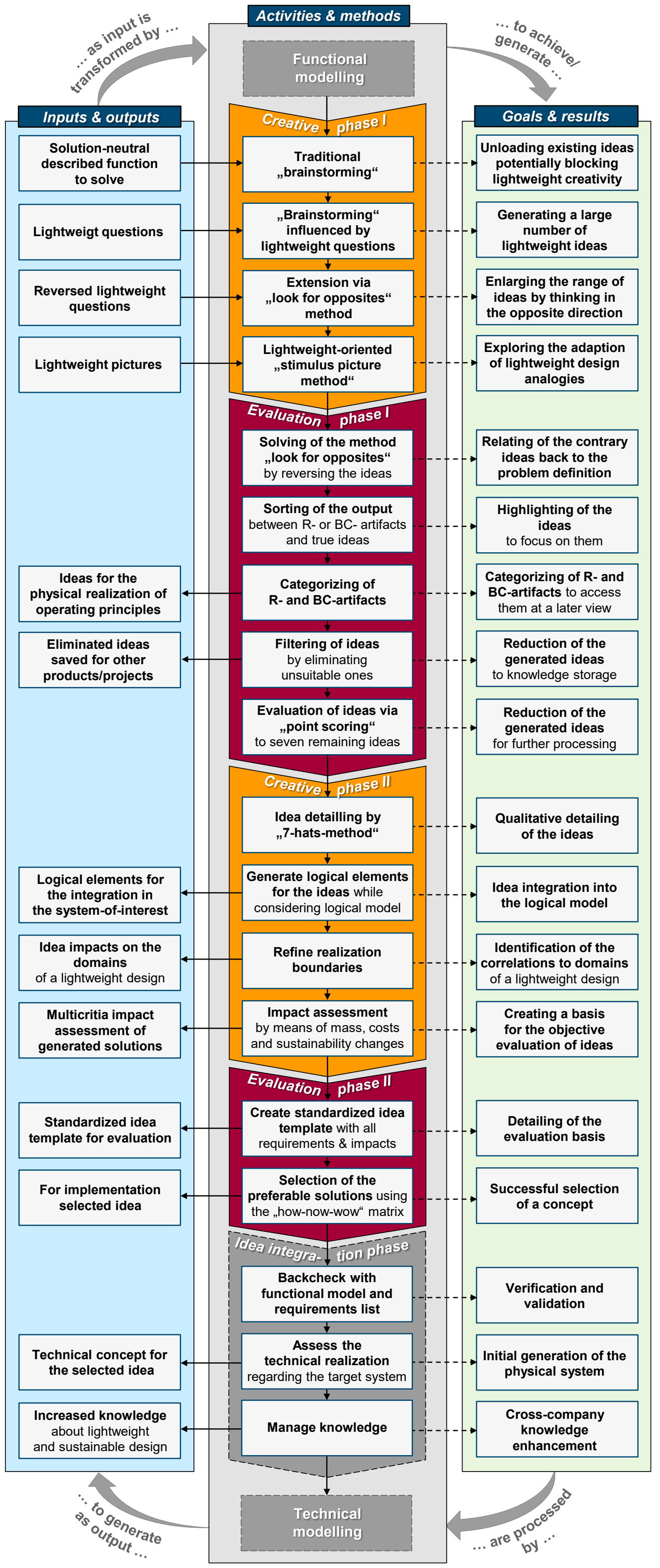

Fig. 3. Systematic process for the application of LWCM based on inputs and outputs as well as activities and methods to achieve goals and results.

3.1. Creative Phase I

In the first creative phase, the creativity of the participants gets triggered through “brainstorming” [13,14], as this method is widely known, intuitive and suitable for the quantitative generation of ideas (see Fig. 1). For the LWCP, this technique requires between five and ten participants, whereby one of whom acts as a moderator. Therefore, no expertise of the members is needed, but it can be supportive. The creative phase is performed on a whiteboard of an online collaboration platform (e.g., “miro dashboard” [15]). On the one hand, such online whiteboards offer an anonymous development of ideas during the LWCP, ensuring no defamation of anyone, while on the other hand, enabling traceability for patenting purposes, if necessary. As soon as all initial ideas have been unloaded, the moderator intersperses specific questions regarding lightweight and sustainable design out of a catalog (e.g., "what does a solution with minimum weight look like?"), comparable to “Osborn's checklist" [13] or the “SCAMPER”-method [16]. These questions can be extended by their contrary formulation (e.g., "what does a solution with maximum weight look like?") along the method of "look for opposites" [17] to obtain a solution space as wide as possible. If no further results are generated, it is up to the moderator to use the “stimulus picture method” [18] and sprinkle the idea generation with some examples of the application of a lightweight and sustainable design in products (e.g., bionic structures) enabling a thinking in analogies.

3.2. Evaluation Phase I

Since the first creative phase generates numerous ideas, their number needs to be reduced before the more complex and time-consuming process of idea detailing proceeds. Firstly, the ideas of the method “look for opposites” have to be traced back to the problem definition. As ideas for lightweight- and sustainability-oriented idea generation often also directly affect the product realization (e.g., "use wood as material"), the next step consists of sorting between innovative conceptual ideas and these requirements (R) or boundary conditions (BC) regarding the physical realization of the product. The filtered R- and BC-artifacts are saved in a knowledge storage and categorized by disciplines (mechanics, electrics/electronics and software), domains (product, production, material and joining technology) and optimization goals (lightweight design, sustainability and costs) to ensure their availability in the relevant process steps of the further development. The artifacts identified as conceptual ideas will now be evaluated and ranked using the "point scoring" method [19] before they get detailed, as this method is less complicated and useful for a large number of concurrent ideas (see Fig. 2). A maximum of the seven best ideas resulting from the "point scoring” will be passed on to the second creative phase.

3.3. Creative Phase II

The second creative phase focuses on idea detailing. Therefore, the “6-hats-method” [20] gets applied, because of its character of multidisciplinarity (see Fig. 1), whereby it is adapted to seven hats instead of just six with the changed perspectives to product, production, material, joining technology, lightweight design, sustainability and costs. This represents an adaptation of the original method for a lightweight and sustainable design. In this context, the team composition should preferably be arranged in such a way that each hat is worked on by a person specialized in the corresponding subject area (e.g., "costs" by a member of the company's controlling). The ideas transferred by evaluation phase I are further refined by each participant in rotation from their individual perspective. During this creative phase, the successively more detailed ideas must not be rejected by individual perspectives, instead working towards the best possible realization should be aimed in each case. Consequently, the requirements for materials, production and joining technologies are now defined based on a catalog enabling a holistic evaluation regarding all relevant aspects. Due to the now available concretization, it is either possible to determine expected absolute values or at least relative changes in the impact categories lightweight design (mass in kg), sustainability (depending on the target system, e.g., CO2 emissions) and costs.

3.4. Evaluation Phase II

For the second and final evaluation phase, the refined ideas are transferred to a standardized template that summarizes and clearly presents all the information from the previous idea detailing phase. Based on this, the seven remaining ideas get arranged in a "how-now-wow" (also known as "portfolio") matrix, where both axes are redefined to consider on the one hand the quantifiable degree of fulfillment of the target system (lightweight design, sustainability, and costs) and on the other hand the qualitative assessment regarding the feasibility and chances of the product of market success. This method was used as many ideas can be evaluated simultaneously, while the criteria can be freely defined, and the method can be implemented digitally (see Fig. 2). After entering the ideas into the matrix, the most promising solutions can be passed on to the technical design.

3.5. Idea Integration Phase

Even if the idea integration phase is not a direct component of the LWCM, it should be an essential part of any concept generation process regarding cross-product and company-internal knowledge enhancement. Ideas that are not identified as promising ones during the application of LWCM should be stored within this phase in a knowledge storage, so that they can be reused if boundary conditions like feasibility or expected market success change.

4. Case Study of LWCM: Gripping System

The presented LWCP has been implemented in the development process of a gripping system as a part of a handling system, that transports heavy tools from a magazine to a tool machine. Since this use case covers a portal robot, the concept generation focuses on realizing the function of "gripping" in a lightweight and sustainable way to increase the energy efficiency along the product's use phase. Due to the industrial environment and the heritage of the manufacturer, reliability must be a key characteristic of the generated solution besides any optimization goal, which includes safeguarding the load within the gripper in case of a power failure. Given the problem definition with its inevitable constraints, the following sections present the results and lessons learned from the application of LWCM based on this use case.

4.1. Method of LWCM Application

The LWCP was performed in five discrete steps in accordance with the presented phases. After a general introduction to the LWCM philosophy, the team composition was carried out, whereby a total of seven experts from interdisciplinary fields (development, production, commissioning, and management) have been assembled. The first creative phase consumed 60 minutes, whereby about 15 minutes were spent on each individual method. The moderator was free to select from a catalog which lightweight questions to ask during the "brainstorming" session and which pictures to show during the application of the "stimulus picture method".

After a one-week break, prior to the intended second creative phase concerning idea detailing, assessing steps were carried out in the first evaluation phase with an unchanged team composition. Therein, the artifacts generated by the method "look for opposites" were transformed back to the problem definition and then all artifacts were filtered, the R- and BC-artifacts categorized as well as the ideas evaluated using the "point scoring" method. This step lasted another 60 minutes.

In a further session, the second creative phase was performed with a time limit of one hour. Therein, the adapted "7-hats-method" was performed on seven different remaining ideas for detailing them into logical elements. Here, the previously stored R- and BC-artifacts were considered, leading to a comprehensive standardized template for each idea.

Based on this, the ideas were finally sorted into the "how-now-wow" matrix to bring out the two most promising ones, so that they could be prioritized and implemented in two concepts, while the other ideas are saved in the knowledge storage. In total, this part took one and a half hours.

4.2. Results of the Use Case

Most of the results from traditional "brainstorming" focused on technical solutions and physical working principles, with almost no R- or BC-artifacts being generated. As the flow of ideas subsided and the moderator introduced specific questions in the area of lightweight design, sustainability and costs, an increase in the density of responses was noted, whereby approximately over 70 % being of the R- or BC-type. The application of the method "look for opposites" succeeded in generating unconventional ideas, although a large proportion of the generated artifacts represented requirements or boundary conditions. In contrast, the "stimulus picture method" nearly exclusively yielded innovative solution principles. In total, over two hundred solution ideas were developed during the one hour of creative phase I. Ideas of varying levels of detail represented a challenge in the subsequent first evaluation phase. Whereas certain ideas were more focused and already described more specifically, others were only broadly outlined. This difference caused discussions within the evaluator group, notably during the evaluation of ideas via the "point scoring" method. It was supportive that anonymity of the idea originally was emphasized during the idea generation process so that no team member could be defamed, and the suggestions could be discussed constructively. The filtering process within this evaluation phase enabled to distinguish between 50 inventive solution ideas versus 150 R- and BC-artifacts. The second creative phase allowed seven remaining ideas to be clearly concretized and refined from each perspective to technical solutions. These resulting rough concepts were ranked via entering the idea titles in the "how-now-wow" matrix in the second evaluation phase.

4.3. Discussion of the Use Case

By applying the LWCM within the LWCP to a specific use case, it was initially possible to explore the applicability and the theoretical potential for optimization of the methods under real-life conditions. Thereby, a wide variety of ideas for realizing a product function were generated in a logical way. Selectively, new ideas (e.g., "clamping via carbon leaf springs") could be generated showing promising results for mass reduction of the gripping system. While the usage of carbon offers a minimalistic solution, it also faces some challenges in the design phase, as existing damage and life cycle models are not sufficient for application in an environment that requires high reliability. Despite offering an extremely lightweighting solution, a certain scepticism among the developing engineers was noticeable. This may be related to the great expertise in the conventional solution and the consequential questioning of new and uncommon solutions. In selecting the lightweight questions and the stimulus lightweight pictures, the moderator was explicitly permitted the freedom to select the stimuli most meaningful. The acceptance of solutions is supported by such pictures since they show an existing technical application in a different field of practice. Depending on the target system, a conscious selection can be made in further steps with the aim of generating fewer R- and BC-artifacts while focusing more on the fulfillment of the target system.

5. Conclusion and Outlook

The case study proved that the LWCM philosophy supports the generation of innovative lightweight and sustainable concept ideas. Nevertheless, the degree of effectiveness regarding a lightweight and sustainable design must be validated in further use cases so that a general statement can ultimately be derived across industries. For this specific use case, an improvement in the weight of the solutions as well as to the conventional and established way of product development was credited by the participating company. Facilitated by the close alignment of the LWCP with the company's established process, the acceptance by the developers was high. Nevertheless, a generalization of this statement for all developing companies is currently not possible. Therefore, in further research, the transferability of the presented LWCM to other topics (such as total sustainability) or to other phases of the PDP should be investigated. Especially in the context of product planning, by including business models and product systems a maximum degrees of freedom results and may lead to even greater effects.

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