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Lightweight Design in the Planning Phase – Lightweight Requirements List

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Abstract: Due to rising material costs and the climate change, the sustainable use of resources is becoming increasingly important. Resource-saving product development processes such as lightweight design are therefore required, especially in resource-intensive industries. To fully realise the benefits of lightweight design, lightweight measures must be applied along all phases of the product development process. For a few years now, the focus has been on the early phases of product development. However, previous lightweight methods that focus on these phases often do not consider the planning phase and do not offer easy-to-apply lightweight design measures. Consequently, they are hardly applicable in the industry without expertise. For this reason, there is a lack of more intensive consideration of the planning phase, including applicable measures. Against this background, an approach for the targeted integration of lightweight design into the planning phase by means of an easy-to-apply lightweight requirements list was developed.

Keywords: Product Development, Lightweight Design, Requirements Management, Planning Phase

1 Introduction

The primary goal of a lightweight product development is not simply to reduce the existing component mass, but rather, goal-oriented lightweight measures are intended to raise lightweight motivators (Laufer et al., 2021). These motivators extend over the entire product life cycle and are interdependent: mass reduction can reduce the amount of materials required in production. Consequently, the use phase of the product can become more resource-efficient. Furthermore, the machine dynamics can increase. Disposal is also more efficient due to a lower amount of materials used. In order to raise these motivators, the phases of the used lightweight product development process must be considered holistically. Previous processes have only recently focused on the early phases of product development (Lüdeke, 2016; Posner, 2016; Albers, 2021). In most cases, only individual phases are considered and the potential of the planning phase is not exhausted. In addition, due to their complexity, the processes usually require in-depth expertise in lightweight design (Klein, 2013). Also, changing requirements because of current developments in industry and science, such as the shortage of skilled workers and the decreasing number of engineering students, create new challenges for lightweight product development (Rommel et al., 2012) Inexperienced users must be provided with targeted lightweight measures throughout the entire development process, from planning to identifying lightweight potential to designing. Consequently, it is necessary to develop new easy-to-apply lightweight measures in such a way that the planning phase can already be used for lightweight optimization.

Considering this, a lightweight requirements list was drawn up for the use in the planning phase. This list supports inexperienced users and makes it possible to consider a first measure to promote lightweight design even before the concept phase.

2 State of the Art

The following chapter provides an overview of relevant preparatory work in the field of (lightweight) product development. At the beginning, general and lightweight-specific methodological product development processes are presented. This is followed by a short placement of lightweight development processes in the so called “Design for X” and a conclusion regarding the planning phases in the presented lightweight development processes.

2.1 Methodological Product Development Processes

The use of methodological processes is a key component for the targeted development of products. The VDI guideline VDI 2221 (1993) provides a multi-step development methodology starting with product planning, through the creation and evaluation of product concepts up to the elaboration and control of development objectives. The methodology is iterative and not limited to a specific industry or product. Pahl et al. (2007) use the process according to VDI 2221 for product development in mechanical engineering and extend the previous process by several steps. Similar to VDI 2221, the process can be iterative, so that the introduced phases of planning and task setting, conceptual design, embodiment design and detail design are always closely linked (see Figure 1). Pahl et al (2007) also lay a focus on the continuous adjustment of the requirements list and the improvement of the product.

A further process for systematic product development is presented in VDI 2206 (2004). This is based on VDI 2221 (1993) and Pahl et al. (2007) and uses the V-model consisting of three sub-steps: decomposition, implementation and integration. The focus is on the development of mechatronic products and the construction of cyber-physical systems. Ponn and

Lindemann (2011) offer a seven-step product development process. This includes the steps of planning goal, analyzing goal, structuring problem, identifying solution ideas, determining properties, making decisions and securing goal achievement. This model is supplemented by the Munich Product Concretization Model (MPCM), which includes further aspects, such as the functional and effect level or the building levels for a systematic finding of product solutions.

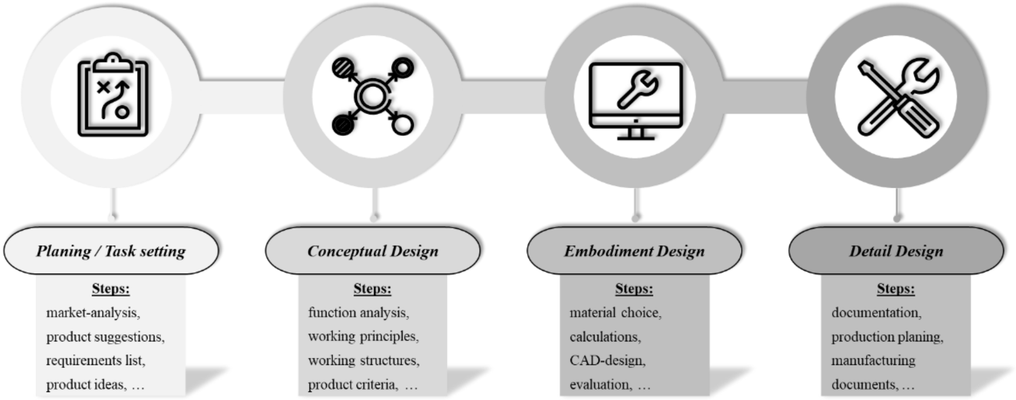


Figure 1: Product Development Phases based on Pahl et al. (2007).

In addition, the integrated product development model (iPeM) of Albers et al. (2016) or the Gausemeier approach (2014) can be cited. Due to the different focus in this paper, these will not be further elaborated.

2.2 Methodological Product Development Processes in Lightweight Design

Lightweight design has been an integral part of methodological product development for decades, and in recent years has increasingly focused on the consideration of the early phases. As a pioneer in methodological lightweight product development, Feyerabend (1991) uses value-analysis-costs and projects them onto the mass of products. Based on DIN 69910 (1987), he tries to reduce mass by means of six consecutive steps - without fully exploiting the mass reduction potentials in the planning phase. Schmidt (2003) takes a deeper look at the methodological development of innovative lightweight products and presents a two-phase process consisting of analysis and synthesis phases. He does not offer a systematic product development process. McLellan et al. (2010) focus on the analysis of mass-critical requirements at the beginning of product development. Requirements are assigned to the components of a previous version and the requirement-specific mass is determined. Finally, mass-critical requirements are presented. However, there is a lack of a clear prioritisation of the requirements, based on which further potentials for mass savings could be developed.

Ponn and Lindemann (2011) use a systematic product development process to create lightweight-products. Starting with a requirements analysis in the planning phase, a target mass of the product is proposed. With regard to the concept phase, Ponn and Lindemann apply functional cost analysis and a variation of operating principles to find the lightest principle. The process addresses the planning phase. Nevertheless, users should be aware of how requirements conflict with each other. In contrast to the product development processes presented so far, Krause (2012) presents a comprehensive process based on the VDI 2221. It is divided into eight main steps including occasional secondary steps. The main steps include planning, conception, design and elaboration. The secondary steps are divided into lightweight knowledge, which an experienced user should bring along, and calculation tools. Krause does not offer any instructions or measures for the implementation of lightweight solutions.

Ellenrieder et al. (2013) use the three key phases of strategic, tactical and operational lightweight. In the first phase, the goal setting of the lightweight project takes place. This is followed by the tactical lightweight design phase as part of the planning phase. Finally, the operative lightweight design phase takes place. However, Ellenrieder et al. do not have a clear focus on the early phases of product development and in some cases, there are no explicit instructions for the implementation of the product development phases. Klein (2013) presents a further process, which requires lightweight expertise. Klein sees the lightweight development as an engineering task to implement mass-driven product development with holistic functional fulfilment as successfully as possible. To achieve this goal, a process consisting of seven main steps with additional secondary steps, similar to Krause (2012), is proposed. Although the early phases of product development are addressed here, the lightweight design takes place in the late phases.

In his dissertation, Lüdeke (2016) presents a product development process for the mass-optimized development of mechatronic products based on the VDI 2206. Two micro V-models are used in a modified W-model and product optimizations are carried out at system, subsystem and component level by means of the product planning, concept development, modelling and simulation, detailing and prototyping and testing phases. Similarly, to Ponn and Lindemann (2011), Lüdeke identifies conflicts of objectives and relationships between requirements in the planning phase and, as

McLellan et al. (2010), calculates the linkage and weight intensity of requirements. Lüdeke also offers a calculation of secondary lightweight potentials. The applicability of this method is difficult to implement without expert knowledge.

In his dissertation, Posner (2016) presents a method kit that includes various lightweight measures for the conceptual phase. Posner extends the value-analysis-weight of Feyerabend (1991) to the so-called functional-mass-analysis (FMA), which is used at the beginning of the design process for a first estimation of the component mass. Subsequently, Posner presents lightweight solution development steps at the functional, design and structural level. He states that the requirements list drawn up in the planning phase has an important influence on the concept phase, but he integrates this list into the concept phase. It is therefore not clear to which phase this list is assigned. In addition, the application of the process requires experience in the field of product development, as well as knowledge in lightweight design. Posner also emphasises the importance of identifying lightweight potential at the beginning of product development. The identification takes place largely via the FMA and a defined desired percentage mass reduction.

Albers et al. (2017) introduce an Extented Target Weighing Approach (ETWA) in which they assign mass to existing functions similar to Posner (2016). The process starts shortly before the concept phase and consists of the creation of a functional mass matrix and a ranking of the heaviest components and functions. Based on these rankings, creativity techniques, such as World-Café (Brown & Isaacs, 2005), are used to generate concept ideas. In addition to the criteria of mass and cost, the ETWA also takes into account CO_2 emissions, which is an extension to that of Albers et al. (2013). Lightweight measures, particularly for the planning phase, are not described in detail.

In a further approach, Albers et al. (2021) provide a framework for continuous support in the development process. It does not explain a systematic development process, but rather a collection of lightweight methods and processes that should support the user during the lightweight product development. Depending on the application, Albers et al. suggest already available measures (e.g. ETWA) for each focus area. The user is supported by the suggestion of measures to be applied over a large part of the product development, but there is no clear concentration on the planning phase.

In contrast, Laufer et al. (2019; 2020; 2021) present a lightweight methodology for the identification of lightweight potentials in the concept phase. In Laufer et al. (2019) an analysis of criteria for the identification of lightweight potential was carried out, focusing on the achievement of lightweight motivators. Laufer et al. (2020) developed an approach for the multi-criteria analysis of lightweight potential. The aim is to elaborate the lightweight potential of individual components by means of a cost-benefit analysis. The approach is goal-oriented and takes into account secondary lightweight potentials. However, since the identification is based on the achievement of lightweight motivators, it remains to be seen whether the identified potentials is technically feasible and which measures can be used for this purpose.

Zeidler et al. (2020) present an approach for the analysis of lightweight potential at the interface between product, production and material. Based on 50 identified criteria relevant to lightweight design, a linkage analysis is carried out in order to develop interferences between the criteria. By means of this analysis and a further, unspecified collection of machine and material data, the potential calculation can take place. The planning phase is taken into account at the beginning of the approach. Lightweight measures for this phase are not presented.

Kartes (2023) presents a methodology for the selection of lightweight strategies, construction methods and methods along product development. He also shows a requirements list with a focus on lightweight design and suggests using the Kano-Model to specify customer requirements and classify them in a satisfaction portfolio (see Spath et al., 2011). The Kano-Model presented by Japanese Noriaki Kano is used in product development to capture and consider customer wishes to meet customer satisfaction. Kano uses five quality levels: basic, performance, enthusiasm, insignificant and rejection characteristics. Depending on the type of characteristic, these criteria must, should, cannot or should not be met. The insignificance characteristics, on the other hand, is irrelevant. (Marx, 2014) Kartes does not explain how the Kano-Model is used with respect to its requirements list, and how the elaboration of this list can be done step by step.

Finally, the approach from Bjelkengren (2006), Ashby (2010), Zhao (2010) or Caldwell et al. (2013) can be cited. Due to the specific topic of their approaches and the addressed topics in this paper, these are not further elaborated.

2.3 Lightweight Development Processes and Design for X

As Posner (2016) points out, there are various suitabilities in design theory ("Design for X"). These relate to whether fundamental development goals exist in a project and to what extent the product must be developed accordingly. Examples of suitabilities are, for example, suitability for joining, suitability for production or mass suitability ("Design for Lightweight") (Pahl et al, 2007; Posner, 2016). In order to fully achieve these suitabilities or goals, methods, measures, etc. adapted to these suitabilities must be offered along all phases of the product development process. The state of the art presented shows that there are already various processes in lightweight design that support lightweight design-friendly development in different phases of product development without explicitly linking measures with Design for Lightweight. Only Lüdeke (2016) and Posner (2016) provide a detailed classification and emphasize the importance of lightweight design measures for successful lightweight product development. Posner (2016) correctly states that mass balance has developed as an intersection of lightweight design engineering and general design methodology.

Design engineering focuses in particular on the conception and design of lightweight-optimized structures and thus creates valuable contributions for Design for Lightweight by using existing methodologies and measures, such as the Contact & Channel approach (Matthiesen, 2011). However, planning, as a further phase of the product development process, has so far only been given limited consideration with regard to mass suitability.

2.4 Conclusion

As presented in the previous chapters, the scientific literature contains several methodological lightweight product development processes that often refer to traditional product development processes (VDI 2221, 1993; VDI 2206, 2004; Pahl, 2007; Klein, 2013). Most of these processes are divided into distinct phases like the planning, conceptual, embodiment and design phase that play a key role in the holistic development in lightweight design.

On the one hand some approaches (Ponn and Lindemann, 2011; Krause, 2012; Lüdeke, 2016) address multiple of these phases but do not offer measures for all of these phases – especially not for the planning phase. On the other hand, many processes focus mainly on one phase (Caldwell, 2013; Posner, 2016; Laufer, 2021), but they do not consider measures for the planning phase, too. Only McLellan et al. (2010) offer a lightweight measure in the planning phase, which supports the identification of lightweight-relevant requirements. Kartes (2023) proposes the use of a Kano-Model in a lightweight requirements list, but details of the requirements list or an application of the Kano-Model are missing. Thus, the literature and the placement of lightweight development processes in the Design for X show that the planning phase, despite its influence on lightweight design, is not considered in depth and there are few applicable measures for this phase. Against this background and taking into account the changing requirements for lightweight product development processes it is imperative to develop an easy-to-apply lightweight measure for the use in the planning phase.

In order to fill this gap and to extend Design for Lightweight to this phase, the development of a lightweight requirements list is presented in the next chapter, by using and extending measures from general and lightweight-oriented product development. Design for Lightweight is supported on the one hand by measures that directly enable a mass reduction and on the other hand by the presentation of lightweight-relevant information that can be used in subsequent phases.

3 Lightweight Design in the Planning Phase

The following chapter presents a newly developed lightweight requirements list including information clusters and measures to generate lightweight-relevant information for the use in the planning and further product development phases. In addition, the results of an application of this list to a module of a handling system are presented.

3.1 The Lightweight Requirements List

Since development projects usually start with the clarification of the task and the elaboration of a requirements list, it is purposeful to use this list as a basis for a lightweight optimization. From the data available here, a variety of lightweight-relevant information can be extracted.

Based on an analysis of requirements lists already used in own development projects and published in the literature (e.g. Schmidt und Puri, 2001; Pahl et al., 2007), the authors present what kind of information clusters can be generated from existing lists. In addition, they describe how the information clusters can be analyzed and what benefit their analysis offers in terms of lightweight product development. Furthermore, a new product information cluster, a new requirements catalogue, the use of the Kano-Model for prioritizing requirements and a procedure based on McLellan et al. (2010) for identifying the interferences in the lightweight requirements list is presented. The entire lightweight requirements list is shown at the end of the chapter. Due to the limited scope of the publication, not all data fields are explained in detail.

Information Cluster 1 – Basic Information:

Requirements lists contain general data about the project, such as responsibilities, project duration, project description and participating companies or departments. The following is an excerpt of the nine basic information data fields of the lightweight requirements list and shows which lightweight-relevant data can be extracted:

- The **project duration** can give an indication of how much focus can actually be placed on lightweight design. Long project durations offer the potential to plan more intensively with external expertise – such as joint projects with lightweight experts from research institutions. If internal expertise is available, it can be used to plan, for example, with time-consuming lifetime calculations. Finally, product knowledge increases and further mass savings are possible.

- The **project name** does not in principle offer any potential for increasing benefit for mass reduction. Nevertheless, the employees involved can be better prepared for the project goal – the reduction of the mass of a product – by means of a description geared towards lightweight design. The main objective can thus always remain tangible.
- The **companies** involved are defined at the beginning of the project. Attention can be paid to attracting and integrating project partners experienced in lightweight design. Similar to the responsibilities, the assignment of individual project contents or the implementation of requirements should take place in a targeted manner. During the duration of the project, it may be possible to draw on the expertise of other companies. Therefore, the possibility of including other companies with the missing expertise should always be considered. It is possible to introduce placeholders in the field "Companies", which are provided with a description of the still missing expertise, e.g. "lifetime calculation".

Information Cluster 2 – Current Product Status:

The current product status serves to clarify the current status of the product to be optimized. Data such as the product name, information on previous and competitor products, the type of construction, further information, as well as costs, delivery time and the current mass contribute to this. The benefits that data can generate for lightweight optimization are:

- The **product name** can give information about the function, the requirements to be met by the product or the benefit of a lightweight optimization. A valid name supports the development of relevant requirements and actually required functions. This directly affects the mass of the product. In addition, it also helps to identify the benefits to be gained from a lightweight-optimization project. For example, the product name "load lift" shows that masses are continuously moved and that the benefit of a mass reduction of the product can result in energy and thus emission savings.
- **Competitive products**, particularly very similar ones, should be included in the requirements list. A benchmarking of these products provides a basis for the functions and requirements to be considered, making it clear what does not need to be installed. There are also approaches such as the FME (Posner, 2016), which rely on competing products to generate ideas for a lightweight product. However, competing products should only be seen as support for the generation of ideas. Otherwise, new measures and ideas to promote lightweight cannot be generated.
- The **mass** is an informative value and usable for benchmarking. Contrary to previous opinions in the literature (see Posner, 2016; Laufer 2021), a fixation of a mass target does not seem to be effective, as it does not increase the potential for further mass reduction. There is an exception if a certain mass has to be observed due to restrictions.
- With regard to the **construction type**, a distinction can be made between new, adaptive and modified design. New constructions usually allow greater product modification (holistic change of concept, etc.) than adapted and modified constructions. Based on the type of construction, the effort as well as the potentially usable lightweight measures and strategies (e.g., conceptual lightweight or material lightweight design) can be estimated.

Information Cluster 3 – Product Information:

The newly introduced product information cluster focuses on a detailed description of the desired product functions and, in the case of an adaptation or modification design, on the existing functions and the appearance of the product:

- The **function description** gives an overview of the actual required functions of the product. Consequently, already relevant requirements can be derived and irrelevant, mass-increasing requirements can be neglected. As a result, the function description is integrated earlier than in previous product development processes. This also contributes to a more efficient product development, since already developed functions can be used for later work steps (e.g. FMA).
- The **graphic** represents the product (usually a previous product generation). Experienced users can use a first graph to estimate, which components offer mass saving potential – e.g. constructive or conceptual changes. This allows ideas to be generated in the planning phase. Likewise, the product understanding is sharpened and the generated benefit of lightweight design becomes clearer.

Information Cluster 4 – Development Goals:

The definition of the **development goals** is essential at the beginning of a project. In lightweight design, the real benefits of mass reduction can be captured in the form of specific development goals. These serve to derive detailed requirements: The objective of "reduction of materials" may indicate that the use of high-strength materials could be useful or that a design optimization can be goal-oriented. Similar to the graphic, first ideas can be generated already in the planning phase. In addition, the focus on lightweight optimization is intensified.

Information Cluster 5 – Requirements:

The requirements are the focus of each requirements list and can e.g. generated by customer questionnaires, benchmarking or in-depth product knowledge. In order to support the requirements determination, a requirements catalogue was developed for the lightweight requirements list. In addition, further evaluation options for the requirements were elaborated based on the Kano-Model (see Marx, 2014) and the approach followed by McLellan et al. (2010). These support the lightweight product development already in the planning phase.

- The **requirements catalogue** is based on Schmidt and Puri (2001) and Pahl et al. (2007) and was expanded by requirements already used in own lightweight projects. Currently it includes 200 requirements. The catalogue serves for the generation of ideas for the efficient creation of the requirements list.
- In order to further focus the requirements and develop mass-relevant data, these can be specifically assigned to the origin. A distinction is made between **customer requirements (load)**, **external requirements** and **company requirement**s **(specification)**. For all requirements it can be immediately clarified whether these requirements should be questioned and adapted. An example: a customer requires a safety factor of two for a mechanical design. The company´s previous assumption is based on a factor of 2.5. The difference is immediately visible in the lightweight requirements list and it should be questioned whether a reduction of the safety factor is possible. The same applies to external requirements, such as standards: are these still relevant for the product? Are there other standards that are more appropriate and allow more leeway in development? All these decisions can enable mass savings in terms of conditional lightweight. When specifying requirements, a clear quantification should take place wherever possible. It is not enough to simply refer to the safety factor requirement as “as high as possible.”
- In addition to the origin of the requirement, an assessment of the **current status** of the requirement should be made. Additionally, a clear agreement on a **final value** has to be achieved. By comparing it with the customer's requirement, the external requirement and the company's requirement, the value of the current state can immediately show mass savings. For example, the mentioned safety factor could currently be three, which again deviates from the value actually required. Finally, it can be stated that a safety factor of two meets the requirements and is desirable.
- Five basic lightweight data fields are integrated in the requirements list: **abbreviation**, **person responsible**, **characteristics**, **product development process (PDP)** and **interferences**. The abbreviation summarizes the cluster and the request number. Therefore, SI01 for example stands for the security cluster and requirement number 1 in that cluster. Based on the abbreviations, it is quickly apparent in which cluster many requirements have to be fulfilled. In terms of lightweight design considerations, a reduction to actually necessary ones, as shown by the Kano-Model below, can be effective for a large number of requirements. The person responsible is named as a further data field. Attention should be paid to the targeted allocation of existing expertise during the elaboration and the implementation of the requirements. The responsibilities can be assigned according to the knowledge about lightweight design of the employees involved. It is therefore advisable to clarify the current level of experience of the employees involved with regard to lightweight. Finally, more experienced employees should take greater care of clusters of requirements relevant to lightweight.
- The characteristics are based on the described Kano-Model and are assigned to each requirement individually (1). Subsequently, the characteristics are sorted per cluster in descending order (2): basic characteristic (BA), performance characteristic (PE), enthusiasm characteristic (EC), unimportant characteristic (UN) and rejection characteristic (RC). The sorted characteristics are then evaluated in descending order (3). BA must be kept, PE can be kept, discussed or integrated into other requirements, EC can be discussed or deleted if possible, UN should be deleted if possible and RC deleted. Ultimately, only the actual core requirements (CR) remain. Compared to the original requirements, non-core requirements can be deleted and, at least for mass-relevant requirements, mass savings can be made. Figure 2 illustrates the Kano-Model used in the lightweight requirements list.

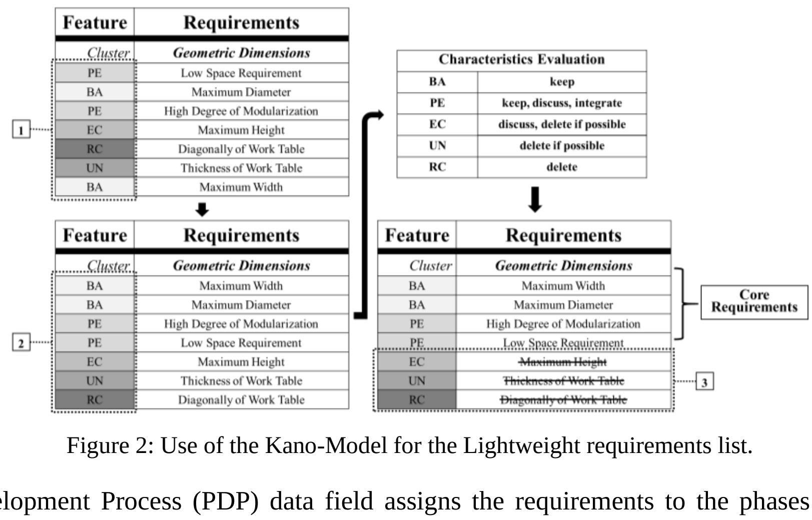


Figure 2: Use of the Kano-Model for the Lightweight requirements list.

The Product Development Process (PDP) data field assigns the requirements to the phases in which they can be influenced. The present process is based on the product development process according to Pahl et al. (2007) with the phases planning and task clarification, conceptual design, embodiment and detail design. The assignment of the phases to the requirements differs from project to project, but it can be supported by the following, exemplary statements:

- Consideration of the phase in the development of the previous products can be used as a basis.
- Requirements with a clear quantification can already be influenced in the planning phase.

- In the case of simple product modifications without a clear change in the product concept, the requirements cannot be influenced at the concept phase.
- Production-specific requirements are usually influenced in the embodiment and detail design phases.

Based on the assignment and the assessed relevance of lightweight design, it is possible to determine in which phase particular attention can be paid to mass reductions. Lightweight product development can thus be focused and specific lightweight measures selected. Furthermore, it is visible in which phases the requirements can be used for further lightweight measures. This makes the lightweight product development more closely linked and easier to understand for inexperienced users. The interferences data field is based on the approach of McLellan et al. (2010) and serves to identify mass-critical requirements. Supplementary to McLellan et al. (2010) the introduction of a mass interference code (MIC), shown in grey colour in Figure 3 on the right, is proposed. This can be integrated into the lightweight requirements list and immediately shows which requirements correlate with each other and which mass influence they have (dark grey = high lightweight potential). Likewise, the abbreviation of the requirements (e.g. SI01) is assigned to the lightweight requirements list and to the results presentation. Therefore, potential cluster segments can be identified and prioritized in the lightweight development process. These clusters are shown exemplary in Figure 3 (1 and 2).

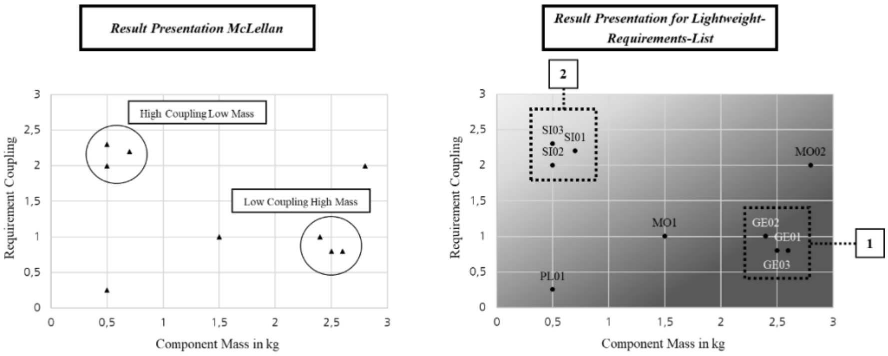
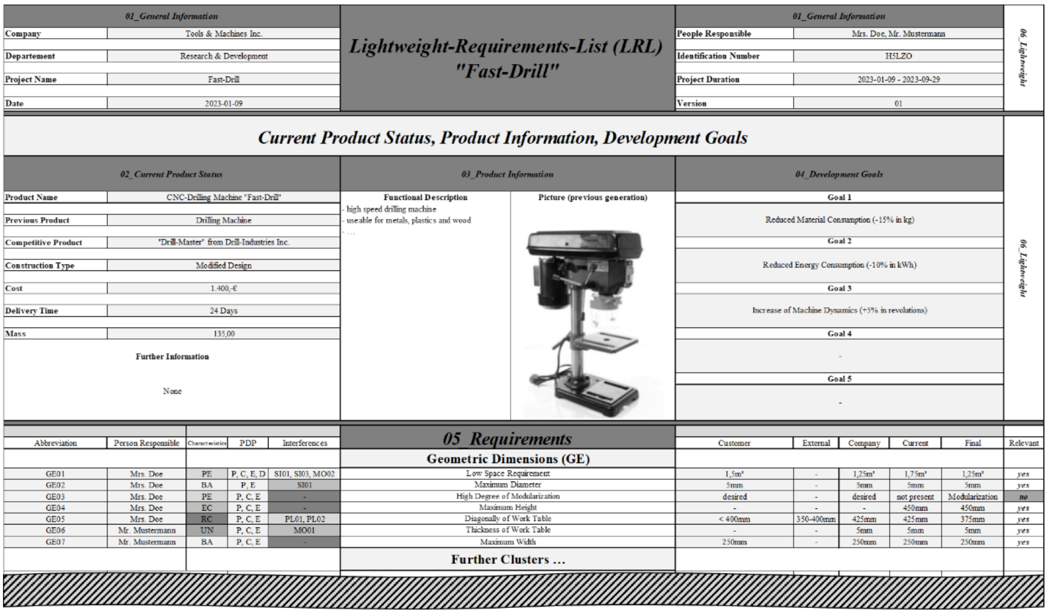


Figure 3: Result Presentation of McLellan et al. (2010) left and extended Result Presentation right

Information Cluster 6 - Lightweight Relevance:



Lightweight-Requirements-List (LRL) "Fast-Drill"

01_General Information		01_General Information	
Company	Tools & Machines Inc.	People Responsible	Mrs. Doe, Mr. Mustermann
Departement	Research & Development	Identification Number	H5LZO
Project Name	Fast-Drill	Project Duration	2023-01-09 - 2023-09-29
Date	2023-01-09	Version	01

06_Lightweight

Current Product Status, Product Information, Development Goals

02_Current Product Status	
Product Name	CNC-Drilling Machine "Fast-Drill"
Previous Product	Drilling Machine
Competitive Product	"Drill-Master" from Drill-Industries Inc.
Construction Type	Modified Design
Cost	1.400,-€
Delivery Time	24 Days
Mass	135,00
Further Information	None

03_Product Information

Functional Description
- high speed drilling machine
- useable for metals, plastics and wood
- ...

Picture (previous generation)

04_Development Goals
Goal 1
Reduced Material Consumption (-15% in kg)
Goal 2
Reduced Energy Consumption (-10% in kWh)
Goal 3
Increase of Machine Dynamics (+5% in revolutions)
Goal 4
-
Goal 5
-

05_Requirements

Abbreviation	Person Responsible	Characteristics	PDP	Interferences	Geometric Dimensions (GE)	Customer	External	Company	Current	Final	Relevant
GE01	Mrs. Doe	PE	P, C, E, D	SI01, SI03, MO02	Low Space Requirement	1,5m²	-	1,25m²	1,75m²	1,25m²	yes
GE02	Mrs. Doe	BA	P, E	SI01	Maximum Diameter	5mm	-	5mm	5mm	5mm	yes
GE03	Mrs. Doe	PE	P, C, E	-	High Degree of Modularization	desired	-	desired	not present	Modularization	no
GE04	Mrs. Doe	EC	P, C, E	-	Maximum Height	-	-	-	450mm	450mm	yes
GE05	Mrs. Doe	RC	P, C, E	PL01, PL02	Diagonally of Work Table	< 400mm	350-400mm	425mm	425mm	375mm	yes
GE06	Mr. Mustermann	UN	P, C, E	MO01	Thickness of Work Table	-	-	5mm	5mm	5mm	yes
GE07	Mr. Mustermann	BA	P, C, E	-	Maximum Width	250mm	-	250mm	250mm	250mm	yes

Further Clusters ...

Figure 4: Lightweight Requirements List for a fictional Drilling Machine.

The emphasis on the **relevance of lightweight** in requirements lists already takes place in the existing literature (see McLellan et al. (2010). By highlighting mass-relevant requirements, the user can see for which requirements special attention should be paid to the lightest possible design. If a requirement is lightweight-relevant and at the same time linked to another requirement, there is also a lightweight relevance for this further requirement. Because of this, the evaluation of the lightweight relevance is therefore be coupled with the adapted process of McLellan et al. (2010) (see Cluster 5).
Figure 4 shows the lightweight requirements list for a fictional drilling machine including the six described clusters. After the requirement cluster "Geometric Dimensions (GE)", Figure 4 was interrupted for reasons of clarity. In the case of application, further requirement clusters would follow the GE-Cluster.

3.2 Application of the Lightweight Requirements List

The lightweight requirements list was applied to and validated on a module of a handling system from the custom machine-manufacturing sector. This system is used to lift and swing heavy containers filled with different materials such as powders used in the pharmaceutical industry. The production of the mentioned module is quite resource intensive and the movement of the system demands energy and therefore causes CO_2-emissions. To improve these mass-dependent properties, a lightweight optimization of the module is targeted. The optimization starts in the planning phase by elaborating and analyzing the clusters of the lightweight requirements list during two workshops with three mechanical engineers from the development department - one engineer from each company involved in the project. The result of these two workshops is the completed lightweight requirements list and related lightweight-relevant information. The clusters compiled in the lightweight requirements list support the direct mass reduction of the module on the one hand, and on the other hand, they affect the mass reduction by providing information that supports the lightweight development (indirect mass reduction).

For confidentiality reasons, it is not possible to show the project-specific lightweight requirements list. Instead of this, the application and its benefits is explained and some project-specific results are summarized in Table 1 and Table 2.

Table 1: Effects of Cluster 1 – 4 on the lightweight optimization

Cluster	Direct mass reduction		Indirect mass reduction	
1	project duration	Time consuming **life-time calculation** possible.	project name	**Focuses** the lightweight development.
2	competitive products	No suitable ideas with competitors.	construction type	Adapted construction **- time saving** by not considering conceptual lightweight design.
3	functions	Several ideas, like **function integration** which leads to **mass reduction**, generated.	---	
4	---		goals	Selection of three lightweight-goals to **focus the development.**

Cluster 1 – 4 were elaborated in the first three-hour lasting workshop, which was held as an online-workshop with all three engineers. In cluster 1, the project name and the scope of the lightweight activities were clarified. The project name chosen is “LiLi - lightweight-lifting-unit”, which directly shows the lightweight reference of the project. Because of the long project duration (~ 3 years), the team decided to plan with a lifetime calculation of the module – to generate further mass savings. Because of the experience of engineer 2, no external expertise regarding the life-time calculation is necessary. Cluster 2 was used for a first collection of already existing lightweight ideas regarding competitive products. Regarding this, products of the two biggest competitors were collected and analyzed, mainly via internet, together. Interestingly, only few competitive products could be found and none of these provided promising lightweight solutions. Consequently, an in-depth benchmarking for the generation of ideas for a lightweight optimization was not considered appropriate and no products or existing lightweight optimization ideas werde noted in the “competitive products” field. Finally, the construction type adapted construction has been determined, because there should be no change of the concept. Therefore, conceptual lightweight design will not be considered as intensively as different lightweight design strategies.

Cluster 3 was used to elaborate 18 different functions of the module. The discussion of these functions led to first ideas for lightweight optimization, like the integration of the functions “display pressure” and “display position“ into the function “display operational readiness” which can be fullfiled by only one display instead of two. The newly integrated graphic allowed a first suggestion for the change of the visibly overdimensioned component “Frontkasten” by engineer 1. He proposed several design changes, which are noted and will be examined in the ongoing project. Cluster 4 was used to focus the development goals – finally three main goals could be summarized based on the mass-dependent characteristics mentioned above: increasing of machine dynamics, optimizing the production process and reducing the necessary materials.

Cluster 5 – 6 were elaborated in the second three hours lasting workshop, which was held as an online-workshop with all three engineers, too. In cluster 5, suitable requirements were developed with the help of the implemented requirements catalogue and the expertise of engineer 2 – in total twelve requirements-cluster with 46 requirements. The abbreviation, the person responsible and their origin were then assigned to these requirements. The involved engineers will divide up the implementation of the requirements to be taken into account according to their personal experience. Engineer 1 focuses on mechanical requirements (geometry, calculation, etc.) due to his experience in materials and calculations. Engineer 2, because of his broad experience regarding the system, concentrates on product- and company-specific requirements (use-phase, industrial design, market, etc.). Engineer 3 takes care of monetary and production requirements (costs, production, etc.) and is responsible for the lightweight development process. Further requirements will be implemented together.

After this, the origin of each requirement was assigned with the product knowledge of engineer 2 and the requirements were quantified with an actual and a final value. The actual value can be found in an earlier requirements list or by using the product knowledge of colleagues. The final value of each requirement results out of a discussion within the three engineers. During this process, several values appeared whose actual size had never been questioned in detail yet, like the safety factor or the actual concept of a safety system. These were discussed and appropriate ideas for the further product optimisation were noted, like decreasing the safety factor from 2.5 to 1.5, which has a direct impact on the mass. By using the Kano-Model for the elaborated 46 requirements, 20 basic characteristics, 13 PE, 11 EC and 2 UN could be identified. Furthermore, a reduction to 20 BA, 11 PE and 7 EC was possible by using the characteristics evaluation shown in Figure 2. This measurement enables further mass reductions in the ongoing project, because less requirements and therefore less functions as well as parts have to be considered in the product development process.

Table 2: Effects of Cluster 5 – 6 on the lightweight optimization

Cluster	Direct mass reduction		Indirect mass reduction	
5	origin	**Differences** between customer and company values elaborated **- change options** noted.	requirements	**Twelve cluster** and **46 requirements** elaborated by using the **catalogue**.
	value	**Requirements without fixed values** elaborated - values, like **safety factor**, defined.	responsible person	**Focus** of the three engineers clarified.
	characteristics	**Reduction of 8 requirements** leads to **mass savings.**	interferences	Lightweight **focus** on **industrial design** and **geometry -** no focus on use, planning, signal.
6	---		relevant	Several requirements without lightweight relevance identified **- not mentioned** further.

The assignment of the requirements to the product development phases was done during a discussion in workshop 2. It showed that most of the requirements could be influenced along the whole process. Finally, all 38 requirements were then assigned to these phases: 30 to planning, 34 to conceptual, 32 to embodiment design and 31 to detail design. The uniform distribution of the requirements in this use case allows no specific focus on one phase and therefore can only be used as an information. The lightweight relevance of all remaining requirements (cluster 6) and the interferences between them were then elaborated with the shown process adapted to McLellan et al. (2010). There were no not lightweight relevant requirements and, in order to highlight the interferences, the MIC including the shortcuts of the requirements was included in the lightweight requirements list (see Figure 3). As a result, it is directly visible that a focus regarding the lightweight optimization should be on requirements of the cluster industrial design and geometry in the ongoing project. They have a moderate coupling while having a high influence on mass and are therefore suitable for the lightweight optimization. In contrast, the clusters use, planning and signal do not have a significant influence on the mass and therefore will not be focused on.

4 Conclusion and Outlook

The investigation within this paper has shown that despite the multitude of benefits that can be raised by lightweight design, it is not yet holistically applied in all phases of product development and particularly usable lightweight measures are missing. The planning phase in particular must be used more intensively and easy-to-apply measures must be offered for this purpose. For this reason, a lightweight requirements list was developed. It supports the user from the beginning of the product development by generating first lightweight optimizations and lightweight-relevant data for the use in the planning and subsequent phases. The integration of targeted methods, like the Kano-Model and the method of McLellan et al. (2010) ensures that all actually relevant requirements and their interdependencies are taken into account. By representing lightweight-relevant criteria for all subsequent phases (conceptual, embodiment, detail design), the lightweight requirements list can easily be integrated into existing product development processes. Furthermore, the division of the list into six clusters supports its applicability and offers a clear visual depiction of lightweight-relevant data. Its usability was evaluated by applying the lightweight requirements list in an ongoing lightweight project in the custom machine-manufacturing sector.

Further optimization potential was identified during this application: in the future, a stronger focus will be placed on the expansion of the requirements catalogue, a further automation of the lightweight requirements list and the application in further projects with different industries. Additionally, the already mentioned links between the generated lightweight-relevant data and the subsequent product development phases need to be given greater consideration, in order to use the data more deeply for a holistic development of lightweight products. It must be clearer which effect the generated lightweight relevant data has on potential lightweight optimizations. In addition to the lack of consideration of the planning phase in lightweight development processes, the literature review also showed that the definition of lightweight-potential and its identification is not yet comprehensively covered by methodological approaches. A detailed examination of research needs regarding lightweight potential and its holistic identification will be given in a future work.

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References

Albers, A.; Wagner, D.; Ruckpaul, A.; Burkhardt, N.; Matthiesen, S., 2013. Target Weighing – A new approach for conceptual lightweight design in early phases of complex systems development, in: Lindemann, U.; Venkataraman, S.; Kim. Y. S.; Lee, S. W. (Ed.): Proceedings of the 19th International Conference on Engineering Design (ICED13). Seoul, pp. 301-310.

Albers, A.; Reiss, N.; Bursac, N.; Richter, T., 2016. iPeM - integrated Product engineering Model in context of Product Generation Engineering, in: Wang, L.: Procedia 26th CIRP Design Conference. Elsevier, Stockholm, pp. 1-6.
Albers, A.; Revfi, S.; Spadinger, M., 2017. Extended Target Weighing Approach – Identification of Lightweight Design Potential for new Product Generations, in: Proceedings of the 21st International Conference on Engineering Design (ICED17), vol. 4: Design Methods and Tools. Vancouver, pp. 1-10.
Albers, A.; Holoch, J.; Revfi, S.; Spadinger, M., 2021. Lightweight design in product development: a conceptual framework for con-tinous support in the development process, in: Proceedings of the 31st CIRP Design Conference. Elsevier, Enschede, pp. 1-6.
Alonso, E., Lee, T.M., Bjelkengren, C., Roth, R. & Kirchain, R.E., 2012. Evaluating the Potential for Secondary Mass Savings in Vehicle Lightweighting, Environmental Science and Technology, vol. 46. Cambridge, pp. 2893-2901.
Ashby, M.F., 2010. Materials Selection in Mechanical Design, 4th Ed. Butterworth-Heinemann, Oxford.
Bjelkengren, C., 2008. The impact of mass decompounding on assessing the value of vehicle Lightweighting, Master-Thesis, Massachusetts Institute of Technology, Cambridge.
Brown, J. & Isaacs, D., 2005. The World Café – Shaping our Futures through Conversations that Matter. Berrett-Koehler Publishers, Oakland.
Caldwell, B.W.; Mocko, G.M.; Sen, C.; Summers, J.D., 2013. Automotive lightweight engineering. A method for identifying lazy parts, International Journal of Vehicle Design, pp. 2893-2901.
DIN 69910, 1987. Wertanalyse. Beuth, Berlin.
Ellenrieder, G., Gänsicker, T., Goede, M., & Herrmann, H.G., 2013. Die Leichtbaustrategien, in: H.E. Friedrich (Ed.), Leichtbau in der Fahrzeugtechnik, ATZ/MTZ-Fachbuch. Springer Vieweg, Wiesbaden.
Eckstein, L.; Göbbels, R.; Biermann, J.; Urban, P., 2010. Analyse der sekundären Gewichtseinsparung. FAT-Schriftenreihe Vol. 230. Verband der Automobilindustrie. Berlin.
Feyerabend, F., 1991. Wertanalyse Gewicht – Methodische Gewichtsreduzierung am Beispiel von Industrierobotern, in: Verein Deutscher Ingenieure (Ed.), Fortschrittsberichte der VDI Zeitschriften, Vol. 1, No. 201. VDI-Verlag, Düsseldorf.
Gausemeier, J., 2014. Strategische Planung und integrative Entwicklung der technischen Systeme von morgen. Schöningh, Paderborn.
Kartes, M., 2023. Methodik zur Auswahl von Leichtbau-Strategien, -Bauweisen und -Methoden entlang der Produktentstehung, Masterarbeit, Lehrstuhl für Konstruktionstechnik. Universität des Saarlandes.
Klein, B., 2013. Leichtbau-Konstruktion, Berechnungsgrundlagen und Gestaltung, Vol. 10. Vieweg+Teubner-Verlag, Wiesbaden.
Krause, D., 2012. Leichtbau, in: F. Rieg et al. (Ed.), Handbuch Konstruktion. Carl Hanser Verlag, München, pp. 463-484.
Laufer, F.; Roth, D.; Binz, H., 2019. Derivation of Criteria for Identifying Lightweight Potential – A Literature Review, in: Proceedings of the 22nd International Conference on Engineering Design (ICED19). Delft. DOI:10.1017/dsi.2019.274
Laufer, F.; Roth, D.; Binz, H., 2020. An approach for the multi-criteria derivation of lightweight potential, in: Marjanovic, D.; Storga, M.; Skec, S.; Bojcetic, N.; Pavkovic, N. (Ed.), Proceedings of the DESIGN Conference, Vol. 1, pp. 977-986.
Laufer, F.; Roth, D.; Binz, H., 2021. A methodology for identifying the lightweight-driven mass potentials for the early conceptual phase, in: Stuttgarter Symposium für Produktentwicklung (SSP2021). Stuttgart.
Lüdeke, T. F., 2016. Beitrag zur gewichtsoptimierten Entwicklung mechatronischer Produkte, Dissertation, Lehrstuhl für Konstruktionstechnik. Universität des Saarlandes.
Matthiesen, S., 2011. Seven Years of Product Development in Industry – Experiences and Requirements for supporting Engineering Design with 'Thinking Tools', in: Culley, S. J.; Hicks, B. J.; McAloone, T. C.; Howard, T. J.; Clarkson J. (Ed.): Proceedings of the 18th International Conference on Engineering Design (ICED11). Kopenhagen, pp. 1-10.
Marx, D., 2014. Das Kano-Modell: Ein Modell zur Analyse von Kundenwünschen in der Praxis. Igel Verlag RWS, Hamburg.
McLellan, J., Maier, J.R.A., Fadel, G.M., & Mocko, G.M., 2009. A Method for Identifying Requiremtents Critical to Mass Reduction using DSMs and DMMs, in: Proceedings of 11th International Design Structure Matrix Conference. Greenville, pp. 197-205.
Pahl, G.; Beitz, W.; Feldhusen, J.; Grote, K.-H., 2007. Pahl / Beitz - Konstruktionslehre - Grundlagen erfolgreicher Produktentwicklung, Vol. 7. Springer-Verlag, Berlin, Heidelberg.
Ponn, J. & Lindemann, U., 2011. Konzeptentwicklung und Gestaltung technischer Produkte - Systematisch von Anforderungen zu Konzepten und Gestaltlösungen. Springer, Berlin.
Posner, B., 2016. Methodik zum leichtbaugerechten Konzipieren, Dissertation, Institut für Konstruktionstechnik und Technisches Design. Universität Stuttgart.
Rommel, S., Geiger, R., Schneider, S., Bergold, D., Schneider, M., Großmann, M., Kopp, G., Schmitt, A., 2012. Leichtbau in Mobilität und Fertigung. Studie für die e-mobil BW GmbH, Stuttgart.
Schmidt, W., 2003. Methodische Entwicklung innovativer Leichtbauprodukte, in: VDI (Ed.), Fortschrittsberichte der VDI Zeitschriften, Vol. 1, Nr. 369. VDI-Verlag, Düsseldorf.
Schmidt, W. & Puri, W., 2011. Betrachtungen zur Konzeptphase im Konstruktionsprozess von Leichtbauteilen, in: Meerkamm, H. (Ed.), Beiträge zum 12. DfX-Symposium, Lehrstuhl für Konstruktionstechnik. Universität Erlangen-Nürnberg, pp. 21-28.
Spath, D., Warschat, J., Ardilio, A., Bunzel, S., 2011. Technologiemanagement - Radar für Erfolg. LOG_X, Ludwigsburg.
VDI 2206, 2004. VDI-Guideline 2206: Design methodology for mechatronic systems. VDI-Verlag, Düsseldorf.
VDI 2221, 1993. VDI-Guideline 2221: Systematic approach to the development and design of technical systems and products. Beuth, Berlin.
Zeidler S., Scholz, J., Friedmann, M., Fleischer, J., 2023. Approach to Develop a Lightweight Potential Analysis at the Interface Between Product, Production and Material, in: M. Liewald et al. (Eds.): WGP 2022, LNPE. Springer Nature Switzerland, Cham, pp. 696-704.
Zhao, L., Jianfeng, M., Ting, W., Xing, D., 2010. Lightweight Design of Mechanical Structures based on Structural Bionic Methodology, Journal of Bionic Engineering, vol. 7, pp. 224-231.

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