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DERIVATION OF CRITERIA FOR IDENTIFYING LIGHTWEIGHT POTENTIAL – A LITERATURE REVIEW

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ABSTRACT

Lightweight potential is a powerful indicator – but not as powerful as it could be. Current methods for analyzing a product's potential to be reduced in mass only deal with a few of the most important criteria for lightweight design. The amount of literature dealing with lightweight design is significant, yet it can help to understand these versatile criteria. Firstly, the literature on this topic will therefore be reviewed to derive a broad set of criteria used in contemporary lightweight design. Secondly, a further review will reveal the criteria used to derive lightweight potential. Subsequently, both sets will be compared to identify the missing criteria used for the derivation of lightweight potential. This will support designers in two ways. On the one hand, matching and combining both criteria sets will enable the most representative criteria for a particular design case to be chosen, thus leading to a more comprehensible derivation of lightweight potential. On the other hand, the combination set will provide a basis for designers and design teams to refine their understanding of their own motivations for conducting lightweight design.

Keywords: Lightweight design, Decision making, Design for X (DfX)

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1 INTRODUCTION

The focus of research in lightweight design has shifted toward the conceptual stage in the product-design process over the past few decades. This conceptual stage provides significant design freedom, thus enabling the product designer to analyze mass-relevant product parts to be optimized (Friedrich, 2017). This consideration is often related to the assessment of different lightweight potentials. In this case, the way in which the term "lightweight potential" is viewed in literature is ambiguous.

On the one hand, lightweight potential describes the potential of a substitution of a certain shape, material or technology for a respective counterpart. When considering a substitution of a certain product component made of steel for carbon-fiber-reinforced plastic, for instance, carbon fiber has a high lightweight potential compared to steel (Zhu *et al*., 2018).

On the other hand, lightweight potential is also used with regard to the analysis of where the most promising mass reductions can be achieved in a given product (Albers *et al*., 2017). In this case, a high lightweight potential does not refer to a certain shape, material or technology that is being quantitatively compared to their respective counterparts. Here, the comparison is made between a current component mass and a set mass goal (target mass) for the component in question based on a set of different criteria (Posner *et al*., 2014; Albers *et al*., 2013; Laufer *et al*., 2018). The criterion "energy consumption" results in the energy-consuming spindle of a tooling machine having a higher lightweight potential than the static casing of the machine, therefore the spindle is the more suitable part for mass reduction (Laufer *et al*., 2018).

In the context of this second interpretation of the term "lightweight potential" (which is the interpretation used throughout this entire paper), a wide set of relevant criteria is required. This core set – which considers the different aspects of lightweight design (Kaspar *et al*., 2018) – enables the designer to select the most representative criteria suited to a particular lightweight-design scenario in order to derive individual lightweight potential.

2 PROBLEM STATEMENT AND GOAL

The term "criterion" in engineering design is often used with different connotations. The Oxford English Dictionary (Soanes and Persall, 2005) defines "criterion" as being the "[…] *standard or principle by which something is judged* […]". Consequently, in the lightweight-design context of this paper, "criterion" is used as the standard by which the potential of a design object (e.g. a product component) is assessed with regard to mass reduction. To be more precise, within this paper's context, "criterion" refers to a certain motivation for performing a lightweight optimization, which is thus referred to as a "motivational criterion". If the motivation for lightweight design is the reduction of the environmental impact of a product, for instance, the amount of CO2 emissions produced over the entire lifecycle might be an appropriate criterion for assessing the impact (Mayyas *et al*., 2017). If the motivation is to reduce the product's costs during use, fuel efficiency is one possible factor for assessing the reduction (Hottle *et al*., 2017). Furthermore, different motivations for lightweight design may occur simultaneously during the product-development process, thus yielding a wider set of diversified criteria. However, initial research studies have shown that there are discrepancies between the criteria currently used in literature for conducting lightweight design and the criteria used for deriving lightweight potential. This non-exhaustive criteria set can lead to an imprecise or even incorrect assessment of the lightweight potential.

The primary goal of this paper is to derive a broad set of criteria that can be used to derive lightweight potential. This set should support designers in choosing the most representative criteria for a particular design case as well as in refining the understanding of the motivation for conducting lightweight design. These considerations result in the following hypothesis: *The number of versatile criteria existing in lightweight design is not comprehensively used for deriving lightweight potential*. A twofold investigation should therefore be conducted which, on the one hand, examines criteria for lightweight design and, on the other hand, examines criteria used for deriving lightweight potential in the conceptual stage of the product-design process. Subsequently, a matching and comparing of the two investigations allows identifying gaps and deriving a broad combination set. A clustering of the criteria found should provide systematized access to the set.

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3 METHODOLOGY

The Design Research Methodology (DRM) according to Blessing and Chakrabarti (2009) provides the methodological framework for research within this paper. The type of research chosen is type 2, including a review-based research clarification within Sections (Sec.) 1 to 3 (i.e. first step of DRM). Descriptive Study I (2nd DRM step; not performed comprehensively in this case, rather review-based) is then conducted as a systematic literature review to answer the following research question: *Which criteria influence lightweight design and which criteria are used to derive lightweight potential?* The detailed procedure, including all constraints, is illustrated in Section 4. Subsequently, for the initial prescriptive study in Section 5, a comparison of both criteria sets is conducted. The transfer of criteria influencing lightweight design (set 1 found in literature) missing from the set of criteria used to derive lightweight design (set 2 found in literature) constitutes a concept sheet (third step of DRM), which functions as a comprehensive set for deriving lightweight potential. Furthermore, it can serve as a basis for designers to choose the appropriate sub-set of criteria for a particular lightweight-design application. Figure 1 illustrates the entire procedure followed within this paper.

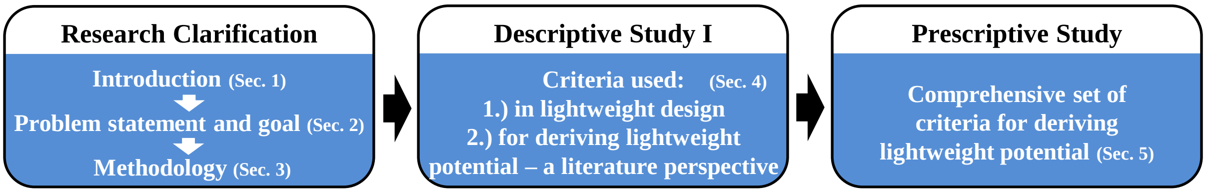

Figure 1. Procedure followed in this paper for elaborating criteria for lightweight potential

4 CRITERIA USED FOR BOTH LIGHTWEIGHT DESIGN AND THE DERIVATION OF LIGHTWEIGHT POTENTIAL – A LITERATURE PERSPECTIVE

To gain an insight into the way in which criteria for lightweight design are viewed in literature, the procedure of the systematic literature review is presented in this section. In the first subsection (4.1), the focus is on the procedure for identifying criteria for lightweight design, while the second subsection (4.2) focuses on the criteria for deriving lightweight potential.

4.1 Criteria for lightweight design

Initially, the following procedure was planned in order to perform the systematic literature review. It is subdivided into four basic steps:

1. Initial examination of relevant synonyms of the terms “criterion” and “lightweight design”.
2. Execution of the actual review in four indexed, electronic databases with the relevant synonyms identified in (1.).
3. Initial selection of the papers found in step (2.).
4. Detailed analysis of the selection in step (3.).

The results of this four-step procedure are illustrated in Section 5.

To begin with, a list of synonyms for the term “criterion” and the term “lightweight design” were defined based on an initial investigation of papers with high relevance for lightweight design. As can be seen in Table 1, seven synonyms for the term “criterion” and eight synonyms for the term “lightweight design” were used in both singular and plural form.

Table 1. Relevant synonyms for the terms “criterion” and “lightweight design”

Synonyms for the term “criterion*”	Synonyms for the term “lightweight design*”
“Parameter” (Delogu et al., 2018)	“Lightweight construction” (Schleinkofer et al., 2018)
“Indicator” (Choudry et al., 2018)	“Lightweight development” (defined by the authors)
“Factor” (Hottle et al., 2017)	“Lightweight engineering” (Caldwell et al., 2013)
“Basis” (Koffler and Rohde-Brandenburger, 2010)	“Lightweight optimization” (Wang et al., 2017)
“Measure” (Delogu et al., 2016)	“Mass reduction” (Hottle et al., 2017)
“Multi-objective” (Wang et al., 2017)	“Mass saving” (Qin et al., 2016)
“Multi-criteria” (Kaspar et al., 2018)	“Weight reduction” (Viqaruddin and Reddy., 2017)
	“Weight saving” (defined by the authors)

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Additionally, in order to achieve more relevant results, the term "lightweight design" and its synonyms were searched in the title of the respective papers. This was to ensure that the main focus of the publications found was on lightweight design in order to gather more relevant criteria. By setting this limitation, the number of search hits could be reduced by a factor of up to 15 (depending on the database) in comparison to targeting the title *and* abstract *and* keywords. The search string was then complemented by an additional field with the term "criterion" and its synonyms, which were searched for within the full publications. The described search strings were used in four indexed, electronic literature databases to conduct the actual literature review: *Science Direct, Web of Science, Pro Quest* and *Engineering Village*. The search itself was conducted during September and October 2018.
Filters were used to narrow down the search results. Firstly, only papers published between 1980 and the present were taken into account. Secondly, filters were used to focus exclusively on conference articles and journal articles. Furthermore, filters were set individually according to the database's structure to include only papers related to engineering design (mechanical, energy, civil, environmental, etc.) in the broadest sense. The numbers of search hits are shown in Figure 2 (left). In the final step, the 465 papers found were examined in more detail, which entailed analyzing the title, abstract and keywords following the sequence of requirements below:

- Relevance to lightweight design
- References/information on motivation for lightweight design
- References/information on criteria for capturing different motivations for lightweight design

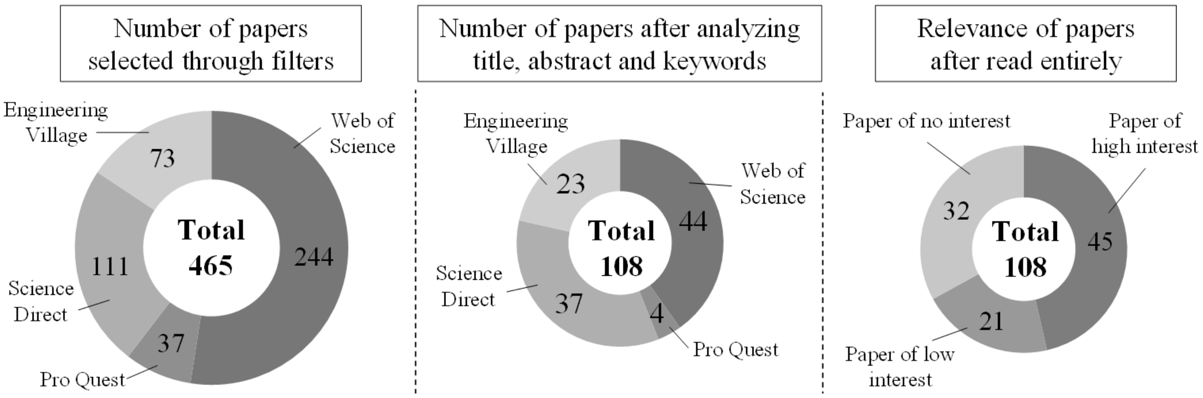

Figure 2. Papers with references to criteria for lightweight design

After this more detailed investigation, 108 papers remained to be analyzed in their entirety according to information on criteria for lightweight design (Figure 2, center). 4 papers were found on both *Science Direct* and *Web of Science*, while 6 papers were found on both *Science Direct* and *Engineering Village*. Finally, the relevance of the papers found was assessed based on the distinct criteria identified (Figure 2, right).

4.2 Criteria for deriving lightweight potential

The basic procedure for searching for criteria for deriving lightweight potential was the same as described in Section 4.1 for lightweight-design criteria. Synonyms for the term "lightweight potential" were thus identified (see Table 2) and searched for in the full papers. The four electronic databases and the filters were set as in Subsection 4.1.

Table 2. Relevant synonyms for the term "lightweight potential"

Synonyms for the term "lightweight potential*"	
"Lightweight-design potential" (Albers et al., 2017)	"Mass-saving potential" (Caldwell et al., 2013)
"Lightweight-construction potential" (defined by the authors)	"Weight-reduction potential" (Hottle et al., 2017)
"Mass-reduction potential" (Kroll et al., 2011)	"Weight-saving potential" (Luedeke and Vielhaber, 2014)

The 663 papers identified – shown in Figure 3 (left) – were then analyzed in detail with regard to the title, abstract and keywords following the sequence of requirements:

- Relevance to lightweight design and corresponding mass-/weight-reduction methods
- References/information on special methods for deriving lightweight potential
- References/information on criteria used within these methods

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This procedure revealed 64 papers to be relevant (Figure 3, center) in terms of criteria used for deriving lightweight potential. Only one paper was found on several platforms. Lastly, the relevance of the papers found was assessed based on the distinct criteria identified (Figure 3, right).

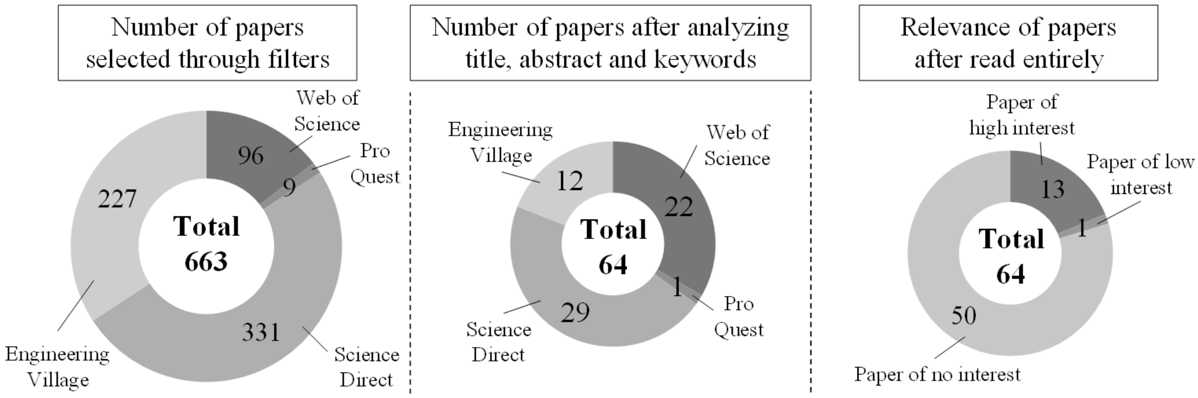

Figure 3. Papers with references to criteria for identifying lightweight potential

5 SET OF CRITERIA FOR IDENTIFYING LIGHTWEIGHT POTENTIAL WITH A BROAD SCOPE

The analysis performed in the previous section enables the results to be summarized and clustered. The overarching aim of this section is to compare the criteria found for lightweight design and for deriving lightweight potential before identifying any gaps. Furthermore, building upon these gaps, the aim is to specify a broader and more holistic set of criteria for deriving lightweight potential.

Overall, 14 different criteria used in lightweight design were found in the 45 relevant papers (Table 3, top 14 rows) mentioned in Section 4.1. In order to cluster these different criteria, the papers analyzed in detail were screened for different potential clustering dimensions. Lifecycle engineering is one method for addressing different dimensions. Three dimensions used in this context proved sufficient for lightweight-design applications (Kaspar *et al.*, 2018), thus enabling the criteria found to be clustered. The dimensions consider *economic*, *ecological* and *technological* issues of an engineering solution and help to weight the various factors, such as with regard to the material-selection process (Peças *et al*., 2014). Most criteria found could be assigned precisely to one dimension, while some were placed between the *economic* and *ecological* dimensions because they could be assigned to both (Table 3, top left, indicated by double arrow).

Below, some of the criteria found will be briefly discussed. Concerning the *technological* dimension, most lightweight-design cases deal with reducing mass while improving the *structural performance*. This can be traced back to Maxwell (1869), who investigated optimized topology structures theoretically. Since this paper focuses on "motivational criteria" for lightweight design, papers dealing exclusively with structural performance improvements (e.g. bionics for engineering) were not considered. However, if papers contained significant criteria *and* (additionally) structural performance criteria, this was recorded. The criterion which appeared most frequently (16 hits) in this dimension was *improve working performance*; either to improve the acceleration of a production machine (inter alia Schleinkofer *et al.*, 2018), to improve the handling of a product or the ergonomics of a prosthesis (Ahn *et al.*, 2017). When improving performance by reducing the mass of a product, lightweight design usually comes with higher costs, which are tolerated to a certain extent (Friedrich, 2017). With regard to the *ecological* dimension, the focus is noticeably on *reduce greenhouse-gas emissions (GHG)*. A differentiation is made between emissions exclusively during the usage phase (11 hits) and during the entire lifecycle (9 hits). According to Hottle *et al*. (2017), for instance, the usage phase of a vehicle remains the phase which accounts for 84-88% of the GHG emissions. Together with the most significant hit (33) *increase fuel efficiency/reduce operational energy*, these criteria reflect the effort expended to make the certain product vehicle more environmentally friendly (Delogu *et al.*, 2018).

This trend can also be observed in Figure 4. The papers found on criteria for lightweight design disproportionally (over 50%) concerned the automotive industry. In the last dimension (*economic* criteria), the criterion *reduce manufacturing costs* (17 hits) also originated from this industry, thus illustrating the high cost pressure faced by car manufacturers (Mayyas *et al.*, 2017).

Moreover, some criteria influence each other, e.g. the *increase secondary mass savings* and the *increase of the fuel efficiency*. This has to be investigated in further research.

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Table 3. Set of criteria for lightweight design

CRITERION: "Lightweight design is conducted/performed/applied to …"	reduce manufacturing costs	reduce lifecycle costs	increase additional weight loadings (reduce logistic costs)	reduce material consumption (recycling costs & material costs)	increase secondary mass savings (e.g. power unit)	reduce wear/increase lifetime	increase fuel efficiency/reduce operational energy (usage)	increase energy savings (entire lifecycle)	reduce greenhouse-gas emissions (entire lifecycle)	reduce greenhouse-gas emissions (usage)	improve working performance (e.g. acceleration, mass moment of inertia)/improve handling (ergonomics)	reduce assembly space/increase compactness	optimize center of gravity	improve structural performance/torsional rigidity/stiffness-to-weight ratio
Dimensions	Economic criteria	Economic criteria	Economic criteria	Economic criteria	Economic criteria	Economic criteria	⬍	⬍	Eco-logical criteria	Eco-logical criteria	Techno-logical criteria	Techno-logical criteria	Techno-logical criteria	Techno-logical criteria
References														
Ahn et al., 2017											×			
Albers et al., 2018	×								×					
Alonso et al., 2012		×					×			×				
Bein et al., 2016	×						×		×					
Belingardi et al., 2010							×			×				
Block et al., 2017	×						×					×		
Borazjani and Belingardi, 2016							×			×				×
Butterfield et al., 2005	×						×							
Caldwell et al., 2013							×		×		×			
Choudry et al., 2018	×			×			×	×						
Delogu et al., 2016	×				×		×		×					
Delogu et al., 2018		×			×			×	×					
He et al., 2017				×			×				×			
Hottle et al., 2017	×				×	×	×			×				
Kaspar and Vielhaber, 2017	×			×			×	×						
Kaspar et al., 2018	×			×			×	×						
Keane et al., 2007							×				×			
Kelly et al., 2015							×		×					
Khode et al., 2017						×	×				×			
Koenig and Friedrich, 2015			×		×		×				×			
Koffler and Rohde-Brandenburger, 2010					×		×	×						
Li and Liu, 2017	×		×											
Lowrie et al., 2017			×				×			×				
Maier et al., 2009			×	×			×				×			
Mayyas et al., 2017	×						×		×		×	×		
Naji et al., 2014		×		×				×						
Nie et al., 2015				×			×		×					
Pan et al., 2010							×		×					
Paquet et al., 2013			×								×			
Pine et al., 1999	×						×							×
Prawoto et al., 2013							×			×	×			
Qin et al., 2016	×			×								×		
Sakundarini et al., 2013							×			×				
Schleinkofer et al., 2018	×				×						×		×	
Shi et al., 2007	×									×				
Takahashi et al., 2017	×										×	×		
Tawfik et al., 2017			×				×						×	
Tornow et al., 2014					×		×							
Tsai et al., 2014							×			×				
Viqaruddin and Reddy, 2017							×				×			
Wang et al., 2017a										×	×			
Wang et al., 2017b											×			×
Xu etr al., 2012	×						×							×
Zhang et al., 2007							×	×						×
Zhu et al., 2018							×			×	×			
Appearance	**17**	**3**	**6**	**8**	**7**	**2**	**33**	**7**	**9**	**11**	**16**	**4**	**2**	**5**

At this point, it should be mentioned that the systematic literature study is subject to limits regarding its holistic nature. The derived criteria set (Tables 3 and 4) makes no claim to being exhaustive. Further investigations (e.g. in fundamental books for lightweight design) will need to address the evaluation of the criteria found, in addition to expanding the set.

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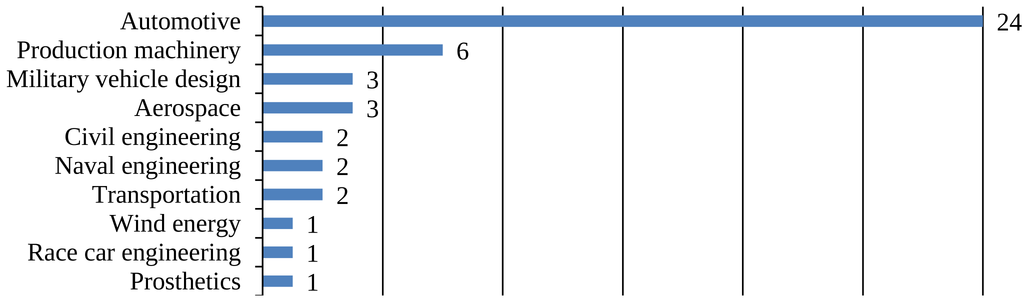

Figure 4. Distribution of papers sorted by industry

The second part of the literature review focused on the criteria for deriving lightweight potential. The methods actually used for deriving lightweight potential are numerous, although the paper's framework does not allow these methods to be investigated in detail. In order to be able to compare both criteria sets, the criteria for deriving lightweight potential found within the 13 relevant papers were listed in Table 4, which already included the criteria for lightweight design previously found in order to simplify comparison.

Table 4. Criteria used for deriving lightweight potential

CRITERION: "Lightweight design is conducted/performed/applied to …"	reduce manufacturing costs	reduce lifecycle costs	increase additional weight loadings (reduce logistic costs)	reduce material consumption (recycling costs & material costs)	increase secondary mass savings (e.g. power unit)	reduce wear/increase lifetime	increase fuel efficiency/reduce operational energy (usage)	increase energy savings (entire lifecycle)	reduce greenhouse-gas emissions (entire lifecycle)	reduce greenhouse-gas emissions (usage)	improve working performance (e.g. acceleration, mass moment of inertia)/improve handling (ergonomics)	reduce assembly space/increase compactness	optimize center of gravity	improve structural performance/torsional rigidity/stiffness-to-weight ratio
Dimensions	Economic criteria	Economic criteria	Economic criteria	Economic criteria	Economic criteria	Economic criteria	Eco-logical ↕ Economic	Eco-logical ↕ Economic	Eco-logical criteria	Eco-logical criteria	Techno-logical criteria	Techno-logical criteria	Techno-logical criteria	Techno-logical criteria
References														
Albers et al., 2013							No matches found							
Albers et al., 2017	×								×					
Albers et al., 2018	×								×					
Alonso et al., 2012					×									
Caldwell et al., 2013											×			
Cheah and Heywood, 2011							×							
Hao et al., 2016	×						×			×				
Kroll et al., 2011						×	×				×			×
Laufer et al., 2018							×						×	
Lewis et al., 2014					×			×	×					
Luedeke and Vielhaber, 2014					×									
O'Reilly et al., 2016								×						
Posner et al., 2014							No matches found							
Appearance	**3**	**0**	**0**	**0**	**3**	**1**	**4**	**2**	**3**	**1**	**2**	**0**	**1**	**1**

Firstly, it can be observed that papers in Table 4 which contain criteria for deriving lightweight potential exhibit the most important criteria (*reduce manufacturing costs [3 hits], increase fuel efficiency/reduce operational energy [4 hits], reduce greenhouse-gas emissions [3 hits])* when compared to the appearance of the criteria in Table 3. This can be explained through the high relevance of methods dealing with these criteria in the automotive and production-machinery industry (context of 9 out of 12 papers). Secondly, four criteria (*reduce lifecycle costs, increase additional weight loadings, reduce material consumption, reduce assembly space*) did not appear in any papers with regard to deriving lightweight potential (marked in Table 4, last row). Thirdly, some of the methods found within the papers take other additional criteria into account, such as functional importance (Albers *et al.*, 2013; Caldwell *et al.*, 2013), customer requirements (Posner *et al.*, 2014) and material composition (Lewis *et al.*, 2014). Three papers appeared in both reviews (Albers *et al.*, 2018; Caldwell *et al.*, 2013; Alonso *et al.*, 2012).

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6 CRITICAL DISCUSSION AND OUTLOOK

The investigation within this paper revealed several issues concerning the criteria used for deriving lightweight potential. On the one hand, different motivations for conducting lightweight design lead to different criteria regarding the lightweight potential derived. These motivations are spread over different industries with different emphases. On the other hand, proving the hypothesis from Section 2, a gap was identified between important criteria in lightweight design and the criteria used for deriving lightweight potential. This gap especially concerns cost considerations (*lifecycle*, *logistics*, *material consumption*, Table 4), which can be targeted using methods from other fields such as “target costing” (Ibusuki and Kaminski, 2007) or “life cycle costing” (Woodward, 1997), which are already used in engineering contexts. The main issue here seems to be the selection of appropriate methods for dealing with the various criteria. Conflicting criteria (e.g. manufacturing cost vs. improved performance) pose a particular challenge when methodologically assessing lightweight potential. Furthermore, a decision must be made on whether or not to combine existing methods to capture all relevant criteria for a particular lightweight-design case, or to seek new methods for performing the assessment. Methods from different fields such as management science can yield significant benefits when evaluating lightweight potential with a broad scope. Nevertheless, the broad set of criteria derived enables designers to choose the most representative criteria for a particular design case, thus leading to a more comprehensible derivation of lightweight potential. The set also forms a basis for designers and design teams to refine their understanding of their own motivations for conducting lightweight design. This might help to steer lightweight-design efforts in the most effective direction.

Future work will focus on the assessment and/or development of methods enabling lightweight potential to be derived from all relevant criteria and will deliver a framework for selecting the appropriate methods for a particular lightweight-design scenario. Additionally, the criteria found will be evaluated with experts on lightweight design from different industrial fields to contribute to the question of whether or not the derived criteria set is useful.

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