Approach to Develop a Lightweight Potential Analysis at the Interface Between Product, Production and Material

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Abstract. In this article, a methodology for estimating both the product and the production-side lightweight design potential is presented, which can be used at an early stage of the product development process due to the limited amount of data required. This can help companies to increase the performance of their production facilities through the proper use of their potential and, on the other hand, to identify the lightweight construction potential in their products. This allows for faster integration of lightweight construction in sectors not typically associated with lightweight construction due to the reveal of hidden possibilities in production and ultimately leads to resource savings in industry. For this purpose, possible influencing factors and existing potential analyses are examined first, the requirements for a methodology in the early phase of product development are analyzed and the use cases of calculation for a given component and calculation without a determined component are identified. From the information obtained, a linkage and relevance analysis is used to derive key factors influencing the lightweight design potential of the product and production. The methodology is developed on the basis of these key factors, with a division into potentials of geometric and material lightweight design. Parameters from both areas and their effects on product design and production were taken into account. The lightweight design potential of the production equipment and products is then given as a percentage of the optimal degree of fulfillment.

Keywords: Lightweight design · Methodology · Linkage and relevance analysis

1 Motivation

Environmental awareness is increasing in the society for years. Lightweight construction is a key technology for greater resource efficiency, but apart from the aviation and automotive industries, the advantages of lightweight design are not directly measurable. The relevance in other fields of industry like machine and plant engineering, medical technology or leisure industry has started to increase by a single digit percentage only in the recent past and is still faced with skepticism [1, 2]. The named industries have the missing readiness of the customer in common to pay more for lighter products. Therefore, lightweight solutions are often discarded due to their high material and manufacturing

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costs. To avoid late expensive changes in the product development, an adjusted V-Model was developed withing the research project "SyProLei". With this methodology, the development is an interaction between the domains product, material, production and joining technology from the beginning of the design process until the end of the process [3]. To support the interaction between the domains, a method is missing to identify the potential of manufacturing processes for producing lighter products in an early stage of development and without huge expert knowledge. In Sect. 2, existing analysis approaches in manufacturing are described, followed by the development approach for the presented method and the lightweight potential analysis itself (Sect. 3). At the end, a conclusion is given and an outlook regarding further development of the method.

2 State of the Art

For potential analyses exist a couple of well-established methods. A method known to a large number of applicants is, for example, the spider web diagram. To analyze potentials on a deeper and more specific level there exists a broad variety of specialized tools. In this paper, two potential analyses approaches are presented.

Schmidt [4] focuses on possible weight reduction of parts due to the geometric design freedom when produced by additive manufacturing processes. To achieve this, the two factors of minimal weight and utilization factor are introduced. The utilization factor is hereby derived via a FE-simulation. Additionally, Schmidt takes functional and monetary advantages into account.

In [5, 6], an automation potential analysis is presented which primarily targets the assembly. For this purpose, a systematic analysis of the used processes is used to identify processes technically as well as economically suitable for automation. This basis allows for a derivation of suitable fully or partly automated processes by the means of predefined characteristics. The automation potential analysis shows a possible solution on how an industry-ready solution can be realized. As seen, only specific methods to estimate the lightweight design potential exist as shown by Schmidt. Other potential analysis identified primarily target the automation of production plants. These already proven methods can be used as a basis for a transfer to method to estimate the general lightweight design potential.

To develop a methodology, research has shown that parameters for the assessment have to be identified [7, 8]. A thorough literature review was conducted for this purpose.

3 Approach

As the presented methods in the state of the art shows great potential for supporting the engineer in analyzing the specific cases a methodology is developed to identify the potential of manufacturing processes for the design of lighter products.

3.1 Requirements and Key Factor Identification

First, requirements of the early phase of product development like limited availability of information which restricts the possible parameters, have been identified and noted as boundaries to be considered. Then, 50 factors with an influence on the lightweight design potential have been identified. These can be clustered into production-, lightweight-strategic- and part-specific factors. The aspect of recyclability has been added due to its increasing relevance. In Table 1 some factors of the categories are shown as an example to get an idea which parameters are used. The recyclability is not mentioned in the table because it is used as one factor.

Table 1. Excerpt of the 50 evaluated factors

Production	Lightweight-strategic	Part specific
Flexibility	Conditional lightweight construction	Temperature
Geometry	Material lightweight design	Stress
Manufacturing process	Geometric lightweight design	Material
Volume	Concept lightweight design	Geometry

As research showed have strong interdependencies, the product and production system and therefore the lightweight design potential shows a highly dynamic reaction on changes of one parameter. As a direct result, key factors have to be identified to make the system complexity manageable. The aim is a reduction on the system relevant factors which determine the lightweight design potential. To a achieve a systematic reduction and analysis of the system parameters and to consider the system dynamic created by the interdependencies of the factors, an assessment with a linkage- and a relevance-analysis was chosen [9]. For this, all identified factors span a *m*x*m* matrix where *m* is the number of factors. An excerpt is shown in Fig. 1.

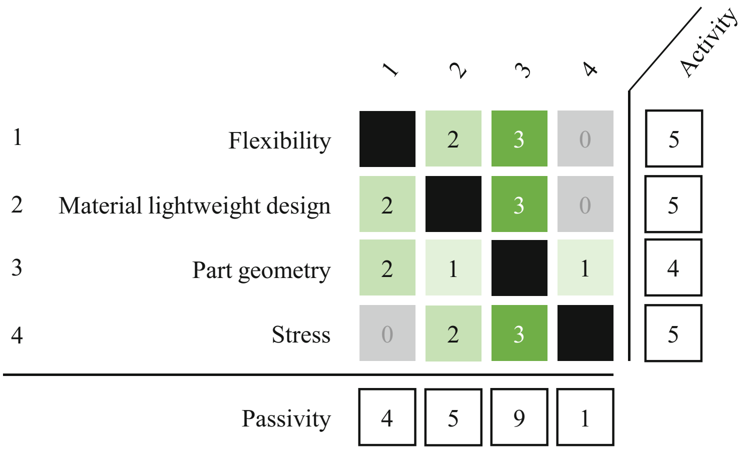

Fig. 1. Example of the linkage analysis

All factors are evaluated on their influence on the other factors following the convention row influences column. For this evaluation, the influence has been classified in four stages. A "0" is given, when no direct influence is occurring, while "1" represents a weak and delayed influence. Value "2" indicates an influence while "3" indicates a strong and direct influence. With this, an initial assessment of the parameters influence is possible. In the shown example the flexibility has influence on the parameter material lightweight design and strong influence on the part geometry. Additionally, the flexibility is influenced by the two factors. Yet, indirect effects have not been taken into account. These can be considered by an effect chain analysis, where "closed loop" influences are assessed. The sum of a row is called the activity and represents the influence of the investigated factor on the system. The sum of a column is called passivity and represents the influence of the system on the investigated factor. With these metrics, the parameters' role in the system can be identified. In the graphical representation a ranking is used rather than the absolute values of the activity and passivity to achieve a quadratic grid. Figure 2 shows the factors in the activity-passivity-grid.

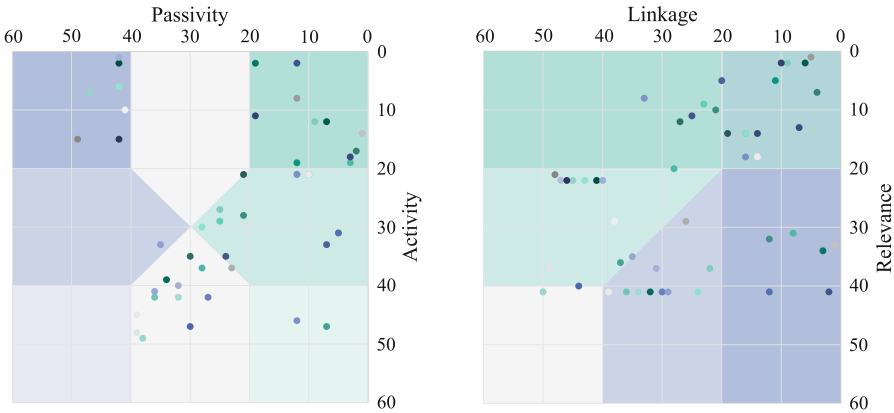

Fig. 2. Resulting activity-passivity-grid (left) and linkage-relevance-grid (right) of the impact factors of lightweight design potential

Depending on their position in the left grid, the factors can be classified. Elements with a high activity and a low passivity are called system levers and are represented by the dark blue area in the upper left corner. Elements with a high activity and a high passivity are called system knots and are represented by the dark green area in the upper right corner. Elements with a low activity and high passivity are called system indicators and are represented by the light green area in the bottom right corner. Elements with a low activity and low passivity are called independent factors and are represented by the light blue area in the bottom left corner. Examples for levers are boundary conditions like the load. For knots, there are the lightweight strategy and the type of production. An indicator is for example, recyclability. Key factors should fulfill three criteria:

1. Have a strong linkage (system knots) to depict a large part of the system dynamic.
2. Target the central topic and show a high relevance (Fig. 2 right) for the design field.
3. Include the central levers (system levers in Fig. 2 left).

Out of the activity-passivity-grid the linkage-relevance-grid is build up with the parameter of relevance, that represents the distance to the central topic. The relevance is identified via an interview with experts in the lightweight area and again consists of integers in the area [1 to m] with the addition of 0, which represents an elimination. The linkage is calculated by a multiplication of the activity and passivity. Again, a ranking is used to achieve a quadratic grid that is shown in Fig. 2 (right). The highest linked (green areas) and most relevant (blue areas) factors are found in the upper right corner and are called safe key factors for lightweight design. These safe key factors are supplemented by factors with a high leverage and linkage. The method will be built up with these in Table 2 depicted factors. The boundary conditions consist of load type, temperature, design space, tolerances and permitted stress or strain.

Table 2. The resulting safe key factors and factors possessing a strong leverage or linkage

Strong leverage	Safe key factors	Strong linkage
Boundary conditions	Process type	Material lightweight design
	Geometry	Geometric lightweight design
	Machine flexibility	
	Material	

3.2 Lightweight Design Potential Analysis

With these key factors identified the methodology will be build up out of three main parts. Part and machine parameters have been identified to strongly influence the lightweighting potential. Therefore, information about them will be gathered by a questionnaire. The needed information regarding machines and materials are already classified and researched for example in [10–13], this information can be stored in a database. Lastly, calculations of the lightweight design potential have to be developed.

Table 3. Excerpt of parameters asked in the questionnaire

General	Machines	Part
Production volume	Process	Material
Part considered	Maximum dimensions	Dimensions
Lightweight design strategy	Degrees of freedom	Volume of material
Recyclability considered		Machining directions
Costs considered		Load type
		Design space
		Operating temperature
		Tolerances

The information about the part to be produced and the machines to produce it vary between possible use cases. Therefore, a questionnaire has to be developed that allows for a collection of all relevant parameters, which are presented in Table 3.

Due to the identified complexity of the lightweight design potential, an approach was chosen to part the potential into subpotentials as seen in Fig. 3. These subpotentials are calculated independently. These subpotentials and the further subordinate calculations will be added together by a weighted mean. The weighting was determined by a survey among experienced engineers within the project consortium. Hereby, a consensus across different industries was observed.

As every potential need a reference, two usecases have been identified: Firstly, the case of a comparison between the potential of different machines. For example, this is the case when the decision between an invest into a machine for future products has to be made. Secondly, the potential of the already owned machines is not fully understood and a certain product should be optimized for this machine. Therefore, depending on the case, two references have been identified. For the first case, the reference is defined per property as the maximum of the machine properties amongst all possible machines. In the second case, the reference is simply the available machine. Equation 1 shows the calculation exemplary for the geometric flexibility. Equation 2 shows the calculation of a potential out of several subpotentials.

$$Potential_{geom} = \frac{\text{complexity}_{geom,part}}{capability_{geom,machine}} \tag{1}$$

$$Potential = \sum_{i=1}^{n} w_i * Subpotential_i \tag{2}$$

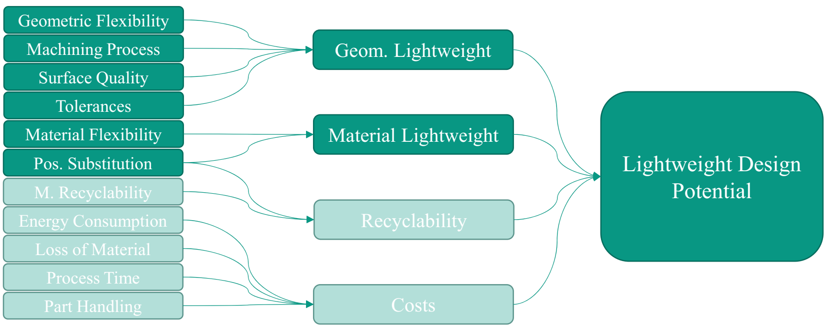

Fig. 3. Structure of the parameters for the lightweight design potential calculation

To verify this methodology, a prototype of an automated tool has been built in excel. Hereby the user adds the parameters already described in Table 3 into a mask. On another sheet, a database was built. This database contains information about selected machinery that has been investigated and evaluated for material and geometrical flexibility, tolerances, processable materials, undercuts, symmetry, surface quality, process and energy consumption. While the material database can be implemented by the means of existing material databases, a simplified one has been built up for testing, consisting of parameters Young's modulus, shear modulus, strength, stiffness, density, operating temperature as well as costs and recyclability. A material substitution can be calculated as in Eq. 3 for bending with regard to stiffness, depending on whether stiffness or strength is the relevant design parameter.

$$\Delta V_B = \frac{\sqrt{E_{original}}}{\sqrt{E_{subst}}} \tag{3}$$

For complex load, a direct estimation is not possible without a thorough analysis. Therefore, the assumption was implemented, that a complex load leads to the worst-case change in volume out of the considered parameters tension/compression, bending and denting.

The results are displayed by a percentage of fulfillment compared to the corresponding reference. There also the two worst fulfilled factors per subpotential are displayed and recommendations for action to tackle these flaws are given for these factors.

4 Case Study and Discussion

Two cases with which the method is to be tested will be discussed. First a CNC-milling process and a SLM process are to be compared. The comparison is viable, as both processes propose a high lightweight design potential. For both processes a maximum dimension of 1000 × 1000 × 1000 mm has been assumed. For the resolution, typical resolutions of IT6 for milling and 0.02 mm for the SLM process were chosen. While the milling process possesses 5 degrees of freedom, the SLM process possesses 6. While both processes showed a high suitability for lightweight design, the results showed the milling process (90.91%) to have a higher potential than the SLM process (82.98%), when only considering geometric and material lightweight design. This is mainly caused by the difference in the material lightweight design potential as the SLM process is limited to metals, while the milling process can process a wider variety of materials. As expected, the potential of geometric lightweight design is a bit higher for the SLM process, even though with 96.25% it does not reach the optimum there. This is due to the needed post processing of functional surfaces by a cutting process. The milling process follows with 94.69%.

The second process is the optimization of a bending beam as a well-known part. The beam is assumed to be 100 × 500 × 100 mm, have no undercuts and be made out of steel. Design parameter is stiffness. Tolerances and surfaces don't need to be highly accurate. Again, the milling process is compared to the SLM process. The potential of lightweight design is used to 40.78% on the milling process and to 33.78% with the SLM process. Recommended actions are an increased usage of the geometric and resolution capabilities of the processes for the geometric lightweight design. For the material lightweight design, a substitution and a check for the usage of fiber reinforced materials is recommended. Following the recommendations, a topology optimization (Fig. 4) increases the usage of the geometric potential drastically.

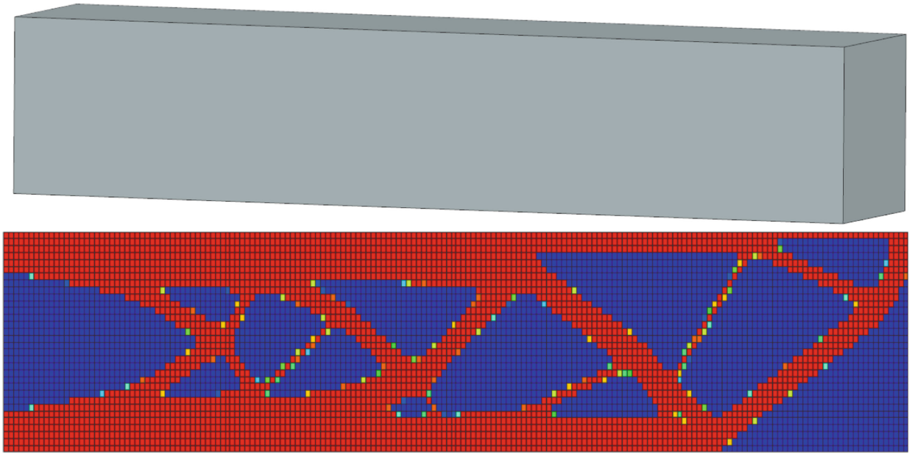

Fig. 4. CAD-model of the beam (top) and its 2D-topology optimization (bottom) with red representing part material and blue representing removed material

Even though the percentages suggest an exact potential, the results are in reality to be interpreted by the user and strongly case dependent. Nevertheless, the guidelines to increase lightweight design are functional and fulfill their purpose of leading the engineer to a more thought-out solution by pointing out unused potential.

5 Summary and Outlook

The paper presented an approach to develop a lightweight potential analysis at the interface between product, production and material. Based on a literature research and activity-passivity-analysis and a linkage-relevance-analysis key factors for the lightweight potential were identified. Based on the key factors a questionnaire for the interaction with the user were developed. Together with the information regarding product structure and manufacturing process the lightweight design potential is calculated based on a database regarding manufacturing processes and material. The developed questionnaire requires expert knowledge regarding the analyzed parts and some of the information is difficult to determine manually. Furthermore, the calculation of the part stress is inaccurate. For this purpose, a connection of the CAD-Model of the analyzed part as well as a FE-Simulation with the presented method would lead to an easier usage of the tool. Additionally, adding cost models to the manufacturing processes will also represent the economic effects of lightweight design in the model.

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