# Multi-material design for the optimization of the automotive production process

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# 1 Preliminary notes and introduction

The automotive industry and thus the automobile production processes have to face new challenges constantly. Changing mobility concepts, alternative approaches to mobility, urbanization and demographic change lead to alterations of the buying behavior of potential customers. This results in a higher rate of product diversity, which increases steadily. Through the constant growth of Asia and China, in particular as automotive manufacturing sites, and the gain in purchasing power of the population of emerging and developing countries, new markets appear, developing with high growth rates. This process has also impacts on the production technology.

A key issue is the transition from finite fossil fuels to alternative fuels and drive systems. Significant rating values are $CO_2$ and pollutant emissions. Downsizing conventional combustion engines and the use of alternative fuels are means to achieve minimization of emissions. Innovative electric motors, solar and fuel cells or hybrid solutions are other approaches to realize a pure electric vehicle. Requirements for that are suitable energy sources and storage systems. Another approach to reduce emissions is the application of new types of materials in the engine, chassis or body. These measures lead to weight reduction and therefore lower fuel consumption. Such materials require the development of entirely new process chains, which includes recycling, manufacturing processes and logistics concepts. Due to the availability of modern methods and materials, coming automobile generations will be realized by multi-material mixing. In this concept, the materials are combined and can be optimized according to the operational demands. The manufacturing, working and processing as well as the calculation of such structures and the development of associated process chains are enormous challenges for future car generations.

The networking of vehicles and the coupling to modern means of communication offers further innovation potential. In its simplest configuration, only consumer electronics, the internet and messaging services are provided in the vehicle. As a further extension level, vehicles will be able to communicate with each other. These smart vehicles will be autonomous cars, while the driver will be able to see personalized advertising, adapted to the particular current location, or to send short messages to the cloud via intuitive user panels.

To conclude, it can be said that innovative and flexible production-methods, that are able to implement the advanced technological, economic and social conditions, are needed.

# 2 Lightweight design by means of multi-material mix

The introduction shows that highly automated mass production is not possible without adequate manufacturing technologies. In the context of the automotive manufacturing industry, the primary objective is to achieve the highest possible level of process reliability and minimum cycle times at the same time. Designs based on multi-material composites (hybrid structures) are a suitable approach in order to achieve this aim. In this paper, the design process and calculation of multi-material composites is presented. The main calculation tools are described and a short summary of the basics is shown. The paper concludes with a list of successfully implemented design examples which demonstrate how lightweight design and especially hybrid lightweight design can be used to optimize manufacturing systems.

## 2.1 Calculation tools and analysis tools for structural optimization

For a technical component of manufacturing system, different types of stiffness can be distinguished according to the main applied loads: tensile/compressive stiffness, bending stiffness and torsional stiffness. Factors influencing the static stiffness of a technical component are:

- the selected material and its correspondent Young's modulus and shear modulus,
- the distance between supports and loads,
- the cross-sectional shapes and dimensions (moment of inertia $I$ and $I_p$) of the part, including ribs, struts and holes,
- the support conditions (contact surfaces, screwed joints and connections to other parts).

Especially by choosing a proper design of the cross sections and joining or contact areas, the designer can positively influence the static and dynamic behavior of a component. Further mechanical analysis allow the identification of the functional and structural weaknesses of the first design drafts– regardless of whether they are derived from existing designs or completely new developed. In a subsequent optimization, improvements up to 50 % of performance and a cost reduction of about 20 % may be simultaneously achieved. As an example, a comparison between weldments and cast components is given.

The use of computational analysis and optimization methods enhances the design possibilities of cast parts. The results of these analyses show often a very complex geometry as the more efficient solution, in terms of less use of material, to fulfill a specific function and requirements. Casting allows the production of such complex-shaped parts which are then, compared to welded structures, more efficient designs.

## Understanding structural optimization

The optimization of mechanical structures is referred to as structural optimization. Considering its boundary conditions, which may even vary with time, a structure must be optimized in order to withstand acting loads. As objective functions of structural optimization, the following properties of a technical component are generally used:

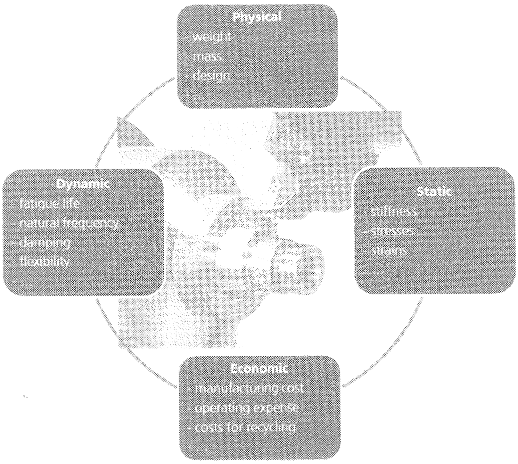


Figure 1: Objectives of a technical structure

These objective functions can be – optionally using weighting factors – individually or simultaneously minimized or maximized to optimally absorb the applied loads. In addition to the objective functions, optimization problems usually have constraints. On the one hand, these restrictions can be directly set by the objective functions, e.g. by limiting the possible solutions. On the other hand, the choice of manufacturing or processing methods generates external constraints too. The design variables in structural optimization represent the parameters that characterize the structure. The kind of design variable defines the various disciplines of structural optimization. A distinction is usually made between optimization of design, topology, material properties, shape and cross-section. The following is a rough overview of three types of structural optimization: topology, shape and parameter optimization as well as of the important class of material of composites for hybrid structures.

In the optimization process is essential that the 3D CAD design and FEM calculations (particularly vibration and stiffness analyses), also topology and shape optimization if needed, are carried out simultaneously.

Such an approach allows the complete virtual development of functionality and manufacturability in an extremely effective and inexpensive design process. In Figure 2 are shown the fundamentally different types of structural optimization and their significant influencing parameters.

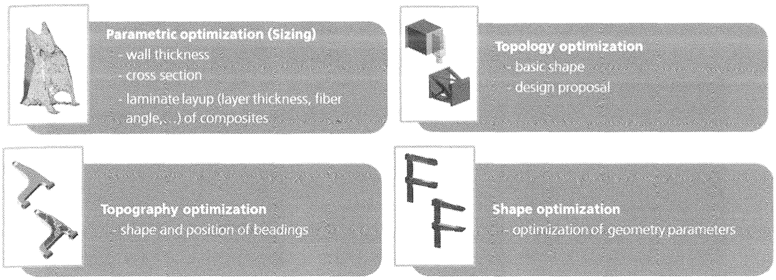


Figure 2: Types of optimization

## Topology optimization

In the early stages of the product development process, topology optimization can be used to identify suitable design proposals within a given design space, in which no geometry has been defined yet. The design space is the basis on which loads, material parameters and further restrictions are applied. For the given boundary conditions, topology optimization is able to find a design proposal which meets the defined performance targets, improving part characteristics such as weight and static and dynamic properties. The optimization algorithm runs fully automatic. Since the design proposal is usually based on finite elements, the proposed layout for the design space has to be afterwards smoothed and transferred into a manufacturable design drawing in CAD by the designer in a further post-processing step. In addition, topology optimization always includes a validation run by the finite element calculation to confirm the suitability of the design proposal. State-of-the-art topology optimization programs allow the definition of additional manufacturing restrictions regarding for example machining processes, demoldability of cast parts, wall thicknesses, symmetries or tightness.

The algorithms for topology optimization can be divided into mathematical and empirical methods. In empirical methods empirical, iteration regulations are used for optimization, while in mathematical algorithms a mathematical optimization problem is solved by a constrained objective function [1].

Many of the commercially successful software solutions for topology optimization imitate growth in nature. Especially the so called soft-kill-option (SKO) methods have delivered an outstanding performance in practice. This method simulates the adaptive mineralization process in bones. The biological growth rule is reproduced here. Areas withstanding higher stresses are stiffened, whereas in less stressed areas the material is softened and finally removed completely. Figure 3 shows examples of natural structures which, due to their environmental conditions, must have a lightweight design and at the same time be extremely stiff. Such very stiff structures made with a small amount of material are not only found in bones but also in trees, leavers or plant stems.

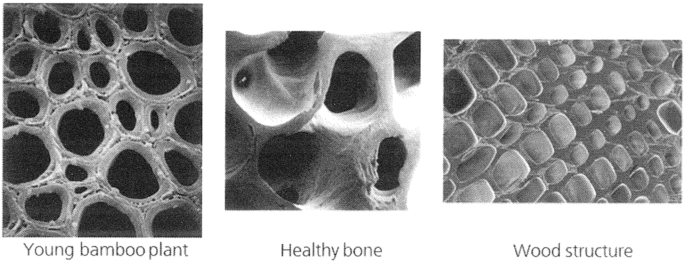


Figure 3: Natural lightweight structures ([2], [3], [4])

This bionic optimization principle has already demonstrated good results in many technical applications. In many cases, manufacturing systems and equipment must fulfill lightweight design requirements too. While the system has to show maximum stiffness, minimum mass of accelerated components is required in order to improve their dynamic behavior. Another argument in favor of minimal use of materials is the associated reduction of manufacturing or investment costs. Figure 4 shows examples of topology optimized machine components for manufacturing systems.

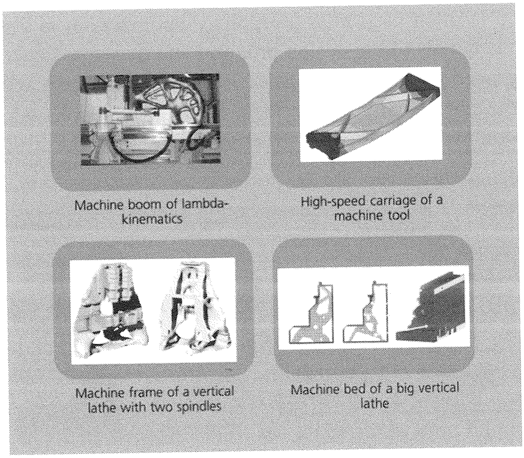


Figure 4: Examples of computationally optimized components in manufacturing systems ([5], [6], [7])

## Shape optimization

Unlike the SKO method, the CAO method does not optimize the entire design space, but only its surface. CAO stands for computer aided optimization. This method is based on the research of Mattheck [8] and simulates tree growth. The growth of trees is stimulated mechanically, among other reasons, which means that more material is deposited in places where higher stresses exist. In this manner, trees achieve a homogenous stress distribution. This homogeneous distribution of stress is called "axiom of constant stress".

In practice, this adaptive growth is often simulated by thermal expansion. For the given load and support conditions, the mechanical stresses are calculated. Afterwards, the stress distribution is transferred to a fictive temperature distribution. The hottest areas expand most, which means that they experience the biggest growth. In order to simulate growth with a temperature analogy, a growth layer must be defined. This growth layer is initialized with a thermal expansion coefficient unequal to zero and a very small Young`s Modulus. By definition, the remaining structure can not expand. In this procedure, growth is controlled by stresses. There is another direct CAO-method which doesn´t use the temperature analogy, and therefore a growth layer doesn´t have to be defined. This method is suitable for the reduction of local stress concentrations and effects caused by notches. The latter effect is particularly relevant for fatigue-critical components.

The CAO method is often used after a topology optimization to achieve further improvement of some details of the design proposal and therefore generate a higher added value. This procedure optimally places material in the part with respect to the stresses, and at the end of optimization there are neither regions which are oversized nor regions that don't contribute to the structural behavior of the structure.

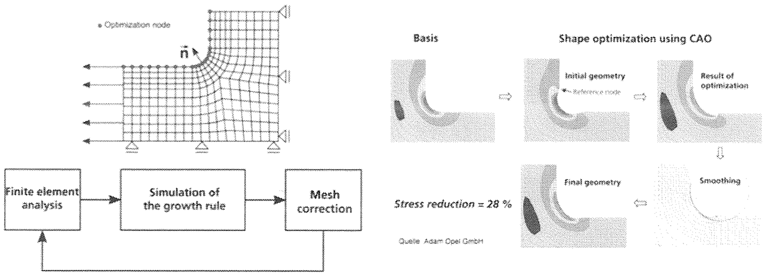


Figure 5: Procedure of CAO optimization using the direct method (left), notch as example of use (right) (according to [9])

After optimization the final engineering and detailing of the design proposal is carried out. Due to manufacturing restrictions (processes, suppliers, cost…), design, marketing, ergonomic reasons or general cost, this version may deviate significantly from the original design proposal in some circumstances. For example, when special manufacturing processes, tools or new materials have to be used. For this reason, at the end of the design and optimization process it should be checked, whether the designed component or system fulfills the requirements under the given boundary conditions.

## Parametric optimization

The method of parametric optimization is normally used on existing designs at an early stage of development. The aim of this method is to find the ideal solution for a design problem and thus to increase the competitiveness of a product. CAE tools for parametric optimization are able to find the best possible design solution even for contrary requirements.

Parameters that can be optimized are, for example, geometric dimensions. Not only the possibilities for the optimization of a part will be identified, but also specific solutions can be developed with variation of the parameters. Sensitivity analyses performed on existing finite element models give information about what parameters and in which degrees have influence on the mechanical properties of the part. The relevant variables are therefore identified and the possibilities for a successful parametric optimization are revealed.

Parameterized models of computation are required to carry out the following optimization of the identified relevant parameters. The specified parameters will be then varied during calculation with efficient algorithms until an optimized parameter configuration is found. This optimal configuration of the design parameters will allow a structural improvement of a component or machine.

As an example, parametric optimization was performed on the rib of an angle bracket. The initial design shows a maximum value of calculated equivalent stress significantly higher than the yield strength of material. A sensitivity analysis was carried out considering different parameters of the rib. In this example, it was found that the height of the rib has the greatest influence on the strength of the part, while the thickness plays only a minor role. The optimization helped to found a design in which the resulting stresses could be reduced below the given stress limit without increasing the total weight of the component.

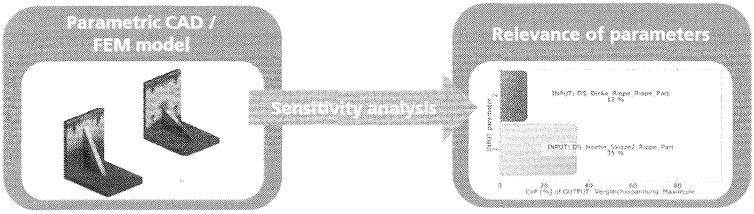


Figure 6: Schematic example for parametric optimization

In order to ensure the reliability of the optimized design solution, a robust design analysis based on the results of sensitivity analysis is performed afterwards. The influence of variability or tolerances of manufacturing process, material properties and loads can be examined with this tool. The effect of these factors on the static and dynamic properties can be quantified, hence predictions about, how reliable the real product will perform during operation can be made.

## 2.2 Fiber-reinforced composites

The objective of lightweight design is to produce products which, on the one hand, have the highest possible strength and/or stiffness and, on the other hand, have the lowest possible mass. Therefore, fiber-reinforced composites are ideal for lightweight designs because of their higher specific stiffness and strength characteristics compared to homogeneous materials. Especially fiber-reinforced plastics offer a significant potential for lightweight design. Not only in the aerospace and automotive industry but also in production machines more and more components are made of fiber-reinforced plastics. The properties of fiber-reinforced plastics make them a significant competitor to conventional materials for manufacturing equipment such as steel or aluminum. In particular, carbon fiber reinforced plastics (CFRP) offer many advantages due to their excellent material properties. The biggest advantage for components made of carbon fiber is their low weight and high stiffness. In addition, through an appropriate fiber orientation the thermal expansion properties of the material can becustomized. Moreover, the favorable ratio of density and stiffness leads to higher natural frequencies, what can be useful for vibration-critical components. A further advantage is the better damping characteristics compared to steel materials.

In order to fully exploit the potential of fiber-reinforced plastics over conventional materials, a comprehensive understanding of this composite material is required. The material has to be adapted to the acting loads, which means that the laminate structure has to be specifically defined for every application. For example, fiber orientation, layer thickness, stacking sequence and fiber volume content will be varied in order to obtain the most suitable composite material for a particular part. The support of computer-based tools is useful for this purpose. Tools based on FE programs are able to build a part layer by layer and generate a realistic model of the fiber-reinforced material. Subsequently, it is possible, as it is with conventional materials, to calculate resulting stresses and strains in a FE simulation. Furthermore post-processing modules specifically made for composite applications offer the possibility to analyze the laminate structure in detail. For example, the detection of the first failing layer or the determination of the critical reserve factor. The Fraunhofer IPA uses the FEM software ANSYS with the additional tool ANSYS Composite PrepPost ACP for such calculations.

# 3 Design examples and added value to the performance of the automotive manufacturing process

Unlike in the aerospace and automotive industry, the added value of a lightweight solution in a machine, or industrial equipment cannot always be predicted with accuracy yet [10]. A 1 kg reduction in weight of an aircraft achieves savings of several tons of fuel over its lifetime. In the automotive sector a weight loss of 100 kg leads to a fuel saving of about 0.3 liters per 100 km [11]. Therefore, the automotive industry accepts approximately five euros additional cost per kilogram of weight saved. For aviation this value achieves more than several hundred euros [12].

In general, production machines must provide high stiffness and dynamics to achieve high productivity rates with maximum process reliability. When the weight of the moving assemblies is minimized and the stiffness is increased, this leads to an optimized production process. In mechanical engineering and especially in highly dynamic moving components such as gantries, clamping devices and end-effectors lightweight design can provide significant advantages.

Lightweight designs usually are highly developed technological solutions. It is extremely difficult to provide an accurate estimate of cost savings of the - often equally or more expensive - lightweight approaches for production machines. The following examples serve to illustrate this:

- Weight reduction of a component causes that coupled parts are less mechanically stressed and thus increases the lifetime of the overall system.
- Reduced weight of some components leads to the so-called secondary lightweight design effects: Dependent standard parts and components such as drives, linear guides and bearings can be downsized (designed or selected with smaller dimensions) which, on the one hand, will further decrease the overall weight of the system and, on the other hand, will reduce manufacturing and operation costs.
- By means of lightweight design, the weight of the new series of a machine can be decreased. Machine foundations and transport systems are then less stressed and can be made simpler in their design.
- A lightweight component may lead to a better dynamic behavior and therefore increases the performance and the productivity of the machine.

An improvement of machine dynamics due to lightweight design can be directly quantified in terms of increased number of produced parts by a machine or reduction of the cycle time. This provides a direct and powerful selling argument for lightweight solutions in production machines. Examples of such machines are machining centers or placement machines for electronic components, where the increased process dynamics leads to a higher number of "placements per minute", which can be directly converted to an added value for the costumer. Only under these circumstances the customer is willing to accept additional costs for a lightweight design. A merely improvement of the performance of a part is not normally considered by the customers as an advantage, especially in machine tools. For example, if an increased system damping is achieved through the use of expensive fiber composites, the end customer is normally not willing to accept the additional costs.

However, there are components and aspects in mechanical engineering and manufacturing where a pure mass reduction can generate added value in these products. Some examples are:

- Machine tool tables, where the maximum payload can be increased
- Transportation and Logistics (machine transport using a fork lift truck, overseas container, truck transport, ...)
- Clamping devices, jigs, hand-held devices and measuring and testing equipment. A minimization of their weight facilitates manual operation with these devices.

At the component level, individual properties can be optimized and ultimately lead to an improved overall system. The exploitation of lightweight potential of a machine or production system should always start with the end-effector of the machine. This is particularly apparent in the case of an industrial robot. Mass and inertia reduction of the end-effector relieves the entire drive train and offers the opportunity to increase the rotational and translational speed of the machine. In addition, the following modules in the load flow path can be designed smaller since the coupled mass is reduced, thus decreasing the load on bearings and parts.

The Function Mass Analysis is a further method to identify potential for lightweight design. In this method, main and secondary functions of a system are defined and weighted relative to each other, considering the product requirements. Together with a defined mass aim, this yields the target mass which is available the respective function. By determining the contribution of a component in the respective functional fulfillment, its target mass can be calculated and a target-actual comparison may be carried out. Customer´s requests can be directly incorporated in the design requirements in the lightweight potential analysis, in which added value through lightweight design is generated. Figure 7 shows the schematic diagram of the procedure.

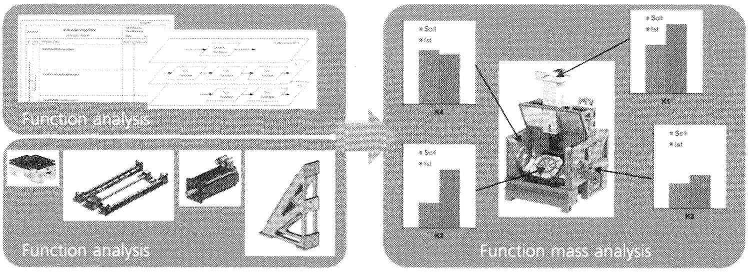


Figure 7: Identification of lightweight potentials through methodical analysis

Apart from the structural mass, some other targets have to be considered when designing machine tools. Low amplitudes and high damping factors have to be ensured in these machines during operation. As stated above, the use of fiber reinforced plastics offers the possibility to improve the properties with regard to damping. Stable thermal conditions are another objective criteria of production machines. The thermal behavior (temperature variations and the associated thermal drift) of such machines is strongly influenced by environmental conditions, aggregates and the machining process. With fiber composite materials, the thermal properties can be "tuned" to a certain extent.

On the basis of several examples from different applications of manufacturing technology it is shown how to generate a direct added value with the use of lightweight hybrid concepts.

## 3.1 Lightweight chucking solutions to minimize operation speed and energy consumption

Chucks are machine components which are located in the force flow path in close proximity to the tool center point. Basically, these machine components represent a rotating cylinder. A reduction in their mass and moment of inertia results directly in a shortening of the acceleration and deceleration times. As a side effect of the mass reduction, the spindle of the machine is less stressed. The lightweight chucks are generally made of a material mix composed of carbon fiber reinforced plastic, aluminum and a steel body.

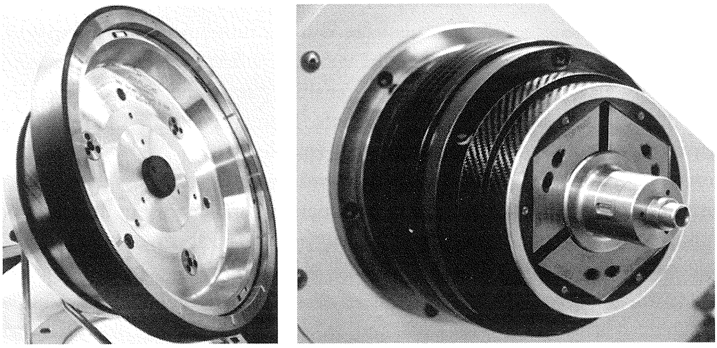

Figure 8: Chuck as a multi-material combination ([13], [14])

Such designs are often compact, resulting in smaller interference contours. The added value of a lightweight design can be directly quantified. Due to lower masses and moments of inertia the energy demand decreases, which has a positive effect on the operating costs.

In the case of a chuck for flywheels of EMUGE-Werk Richard Glimpel GmbH & Co. KG, it was possible to reduce its weight by over 85 % compared to a steel version through the targeted use of a multi-material mix of carbon fiber reinforced plastic-materials, steel and aluminum. Because of the fact that the moment of inertia could also be decreased to about the same extent, the energy consumption can be reduced to about 20 % of the original value. This savings in energy per chuck amount about 5000 € per year, which is approximately the equivalent of the annual consumption of 3-4 average four-person households. In addition to the financial benefits, the mass reduction of the chuck resulted in a reduction of the cycle time and therefore in a higher part output. The added value of the lightweight design measures can clearly be identified in this example.

## 3.2 Assembly equipment and tools to optimize ergonomics

Factors such as demographic change, improved occupational safety and increased health awareness are raising the importance of ergonomics in the mass production sector. Machine operators, assemblers and workers in general should be able to carry out the often repetitive motion sequences in the production and assembly industry without causing themselves any permanent harm during their working life. Using lightweight design concepts in production and assembly equipment is one suitable approach for this purpose. By reducing the mass of the components and tools the workers have to handle or manipulate , the physical damage caused on them may be significantly lowered. Especially in the final assembly of vehicles, a fully automated process is neither sufficiently flexible nor economically feasible due to the very different required tasks for the constantly changing requirements. Manual tasks are often indispensable here. However, due to the compact design of vehicles with a large number of components on a small area, unfavorable working positions often exist. Especially in the vehicle interior due to the restricted space, the operators must work in unfavorable ergonomic positions. To avoid this, they are advised to perform this task in a sitting position, whenever possible. For this purpose assembly aids such as stools are required to perform the assembly activities in an ergonomically suitable working position in the vehicle interior. But, with each new working task, the assembly aid has to be taken in and out of the vehicle. For this reason, a lightweight assembly aid would significantly facilitate the work of the operators at the assembly line. At the same time, the product has to be very robust to resist rough handling during the assembly operations. In addition, assembly aids must be designed in a way that it cannot scratch or cause any damage to the vehicle. Furthermore, other ergonomic requirements must be considered in the design, such as easy manual handling (e.g. by grip recesses or recesses), comfortable sitting for example by upholstery and a firm, non-slip and safe position inside the vehicle. This sometimes very opposite goals could only be achieved through the use of a mix of diverse materials. An assembly aid that fulfilled all these requirements was developed by Fraunhofer IPA by means of a consistent application of lightweight design strategies combined with a generative manufacturing process.

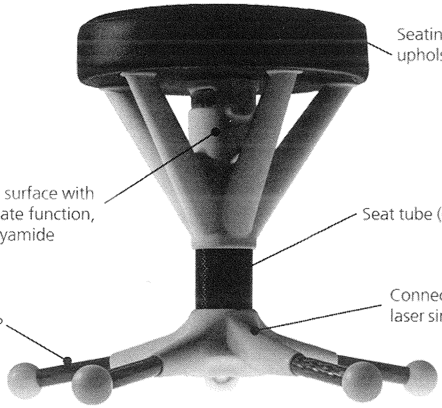


Figure 9: Stool made of a material mix used as assembly aid for the indoor installation

As shown in Figure 9 the stool consists of several lightweight materials, which are selectively used depending on the specific requirements for each component. As a result, the total weight of the stool could be reduced by about half, compared to the previous model.

## 3.3 Lightweight machine tool doors to optimize process safety and ergonomics

New developments in production machines lead towards reduced processing times. By using lightweight design principles, even peripheral components such as safety systems in machine tools can make a significant contribution to this purpose. One example is the redesign of machine tool doors in order to reduce their weight, while still s fulfilling the requirements. By means of multi-material design, not only a merely weight reduction can be achieved, but also an increase in productivity, an improvement of occupational safety and ergonomics and even a long term cost reduction.

A substantial mass reduction of an automated machine door may enhance its dynamic behavior, which in turn reduces nonproductive times and thereby increases process productivity. In some cases, the so-called secondary lightweight effect occurs and it is possible to downsize adjacent system components such as linear guides or drives, resulting in further cost savings. In the case of manual operated machine doors, the task of opening and closing a very heavy door several times a day may cause some physical damage to the operator in the long term, resulting in employee demotivation and additional costs for the company.

Already some scientific work has been dealing with the potential that lies in the weight-optimization of machine doors [15, 16]. For example, a lightweight door of a CNC-lathe machine was developed, reaching a door opening and closing time respectively of 1.5 seconds and thus achieving a reduction of 25 % compared to the current design.

In the field of woodworking machining centers, multi-material designs in their doors are now state of the art. The lightweight materials are used to improve ergonomics and to ensure the safety criteria (e.g. airbag fabric reinforcement), as well as for acoustic insulation purposes (PUR ethers foams) [16]. Figure 10 shows a comparison of several design proposals developed by Fraunhofer IPA for a lightweight door of a CNC machining center, aiming a mass reduction objective of 50 %.

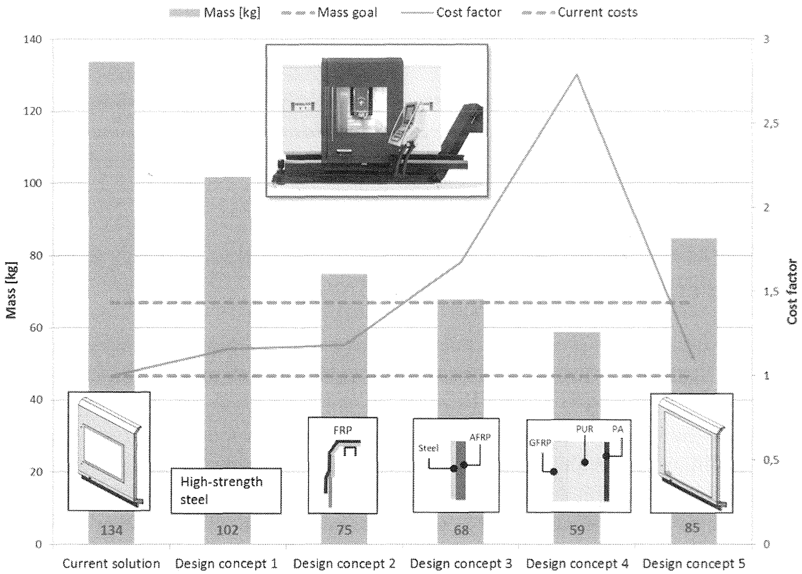


Figure 10: Comparison of alternative lightweight concepts for the door of a machining center

# 4 Conclusion

The added value of lightweight design in mechanical engineering, with respect to machinery and industrial equipment, cannot yet be exactly quantified, as is already the case in the aerospace and automotive industry. However, examples of selected components and devices made clear that it is possible to obtain substantial benefits at the component level.

In some cases, technical improvements such as lower moments of inertia and higher operating speeds generate savings that can be pretty accurately calculated. The effects of lightweight design can be then directly translated into tangible economic benefits. Besides this economic gain, the optimization of products by means of lightweight design may bring non-monetary benefits to both people and nature, such as lower resource consumption, lower emissions and ease of handling.

A direct method for assessing the benefits of the use of lightweight materials and lightweight design principles in machinery and industrial equipment is part of the current research work at Fraunhofer IPA. This method will allow the evaluation and quantification of added value through lightweight design in a machine or production system, also considering the usually higher development and production costs of the lightweight solution.

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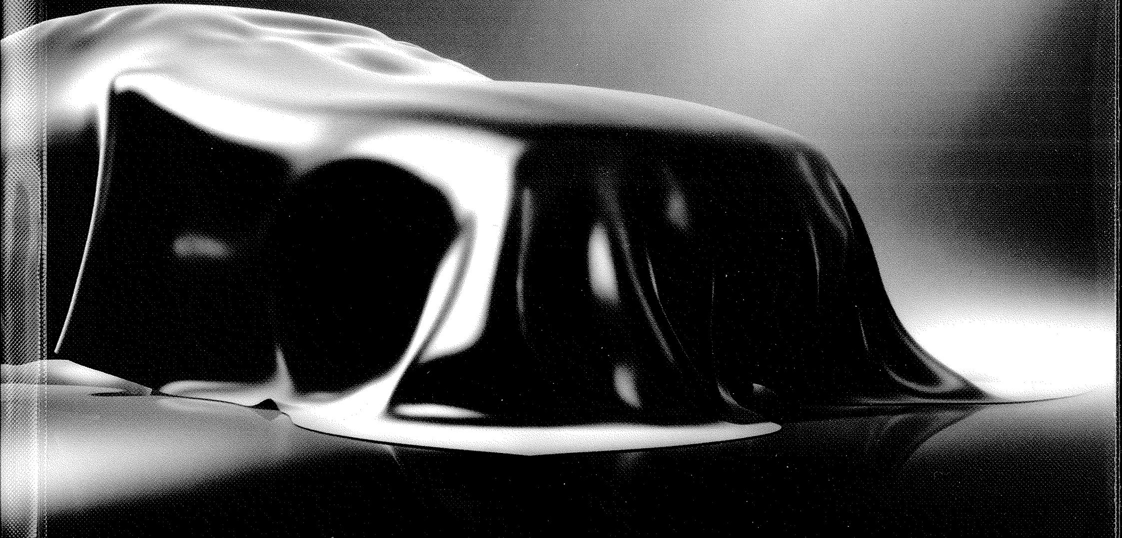

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