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Resource-efficient manufacturing systems through lightweight construction by using a combined development approach

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Abstract

Smart manufacturing systems of the future have to be adaptive, self-autonomous but also resource-efficient in their own manufacturing process as well during their utilization phase. To reach this target within a cost-efficient development and production process, holistic and integrated development methodologies are necessary.
We show that it is possible to combine different development methodologies at an early stage to achieve a cost reduced lightweight design. The combination of the analytical methods function mass, requirement and value analysis with simulation-based topology and frequency optimization in the product development process leads to a resource-efficient and economic manufacturing system in lightweight design. Using the example of a corrugated board conversion machine, this article shows the implementation of this combined development approach with regard to lightweight design.

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Keywords: Resource-efficiency, lightweight construction, product development process

1. Introduction

According to BAUERNHANSL et al. [1] studies show that emerging markets will secure future global demand due to increasing incomes, living standards and population growth. The important question will be, whether this demand can be met by our scarce resources. One indicator that we find ourselves in the middle of the fourth industrial revolution is the fact that countries like the USA or Great Britain start to fundamentally change their view and approach towards how their economies should create value in the future. During the last industrial revolution they thought that their industrial sector would soon be overtaken by their service and educational sector and eventually decreased investing in it. Germany, however, has shown that investing into production research and the respective education in order to maintain and develop the domestic industrial sector pays off. As these economies will try to bring back the value creation of their companies and revive their industrial sector, each economy faces the same challenge of diminishing natural resources. Therefore, the crucial point for economic growth will be their efficient usage in every part of value creation. [1] Hence, manufacturing systems of the future have to be adaptive, self-autonomous but also resource-efficient in their own manufacturing process as well during their utilization phase.

Resource-efficiency in terms of material and energy savings can be achieved through lightweight construction technologies. By focusing on material reducing in the design and manufacturing process of production plants and machines, a specific strategy has to be implemented in a very early developing phase. Energy saving can be a secondary effect of lightweight design, as engines of motion units can be made smaller, which then has a positive effect during utilization phase. However, for a cost-efficient development and

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production process new ways have to be found, because cost and weight are directly related and often conflicting objectives. [2]

Therefore, the cost-benefit ratio must be known very well which often represents a greater challenge for mechanical engineering than in the aerospace sector, where the cost per kilogram payload can be calculated more easily. The potential of a machine to reduce material resources must therefore be identified at an early stage of the developing process.

2. State of the art

There are accepted development approaches in the theory of design, such as those of PAHL et al. and GAUSEMEIER. [3,4] Especially for lightweight structures, there are approaches of KLEIN [2]. They usually focus on the design, development and realization phase, for example by selecting suitable materials for lightweight design and by performing structural and topology optimizations. These approaches can be used for a component or an assembly optimization to reduce weight in the development of manufacturing systems.

The benefits of an early integration of lightweight design during the design phase are described by PONN and LINDEMANN [5] and generally accepted amongst the authors. According to KLEIN [2], a new theory of design for lightweight products is not necessary. Only adaptations to the already available theories of a design process, such as VDI Standard 2221, have to be made (VDI – Association of German Engineers). A separate systematic product development process, called VDI Standard 6224, was defined for developing lightweight structures using biomimetic optimization methods.

However, for a significant mass and cost reduction, it is necessary to use the great potential of the early development phases of task clarification and conceptual design. With the solution concept, the weight, the manufacturing and utilization costs of the system are widely determined – directly or indirectly.

Particularly for products with small initial costs or markets with low requirements (emerging markets), there is an approach called frugal innovation. WEYRAUCH and HERSTATT [6] have defined the following criteria for this type of innovation: substantial cost reduction, concentration on core functionality and optimized performance level.

3. Combined development approach

This section displays the theoretical proceeding of the combined development approach. The application of the approach is shown, based on a case study, in section 4.

According to the state of the art it is necessary that the combined development approach has to include these two development phases (task clarification and conceptual design) as well as the frugal innovation approach, to reach the target of a resource-efficient and economic manufacturing system. As the adaptive design accounts for approximately 55% of the tasks in mechanical engineering, the combined development approach is primarily based on the optimization of existing manufacturing systems or their concepts. The holistic view as well as individual methods from this approach might also be interesting for original design (approximately 25%). [7] For a cost-efficient development, firstly, it is necessary to focus the resources on important tasks. A systematic procedure of the combined development approach is divided into four phases (Fig.1) which are described below.

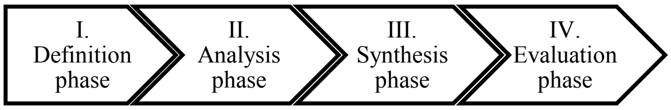


Fig. 1: Four phases for combined development approach

3.1. Definition phase

The definition phase plays a key role in lightweight design optimization. The superior aim of optimization is the weight and cost reduction, while keeping the machine's performance. The stiffness of the structures as well as the speed and acceleration of the components must be maintained or even increased in order to stay competitive. These are often contradictory requirements that can only be implemented through a combined approach, which must be realized within the boundary conditions. It is, therefore, necessary to specify the targets precisely and follow them consistently throughout the development process. At this stage, the system boundaries of the manufacturing system have to be generously dimensioned because of the holistic and integrated development methodologies.

3.2. Analysis phase

After the definition phase, the necessary analytic methods have to be determined. The aim of this analysis phase is to identify assemblies within the manufacturing system with the highest potential for a lightweight optimization with regard to both customer's requirements and costs. The main focus here is on primary lightweight construction, which initially has the greatest impact on resource conservation. Later on, the secondary effects (downsizing of the engine, gears, slides, etc.) are to be considered. They often have a positive effect on the development as well as on the resource conservation during the utilization phase of the manufacturing system.

The start of the analysis phase is the recording of customer requirements and the creation of the functional structure of the manufacturing system in its actual state at the start of the project. To reach the aim of a cost-efficient development, only secondary information of the customer requirements, such as online sources or expert opinions in the company, can be used. The functional structure implements material and energy flow and shows boundaries of the considered system. [8]

In the next step, the "Function Mass Analysis" (FMA) method is performed. The aim of the FMA is to identify and quantify mass loss potentials of a certain product with regard to the customer's requirements. Therefore, the FMA collects the requirements and evaluates their respective importance. In a next step, an interdisciplinary team of engineers forms correlations between the requirements and the functions of the product. Thus, a statement can be made, how important a function is, to fulfill the customer's needs. After that, a target weight for every assembly can be determined from that correlation. Finally, comparing the target weight with the current weight, the optimization potential for every assembly can be derived. [9]

The “function requirement and value analysis” focuses on the core functions of the manufacturing system and thus on the main task to match the customer’s requirements. The aim is to solve the customer’s requirements in the simplest possible and most efficient way and to avoid over-engineering. This approach is used in the development of frugal manufacturing systems. For this analysis, the functional structure and the assemblies must be defined. From the functional structure, the core function of the machine is derived, which describes the customer’s main problem. Now it is evaluated how much the existing assemblies contribute to the fulfilment of the core function. This results in an index (“core index”) of every assembly to show their contribution for solving the customer’s main problem. The most significant assembly that contributes to fulfill the core functions of the system is scaled to “1.0” (see Fig. 3). It can also happen that certain assemblies do not contribute to the achievement of the target and can be removed. This analysis supports efficient development because there is a clear focus on important functions and assemblies.

3.3. Synthesis phase

In the synthesis phase, so-called lightweight construction tools are used to develop holistic structural and design optimizations. Two methods can be applied very effectively in a combined development approach for manufacturing systems, the "Force Cones Method" and the "Contact and Channel Model (C&CM)". [10] The force cones method converts the existing design of a machine into a half-timbered structure and specifically identifies compression and tensile structures. With the help of C&CM, force paths and interfaces between components can be analyzed. Furthermore, weak points can be optimized as well as potential for functional integration of different components can be derived. In the first constructive concept variation, lightweight rules according to KLEIN are applied [2]. The solution variants and overall principle solution paths should then be converted into a morphological box for a comprehensive assessment.

3.4. Evaluation phase

After developing a rough concept of the machine in the synthesis phase, the concept is validated in the evaluation phase. A holistic simulation approach analyzes the structural behavior and measures can be derived if necessary. In addition, the use of topology optimization using biomimetic optimization methods can provide more detailed information on a structurally meaningful design of structural elements, which leads to further material savings and thus to cost reduction. Finally, the weights, costs and system behavior of the concept and the reference model can be compared and assessed.

4. Case study

Based on a corrugated board conversion machine, this article shows the implementation of the combined development approach for lightweight structures.

4.1. Corrugated board conversion machine

The multifunctional corrugated board conversion machine can handle formats of cardboard in the dimensions: widths from 2,500 mm (98 ½”) to 3,600 mm (141 ¾”) and meets the requirements for the production of single or multi-color printed and punched folding boxes.

The machine consists of a large number of sequentially aligned units. At the beginning, the feeder ensures register-accurate sheet feeding into the system. The printing units provide multi-color prints. Further units are rotary cutter, folding machine and clamping unit, extraction unit and – at the end – the stacker (Fig. 2).

To understand the use case, some more information about the system is necessary. The sheets pass through the machine with about 7 m/s, which means up to 32,000 pieces per hour. For a careful handling of the products, package formation and package output are separated. In addition, the stacker must be very flexible to store a wide variety of folding boxes. The damming of the sheets takes place in the transport area by a stop wall, integrated into the inner frame top including top slide (1). Subsequently, the sheets are bundled in a buffer station. With a hold-down system, also called motion unit, consisting of operating fork (2), horizontal cart (3) and vertical cart (4), the packages are transported on to the encompass machine with the inner frame deposit (5)/ rear (6). In order to realize the performance of the machine, a short cycle time and thus a very high acceleration of the motion unit of more than 12 m/s² is necessary. The resulting forces must be derived over the outer frame, later only called frame (7).

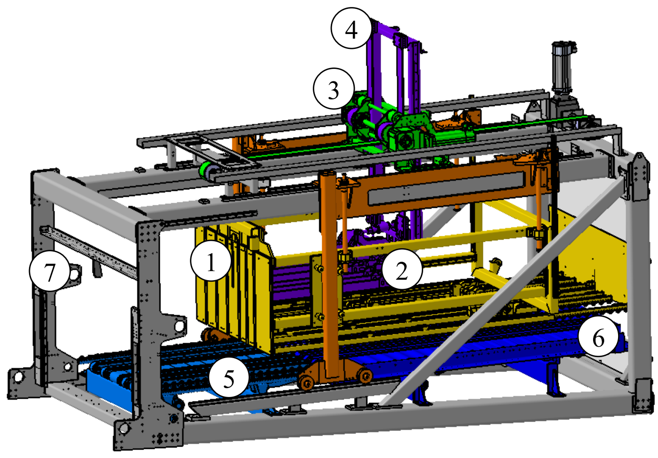


Fig. 2: Reference stacker of a corrugated board conversion machine

4.2. Implementation

In the following, the described stacker is analyzed with the set of methods described in section 3.

4.2.1. Definition phase

In the first phase, the objectives were defined. The rigidity of the system was the trigger for optimization. Due to the high acceleration of the motion unit, the frame has to withstand the reaction forces. For this reason, the frame had previously been built massively, which caused high costs. Target of the optimization: the stiffness of the machine must be increased in order to reduce mechanical compliance. However, the corrugated board processing machine must maintain its performance. In addition, resources must be saved in terms of material and costs.

4.2.2. Analysis phase

At the beginning of the analysis phase, the requirements and weights of the stacker, which also define the system boundaries, have been collected from an expert team. The requirements with their relative importance for the customer are the following:

Table 1. Requirements with their relative importance.

Requirements	Importance (%)
Pick and stack cardboards	23
Transport cardboards with short cycle time	14
High stiffness of the system	3
Reliable and safe operations	23
High cardboard quality	27
High product variability	10

Afterwards, the functional structure of the machine was derived. The FMA method requires an interdisciplinary team of engineers, in order to form correlations between the requirements and the functions of the stacker. After that, a target weight for every assembly can be determined from that correlation. Finally, comparing the target weight with the current weight, the optimization potential for every assembly can be derived. [9] The results of the FMA, illustrated in Fig. 3, show a negative spread between current mass vs. target mass at the frame and at all parts of the inner frame. These are the assemblies subsequently to be optimized with regard to lightweight.

However, a closer look at the technical background is necessary to put the results into the right perspective. The FMA shows an optimization priority for all frame parts. This is consistent with the fact that the main function of the frame parts is to stiffen the processing machine while this requirement has a minor priority to the customer. Nevertheless, the frame is designed as stiff as necessary according to the occurring load conditions. This means that by reducing the acting loads the frame parts can be designed less stiff and lighter. The acting loads on the frame are induced by the motion unit. Hence, this interpretation of the FMA result leads to a high lightweight optimization potential of the motion unit consisting of the horizontal and vertical cart as well as the operating fork. Furthermore, a weight reduction of the motion unit results in lower energy consumption.

The function requirement and value analysis focuses on the core of the machine and thus on its main task to reach the customer requirement. By creating the functional structure, the existing functions of the manufacturing system are also defined. These are, for example, "mechanical energy lead", "signal lead" as well as "sheet lead", "save sheet" or "separate sheet". Overall, the core function of this stacker unit is to stop, collect and transport sheets out of a continuous material flow. Now, the existing assemblies are mutually valued. It is analyzed, which assembly contributes a higher benefit to fulfill the core function. Thus, an index of the assemblies respective importance can be derived. The result is shown in Fig. 3 as core-index. A target-oriented use of resources is possible through this analysis, which follows the frugal approach. First, it concerns the development process that can be made more efficient but then, also the assemblies themselves, being able to assign more accurate cost and weight targets.

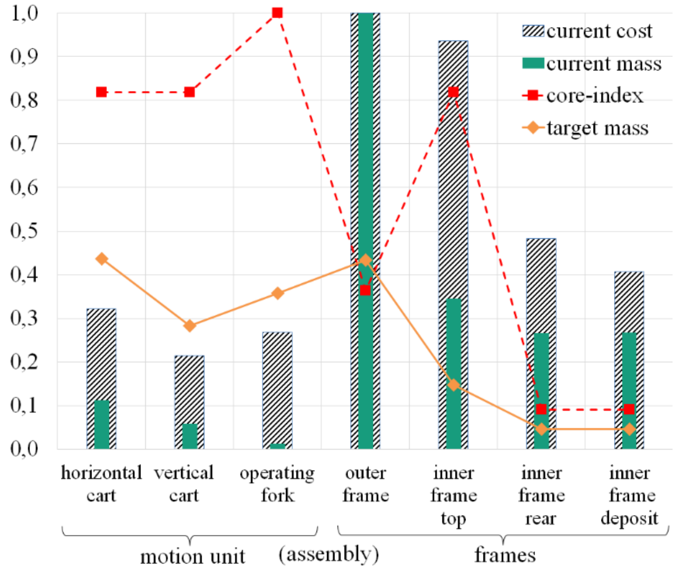


Fig. 3: Normed values of mass, cost and the core-index of each assembly

Through the analysis, the resources of the development can now be focused by considering assemblies with a high core index first. At best, this already has a positive effect on the other assemblies. However, in a second step, assemblies with a lower index and high cost must be considered more closely. In this case, the focus is first on the motion unit and second on inner frame top and outer frame.

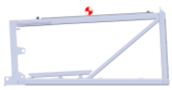
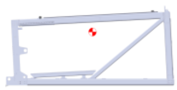
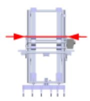
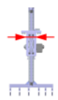
4.2.3. Synthesis phase

The focus of this section is put on the motion unit as an essential output of the analysis phase. Based on the investigated lightweight potentials, different lightweight strategies are applied to the motion unit to reduce its mass.

According to HENNING and MOELLER [11] different superior lightweight strategies can be applied to a product. Two of them are shape and material lightweight design. In consultation with the industrial partner both strategies seem applicable to the motion unit based on the partner's resources with respect to their realization.

Regarding shape lightweight design, the first thing to consider is the position of the motion unit. Placed on the very top of the system, the applied loads on the entire machine due to the acceleration profile of the motion unit induce undesired deformations and high oscillation amplitudes to the frame. Thus, the first step is to lower the center of gravity of the motion unit relative to the frame. This is realized by placing the guiding rails of the horizontal cart on the top end, thus relocating the horizontal operation path to a certain extent inside the outer frame. The upper space inside the frame allows this replacement of the motion unit without re-designing the height of the frame. An overview of the main design changes between the reference and the new lightweight concept is illustrated in Table 2.

Table 2. Design changes between reference and new concept.

Changes	Reference	New lightweight concept
Position of the c.g. motion unit (side view)		
Shape of the motion unit (front view)		
Shape of the hor. cart plate (side view)		
Material of both carts	Steel	Aluminum

In a second step, the shape of the motion unit as a complete subsystem as well as the horizontal cart as a single assembly within this subsystem will be re-designed in order to reduce the mass. The shape of the horizontal cart is examined in detail here because it is the assembly with the largest mass within the motion unit, thus having a big potential for lightweight optimization. First calculations of the bending moments reveal that the vertical cart, consisting of a frame in an O-shape, can be reduced to a lighter I-shape and still fulfill the stiffness requirements, which also significantly reduces the width of the horizontal cart. Focusing on the horizontal cart, the side plate is optimized with regard to the shape, too, as it is one of the heaviest parts of this cart. By using the so-called “Force Cone Method”, the shape of the side plate of the horizontal cart is transformed into a half-timbered construction (see Tab. 2, row 3). Here, the decision has to be made whether the design should lead to a stiffer component with the same mass or lighter component with equal stiffness. This has to be evaluated in a later step.

Finally, using the material lightweight design strategy, the structural components of both the horizontal and vertical cart made out of steel are substituted with aluminum. This also reduces the mass of the motion unit which leads to a reduction of the elastic frame deformations and the energy consumption. The higher costs for the substitution seem reasonable with regard to the importance of the mass of the motion unit.

4.2.4. Evaluation phase

Nevertheless, a weight reduction of components of the conversion machine must not lead to a loss of structural stiffness, which will result in a reduced dynamic performance of the machine and hence in a reduced production rate. Thus, in the synthesis phase of the mentioned methodological approach structural stiffness parameters of the reference machine were identified and set as requirements for the lightweight design concept. These are elastic deformations of relevant machine components for different load cases, as well as the eigenvalues of different machine assemblies (e.g. frame, vertical cart, horizontal cart, operation fork). The comparison of selected and relevant structural parameters between the reference machine and the investigated lightweight concept constitutes the validation. As an example, the elastic deformations resulting from one dominant load case are shown explicitly, where the moving parts of the machine (operating fork, horizontal cart und vertical cart) are accelerated backwards. Due to a high acceleration, the moving parts of the reference machine experience a higher force level, because they are heavier than those of the lightweight concept (Newton’s First Law – force is equal to mass multiplied with acceleration/deceleration). Nevertheless this is not the only benefit of the lightweight concept. Due to the shape of the chosen aluminum extrusion profile for the vertical beam and a completely new concept for the horizontal and vertical cart, the assembly of moving parts has a higher moment of inertia and, therefore, a higher structural bending stiffness. Altogether, these measures result in a reduced elastic deformation for this representative load case (see Fig. 4), where the lightweight concept (of the moving parts) has an about four times lower deformation (see fork tips, where the maximum deformation value occurs) in comparison to the elastic deformation of the reference system. Besides the shown load case study, relevant elastic deformations resulting from other load cases are lower or equal for the lightweight concept and the eigenfrequencies are higher or equal to those of the reference machine. So the structural requirements are (over-)fulfilled by the lightweight concept.

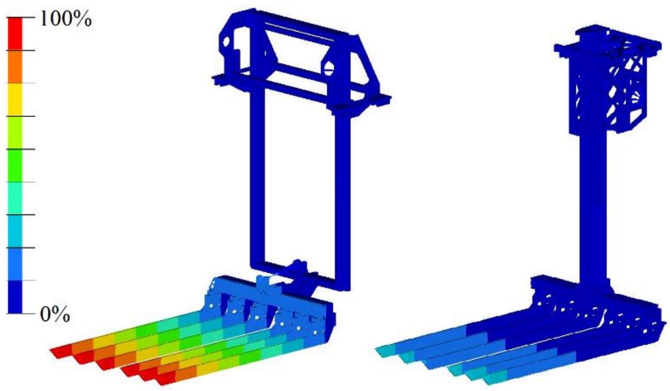


Fig. 4: Vertical elastic deformation of the assembly of operating fork, vertical cart and horizontal cart for the reference machine (left) and for the lightweight concept (right) for the same representative load case

4.2.5. Conclusion and outlook of the case study

The combined lightweight approach using different lightweight methods leads to a significant weight reduction of - in this case - moving machine parts, where a mass reduction of approximately 40% could be achieved by the lightweight concept (see Fig. 5) in comparison with the relevant components of the reference machine.

Thereby, it was to verify, that structural requirements derived by finite element analysis (FEA) of the reference structure in advance, are fulfilled by the new lightweight concept. The validation process using FE-analyses of the lightweight concept shows a rise in relevant structural stiffness parameters. As moving parts have the greatest influence on an economic production, this can be seen as a good outcome: the weight reduction and stiffness increase can be utilized to either reduce production costs or increase production rate, which both have economic benefits. The so-called secondary effect leads to smaller engines and gears and saves costs in the manufacturing process as well during their utilization phase.

The development of a new concept for the moving parts also required a modification of the surrounding structure – the frame – as well. Therefore, lightweight methods were also applied in this assembly. Different methods (e.g. topology optimization, FE-analysis with upscaled deformation values, etc.) lead to an increase in frame stiffness, whereby an almost equal frame mass was achieved. Frame mass reduction was not an objective, as the frame mass is not moved during the machines board conversion process.

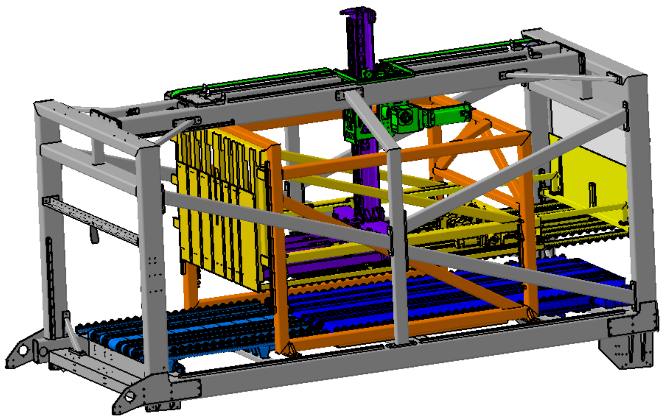


Fig. 5: New lightweight concept of the stacker unit

Overall, a higher stiffness for the machine was achieved, which can be utilized to optimize the speed or economy of the production process.

The computer-aided engineering (CAE) development process forecasts benefits for the lightweight concept in comparison with the reference machine. Nevertheless, further work has to be done to turn the concept into a real and operating machine, where in the end the predicted benefits must be reflected and validated, as soon as the new machine has been manufactured and a test phase is run. Static strength aspects have been looked at as well and they are uncritical, but for the further development process and realization of the machine, fatigue strength aspects have to be looked at in more detail (e.g. at joined interfaces).

At this time, the cost reduction can only be assessed for the concept. Despite a significant reduction in mass, the concept does not lead to a cost reduction in the same dimension because of the non-linear relation between cost and weight. By optimizing the outer frame, smaller cost-efficient profiles can be used and the cost reduction will be about 15%. The material reduction of the motion unit results in cost savings of approx. 20%. As already mentioned above, the lightweight design concept additionally promises significant benefits regarding secondary effects: drive elements like engines and gears as well as control systems and power supply units can be carried out smaller and more cost-efficient. This leads to a calculated cost reduction of approx. 60%. Moreover, energy savings of about 40% are expected.

5. Conclusion

The shown product development approach with a combined and holistic lightweight design approach as well as an interdisciplinary collaboration of different institutions and the machine manufacturer, leads to a resource-efficient and economic manufacturing system. Through this approach, using different lightweight methods, a significant weight reduction of manufacturing systems is possible. Great importance is attached to the early focus on the important core functions and assemblies.

In the future, the verification of the approach should be continued by applying it to different types of manufacturing systems. For further applications it could be useful to integrate a wider set of methods, to provide more choices within the holistic approach. However, this implies that a decision-making tool for the method to be used must be introduced in order to make the effort of the development process efficient.

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