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Towards a Process Model for the Development of Light, Mechatronic Products

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Abstract

Existing process models for the development of mechatronic systems do not consider the task for weight reduction and its positive effects for the manufacturing and usage phase of systems, e.g. savings in resources and energy. Lightweight design only often represents an optimization step after the product development which leads to problems like restricted functionality, increase of development costs and development time or quality.

In this paper, a process model on the basis of the known V model of the guideline VDI 2206 is developed whereas weight reduction is no longer seen as optimization task at the end of product development. Instead, it will be integrated into the process itself and will be evaluated within several analysis steps which are distributed over the design procedure.

Keywords: integrated product development, lightweight mechatronics design, process model

Introduction

Lightweight design in general is considered as one of the solutions for a responsible and sustainable handling of natural resources during the manufacturing, assembling and usage of products. In contrast to this economization strategy, growing safety requirements, power enhancement and rising customer demands regarding comfort and entertainment often result in an increase of product weight. The realization of these aspects is often based on mechatronic products. One such example is the passenger car as the representative mechatronic product: the increasing percentage of mechatronics is contrary to the idea of weight reduction and savings in fuel and energy. But a precise consideration of the topic shows that there are some innovative answers to reduce the weight of the overall system "car" by the application of mechatronic components and systems, e.g. drive-by-wire, smart structures or adaptronic systems.

But the weight optimization is not in focus during the current development of mechatronic products which are the trigger for innovative solutions. Lightweight strategies are often employed sporadically and individually after the product development without giving any respect to the whole system. For example, it may happen that single components are lighter than before the weight optimization, but the product weight is higher owing to the adoption of the structure around the optimized areas.

For this purpose, it is essential to regard a product development which integrates both disciplines lightweight design and mechatronic design. Therefore, the novel framework "Lightweight Mechatronics Design" describes the systematic, holistic development of light, mechatronic products. In doing so, weight reduction will be achieved through lightweight design of and by mechatronic systems.

Framework of Lightweight Mechatronics Design

Definition

The framework of „Lightweight Mechatronics Design“ is presented in [1]. It deals with the integration of the two different disciplines, mechatronic and lightweight design, into one development procedure. Lightweight mechatronic products characterize in general mechatronic products which are developed regarding lightweight design principles to gain a weight optimum. This optimum can be achieved in two ways: On the one hand, reducing weight of the mechatronic components or systems with the aid of the different kinds of lightweight strategies results in a weight improvement of the system. On the other hand, using mechatronic subsystems in an overall system fulfills the functionality in a weight-saving way. Hence, the term „Lightweight Mechatronics Design“ can be interpreted as lightweight design of mechatronics and by mechatronics.

Structure of the Methodology

Figure 1 shows an overview of the framework of „Lightweight Mechatronics Design“. The methodology provides the basis to which the different elements (process model, strategies and methods, system understanding, organization, modeling and simulation, knowledge and communication) are connected. In view of the aspect that the lightweight mechatronics design is based on mechatronics design [1], the elements of the new methodology primarily resemble the ones of mechatronic design whereas the aspects of lightweight design are regarded in a slightly subsidiary way.

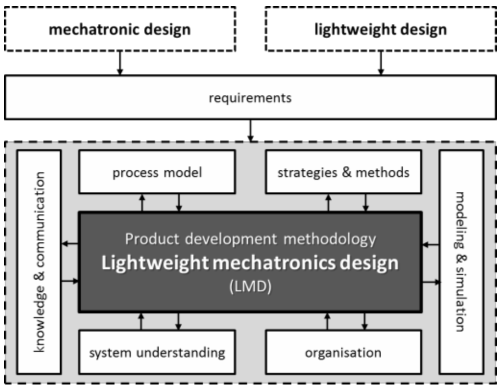

Figure 1: Framework of Lightweight Mechatronics Design [1]

Approach to a Process Model

Classification of Lightweight Strategies to Design Processes

Lightweight Strategies

Lightweight design strategies are applied to generate new and optimized products and thus play an important role from the point of view of product development. They unify a goal-oriented application of different lightweight construction methods, material and manufacturing technologies and allow support during the development process of lightweight products. In literature, there are miscellaneous denotations for these strategies. They can be classified as follows (Figure 2).

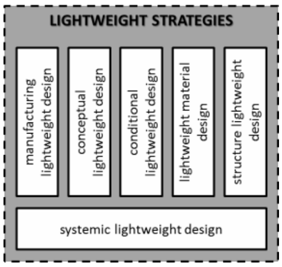

Figure 2: Lightweight Strategies [2]

Conditional lightweight design embraces a critical review of requirements from external conditions (e.g. society, politics, and customer markets) and safety requirements. A weight optimization will be realized by improvement of the factors mentioned above.
Weight reduction by lightweight material design is gained by using lighter material for the given structure. However, the different material properties and thus the associated constructive changes have to be kept in mind.
The structure lightweight design adapts components to a novel structure with an optimal force distribution and a shape of minimal weight could result in weight saving.
In the field of manufacturing, weight saving potentials arise in various processes of production, manufacturing and assembly. Manufacturing lightweight design is very closely linked to material lightweight design and structure lightweight design.
The conceptual lightweight design provides a weight reduction by investigating systematically certain structures and modules and their adaption to the whole system or a subsystem.
As the all-embracing strategy systemic lightweight design embeds the points mentioned above. It is defined as the holistic optimization of a technical system with regard to weight and mass inertia in consideration of all relations and interactions in the system as well as technical and economic general conditions.

Classification to the Traditional Design Process
The lightweight design process in general [3] follows the traditional phases of design procedure: task setting, conceptual design, embodiment design and detail design. The lightweight strategies and their methods can be associated to these stages, see Figure 3 [4].

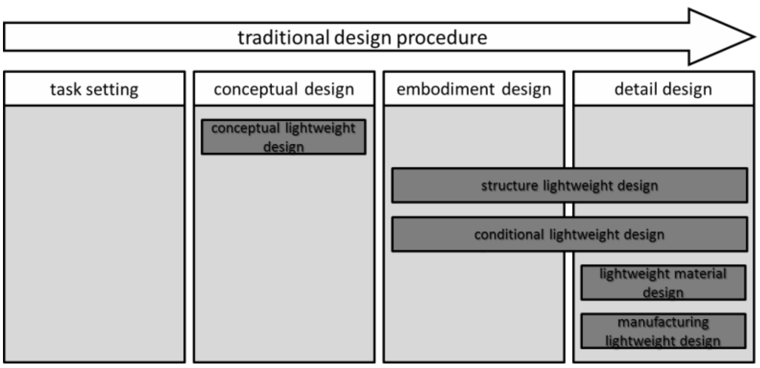

Figure 3: Classification of Lightweight Strategies to the Traditional Design Procedure

Classification to the Mechatronic Design Process
Analogically to the classification in the traditional design process, the lightweight strategies can be linked with the design stages in mechatronic design, demonstrated at the V model of the guideline VDI 2206 [5], see Figure 4.

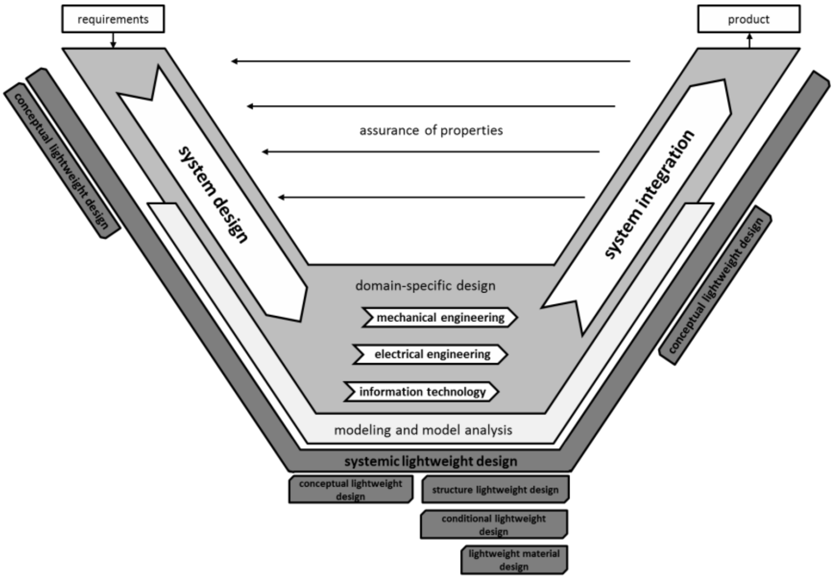

Figure 4: Classification of Lightweight Strategies to the Mechatronic Design Procedure

It should be noticed that additionally to the lightweight strategies the systemic lightweight design strategy is joint to the whole development process of mechatronic design. This strategy has the task to regard the weight optimization for an overall system – thus, the interactions between the different elements – including the optimization for the elements themselves.
The strategies of structure lightweight design, conditional lightweight design and lightweight material design are mostly assigned to the domain-specific design stage. They are very concrete and quite independent of each other. With their aid, the domain solutions are completely specified.
Furthermore, the conceptual lightweight design strategy plays a very important role. The concept in general is significantly responsible for the further design procedure and thus for the application of the resting lightweight strategies. All in all, it has to be employed minimum 3 times: conceptual system design, conceptual domain-specific design and system integration where the domain solutions are merged.

Challenges and Requirements for the Process Model

Requirements from the perspective of lightweight design
The importance of the early phases in lightweight design appears very strong when regarding that the concept is significantly responsible for the further development. To give just an example for the conceptual design phase, the function structure can determine crucial differences in the weight of construction depending on the realization of the functions or function groups. Thus, the techniques of function integration or separation play an important role [6].
Moreover, a single lightweight strategy or measure – for example in the field of lightweight material design the substitution of steel with aluminum – does not lead to the desired objective. Different strategies have to be integrated to gain a weight optimum [7].
Innovative technologies like micro technology, mechatronics or adaptronics are chances to develop new classes of lightweight products. Thus, a multidisciplinary way of thinking will be required [7].
In addition to this, a continuous proceeding to estimate and to evaluate the potential of a lightweight construction represents a very important element to ensure a structured, effective and abbreviated development for lightweight products [6]. For this, it is necessary to follow a

holistic system view which can only be achieved by application of the systemic lightweight strategy.

Requirements from the perspective of mechatronic design

Beside these aspects mentioned above, the requirements for mechatronic design do not have to be neglected. They can be divided into two classes: requirements from complexity and requirements from heterogeneity.

The complexity takes place in mechatronic systems owing to the interlinked cooperation of different knowledge domains and thus, a major number of interconnected elements. In detail, the requirements rooted in the complexity are: the procedure under the conditions of changing the level of detail and concretion, methods to structure and organize into a hierarchy, early modeling and simulation as well as integration and assurance of properties.

The challenge to use the potential of cross-domain collaboration in a synergetic way and to get a global optimum brings the requirements of the heterogeneity, which are in detail the cross-domain teamwork, cross-domain specification, partitioning as well as integration of models and tools. For further information and insight, see [8].

Proposal to a Process Model

A literature study of methodologies of both disciplines mechatronic design and lightweight design shows that the focus of mechatronic design lies in the creation of products in order to fulfill their functions („design to function"), whereas lightweight design has its main task in the weight reduction assumed that the functions are completely retained and not downgraded („design to weight"). Hence, the lightweight mechatronics design combines these two versions of „design for/to X" whereas the generation of functions is considered primarily while the task of weight optimization is still mostly carried out at the end of the product development process [9].

Process Model

Figure 5 shows a proposal for the proceeding on macro level during the design process. Because lightweight mechatronics design is basically originated from mechatronic design, the V model according to the guideline VDI 2206 is used as a basis. It consists of the known elements of mechatronic design (system design, domain-specific design, system integration), but in a modified version. Furthermore, there are analysis gates which guarantee a continuous estimation of lightweight potential throughout the whole process.

The process for the development of light, mechatronic products is divided into 5 process stages (white bars) and 6 analysis gates (black quads) which will be considered in more detail in the following.

- *Analysis Gate 0*
  The desired requirements for the product are investigated in order to point out the requirements which are related to the product weight as well as interactions between and conflicts of objective. Furthermore, it seems to be practicable to perform a comparison of predecessor or competitive products aiming at deriving weight targets for the new product.

- *System Design and Analysis Gate 1*
  Within this stage, the function structure, the operating structure as well as the building structure for the system are designed. Hence, there is a possibility to check influences

on the subsequent product weight after each structure is defined with the help of the conceptual lightweight design strategy.

For example, concerning the weight on the functional level, the determination of weight proportion for function fulfillment plays an important role. This can be done in analogy to the functional cost analysis in the target costing [10]. Thereby, it should be noted that the number of functions has an impact on the product weight. As a general rule, more functions generate a higher product weight. Hence, the methods of function integration and separation are of considerable importance.

The outcome of the process step *system design* is a cross-domain solution concept which describes the main physical and logical operating characteristics of the future product. After the system design step, the cross-domain solution concept undergoes another weight analysis (*analysis gate 1*).

- *Domain-Specific Conceptual Design and Analysis Gate 2*

  In the *domain-specific design* a partitioning is performed. The performance of the functions is divided among the domains involved. After formulating the single domain solution concepts regarding the conceptual lightweight strategy, each one is investigated in terms of weight in the same way described in the system design.

- *Initial System Integration and Analysis Gate 3*

  Following this, a first *initial system integration* of the domain solution concepts into the system concept is applied in deviation to the original V model from mechatronic design. The reason for this adoption is the quite independent development of domain-specific solutions. Interactions between the disciplines are only insufficiently regarded. These aspects are very important especially in systemic lightweight design because the weight of the overall system is the main task, the validation of the whole system is crucial. For example, it is possible that individual components are less heavy than before, but the weight of the whole system is greater than the previous one. With the aid of this first conceptual system integration, interactions between the domains and weak points according to weight in the solutions concepts can be determined and corrected in the following second *domain-specific design phase*.

  This process stage can be applied each time when the concepts are updated or modified. Thus, the domain-specific detail design and system integration steps are alternating.

- *Domain-Specific Detail Design and Analysis Gate 4*

  In this stage, several lightweight strategies (structure lightweight design, lightweight material design, conditional lightweight design, manufacturing lightweight design) are applied and the final domain layouts are developed. This phase can be seen as the standard lightweight optimization. *Analysis gate 4* serves to assure the results of lightweight measurements in each domain.

- *Final System Integration and Analysis Gate 5*

  The *final system integration* unifies the final, weight-optimized solutions from the different domains to an overall system under consideration of interactivities between. The process is finished with a last analysis milestone (*analysis gate 5*) in which the precise product weight is determined.

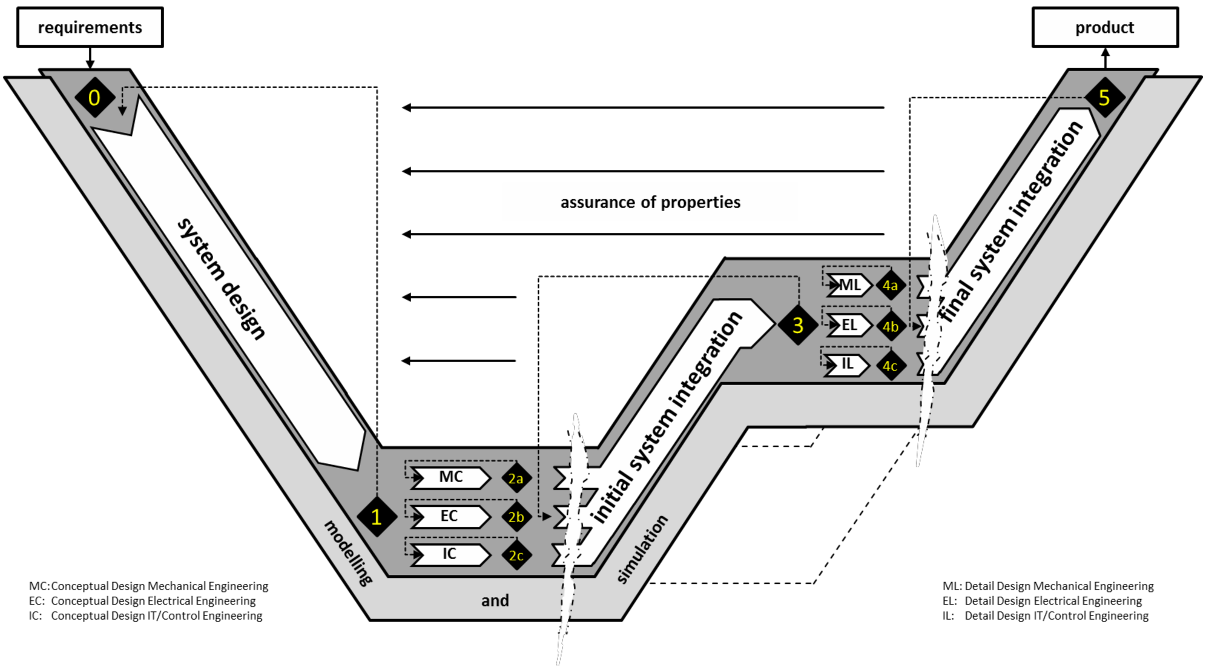

Figure 5: Initial Modell for Lightweight Mechatronics Design

The analyses done in the development process are affected by several aspects. The possibility to analyze and the validity of the analysis results strongly depend on the level of concretization of the product, i.e. the results are the more precise the higher the maturity of the product is. Hence, it is more difficult to give a precise statement of the product in the early phases than at the end of the development process.

Impact on Final Product Weight and Level of Weight Concretization

Figure 6 depicts the level of weight concretization and the impact throughout the development process. It can be stated that the level on weight concretization rises in parallel to the process progress and thus the maturity of the product.

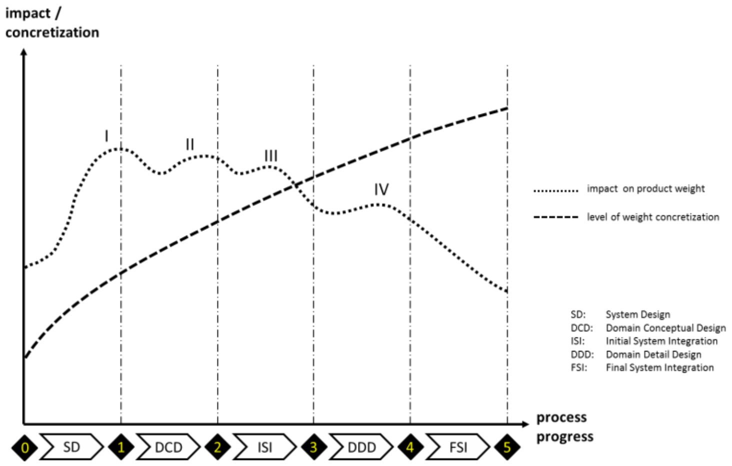

Figure 6: Impact on product weight and level of weight concretization (qualitative curve)

Moreover, the figure shows the impact on the final product weight against the process progress. The highest influence (I) on the weight can be observed in the conceptual phase of the system design (SD, between analysis gate 0 and 1). The weight of the final product will be strongly affected by the functions which will be established in the function structure. In the conceptual domain-specific design (DCD, between analysis gate 1 and 2) the weight of the product will be defined through the functions and their concepts of the single domains (II). The importance of the early phases, especially the conceptual design, is mentioned above or in [6]. The third peak (III) results from the initial integration of the domain concepts (ISI). Through function integration or separation, another exertion of influence is possible although not as strongly as before because the system concept has been already characterized. The final specification of the structure or form and material in the domain-specific detail design phase (DDD, between analysis gate 3 and 4) also allows an intervention to the product weight (IV).

Conclusions & Outlook

The systematic development of light, mechatronic products requires a special procedure. The approach presented in this paper offers a new fundamental process model for the framework of “Lightweight Mechatronics Design”. The V model known from the mechatronic design is adopted through the integration of analysis gates, a spreading and a shifting of the steps of domain-specific design and system integration. It consists thus of 6 analysis gates and 5 process stages. With the aid of this, the requirements out of the lightweight design are fulfilled, the requirements out of the mechatronic design are not failed.

In further research, the initial process model for “Lightweight Mechatronics Design” will be refined in following aspects: detailed characterization of the analysis gates, the procedure during iterations, application of different strategies and methods and their link to the process model as well as the connection of modeling and simulation tools into the process model.

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