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CONSIDERATION OF WEIGHT PROPERTIES DURING THE DESIGN OF WEIGHT-OPTIMIZED MECHATRONIC PRODUCTS

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ABSTRACT

Existing process models for the development of mechatronics products are not or only insufficiently considering the task of weight optimization during the design process. The measures of weight optimization are mostly applied at the end or in late phases of the development process with a consequence that a large number of macro-iterations are necessary when design changes regarding weight properties have to be done. These points result in an increase of development cost and time.
In this contribution, a proceeding model for the design of weight-optimized mechatronic products is proposed which considers a holistic monitoring and management of weight properties throughout the process. The process is structured in a way that between and within the main design stages different analysis points ensure an estimation and calculation of future product weight properties. Furthermore, these analysis gates can also provide input for weight optimizing potentials.

Keywords: design process, design for X, integrated product development, mechatronic products, weight optimization

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1 INTRODUCTION

1.1 Problem Statement

Common product development processes support the task of weight improvement, for example weight reduction and weight distribution, only insufficiently and unsystematically. Weight reduction for example is seen as one possible approach to a resource and energy conserving realization of products during production, usage and recycling lifecycle phases. The weight optimization task is mostly applied at the end or in the late phases of the design process with the consequence that the whole system/product is not covered and sufficiently focused on. Moreover, a large number of macro-iterations with design changes are necessary which results in increasing development costs and time. First approaches from different industrial sectors, e.g. aviation, automotive or railmotive, are aiming at monitoring weight properties throughout the whole development process. In contrast to weight-optimization, growing customer demands of comfort, a call for shortened development time and a not negligible need for safety often induce an increase of weight and deterioration of weight distribution and thus a change of the performance of the product. The realization of these aspects is often based on mechatronic concepts and systems. Thus, it seems that lightweight and mechatronic products are not compatible and contradict each other. But looking at some innovative mechatronic concept solutions, e.g. smart materials, x-by-wire concepts or adaptronics, can disprove this obvious contradictory.

1.2 Framework

The methodology "Design of Weight-Optimized Mechatronic Products" has been introduced by the authors to consider a continuous integration of weight into product development (Luedeke and Vielhaber 2012a, 2012b). It can be understood as an integration of two different disciplines, mechatronic and lightweight design, into one development process. Mechatronics itself is an interdisciplinary and synergetic interaction of the three domains mechanical engineering, electric engineering and IT/control engineering. Thus, there are two development goals existing: on the one side the achievement of the functionality by using mechatronic concepts and on the other side obtaining the lowest weight and best weight distribution as possible.

The framework of the methodology (cf. Figure 1) consists of six elements – process model, methods, system understanding, tools, organization as well as knowledge – which are the basis of the methodology representing two different perspectives, the product view and the process view. The product view – the weight optimization by application of mechatronic products – needs an analysis of given mechatronic concepts in terms of their ability or of their potential for a weight reduction or an improved weight distribution. The process view – the weight optimization of mechatronic products – offers a procedure for the development of weight-optimized mechatronic products following some aspects of the VDI guideline 2206.

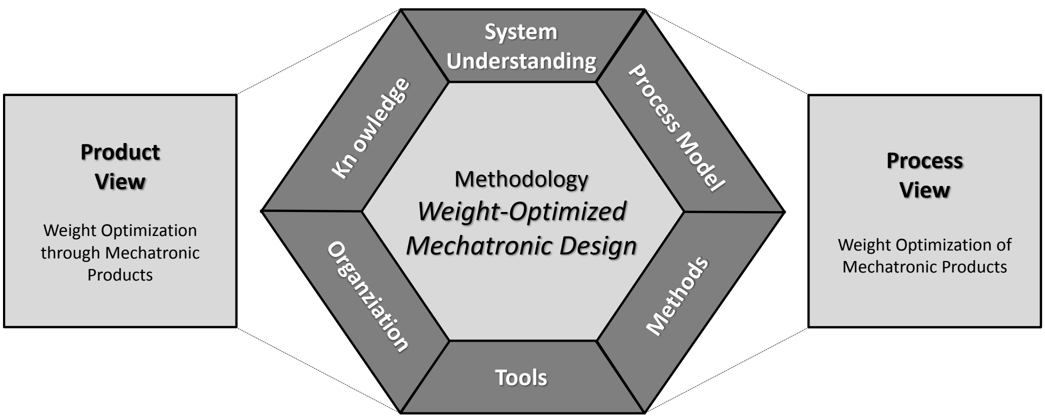

Figure 1. Framework for the Development of Weight-Optimized Mechatronic Products

1.3 Approach

In this contribution focusing the *process view*, an overview is given for the influence of weight properties on other product properties and thus a need is rising for a holistic consideration and the handling of weight properties during the development process of mechatronic products.

Based on these aspects a macro process model is proposed in which the weight properties are considered and monitored with the aid of analysis gates between and within the main design steps as presented by Pahl et al. (2007). Moreover, the topic of primary and secondary weight optimizations is focused in the last chapter. They play a role when the system knowledge and the interdependencies as well as the crosslinks within the system and subsystems are regarded. With the help of this knowledge, the ways and paths of weight propagation throughout the entire system can be detected and optimized.

2 WEIGHT PROPERTIES AND THEIR INFLUENCES ON OTHER PRODUCT PROPERTIES

2.1 Definition of "Properties"

According to Weber (2007) properties describe the product's behavior and cannot be directly changed by the developer or designer. In contrast to that, characteristics which describe the structure, shape, dimensions, materials or surfaces of a product can be directly influenced by the developer. That means that – in this context here – the weight properties cannot be influenced in a straight way, but with the help of geometry and density. Weight itself is a combination of geometry – in this case the volume – and density. All other weight properties are dependent on the weight itself and thus properties in the sense of Weber (2007), too.

2.2 General Process Model and Product Lifecycle

The process model shown in Figure 2 represents on the one hand the traditional process steps of product development, e.g. Pahl et al. (2007) – task clarification and product planning, conceptual design, embodiment and detail design – and on the other hand added important points like modeling and simulation, prototyping and testing as well as different evaluation and decision points (specification, concept selection, engineering release) which are correlating with the traditional design phases.

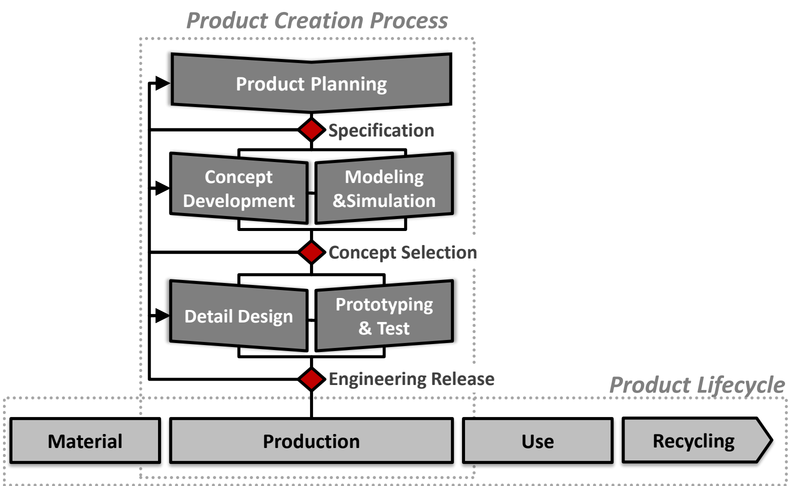

Figure 2. General Process Model and Product Lifecycle (Dohr et al., 2013)

2.3 Weight Properties in Product Lifecycle

Material and Production Phase

Main focus points of weight-relevant properties in the material and production phase are on the one hand the cost for resource extraction and on the other hand the minimization of the cost of production and the simplified handling of parts and products both in the manufacturing step and in the assembly phase. For example, the cost for transport normally increases when the product weight is higher.

Use Phase

The influence of weight and weight-related aspects of a product is a very crucial factor particularly with regard to its use. Thus, a greater mass of a product often results in an increase of energy consumption and a deterioration of acceleration as well as delay times of dynamic systems. Moreover, an unfavorable weight distribution can as well cause higher energy consumption because of high moments of inertia as well as a change of Eigen frequencies and modes. In addition, there are a lot of customer perceptions which are related to weight aspects. For example, noise reduction and vibration absorption play a part as the requirements for active and passive safety. Furthermore, the handling and operating ergonomics by the user are often dependent of the weight.

Recycling Phase

Likewise, the costs for disposal of a product are strongly depending on its weight. Additionally however, the material combination and the disassembling capacity have a substantial effect on these costs, as well.

3 CONSIDERATION AND ASSESSMENT OF WEIGHT PROPERTIES DURING THE DESIGN PROCESS

3.1 Motivation

Primary and Secondary Weight Optimization Potentials

Primary weight optimization measures represent methods for direct weight optimization and regard the selective optimization of individual components with the help of traditional lightweight strategies (e.g. material substitution, manufacturing techniques, conceptual lightweight design etc.). Based on these prominent steps, so-called secondary weight optimization measures can be applied, for example the dimensions of surrounding components can be reduced with the consequence of weight reduction (Eckstein et al., 2011). The handling of the secondary weight optimization potentials represents a greater improvement potential as primary weight optimization steps at all. They are enabled by the understanding and knowledge of crosslinks and interdependencies between weight-relevant properties (e.g. weight, weight distribution etc.) and other product properties (e.g. cost, functionality etc.) which is one of the most challenging tasks during the development of weight-optimized mechatronic products. A better understanding of system and subsystem mass interdependencies and a quantification of the subsystem-specific mass decompounding effects are crucial prerequisites for a detailed analysis of secondary weight optimizations (Bjelkengren, 2008).

Weight Properties in Product Development

The previous chapter shows that the influence of weight and weight-related properties, like weight distribution, center of gravity and moments of inertia, on other product properties takes place in mostly every lifecycle phase of the product, most of all in the usage phase of the product.

It is therefore important that weight targets of the whole product and of its subsystems and components are determined as early as possible and monitored and managed throughout the whole product development process. By experience, weight targets in some design projects are only achieved by elaborate and complex reworking due to a late consideration of weight and weight distribution in the design process. Thus, taking product weight into account in product development is an important and necessary task during design processes. A solution of this task was traditionally achieved through the application of typical lightweight strategies and principles (cf. Schmidt et al., 2001). This approach seems to be no more practical for the reason that on one side the traditional lightweight measures (e.g. structural optimization, material choice or sandwich construction) are supposed to be used only on the physical structure of the product whereas the aspects of the logical and functional structure are neglected. On the other side the lightweight principles are only mainly applied in mechanical systems; that contrasts to the fact that contemporary products are often innovative and very complex, with most of them being mechatronic products.

Approach

For the consideration and the assessment of the weight properties during the whole product development process of mechatronic products the process model following consists of known design steps of mechatronic design (e.g. the VDI guideline 2206) and additionally of analysis gates which guarantee a continuous estimation or calculation of the weight data throughout the process. The analysis gates between the main design stages (task setting and product planning, conceptual design, detail design) describe major decision points for the following process and represent the whole

product. The sub-analysis gates within the main design stages serve rather as monitoring points with a chance to fall back to prior design activities.
Furthermore, the knowledge and understanding of the system structure as well as the abstraction level are taken into account in a way that the crosslinks and interdependencies are illustrated graphically during the whole development process. There are two different types of dependencies: the interdependencies in system structure (system, subsystems, and components) and the interdependencies between different abstraction levels (requirements, functional, logical, and physical level).

3.2 Process Model on Macro Level

Structure of the Adapted Process Model Considering Weight Properties

The general process model shown above is adapted and detailed to a new process model in order to consider weight properties like the weight itself, the weight distribution as well as the center of gravity (see Figure 3).

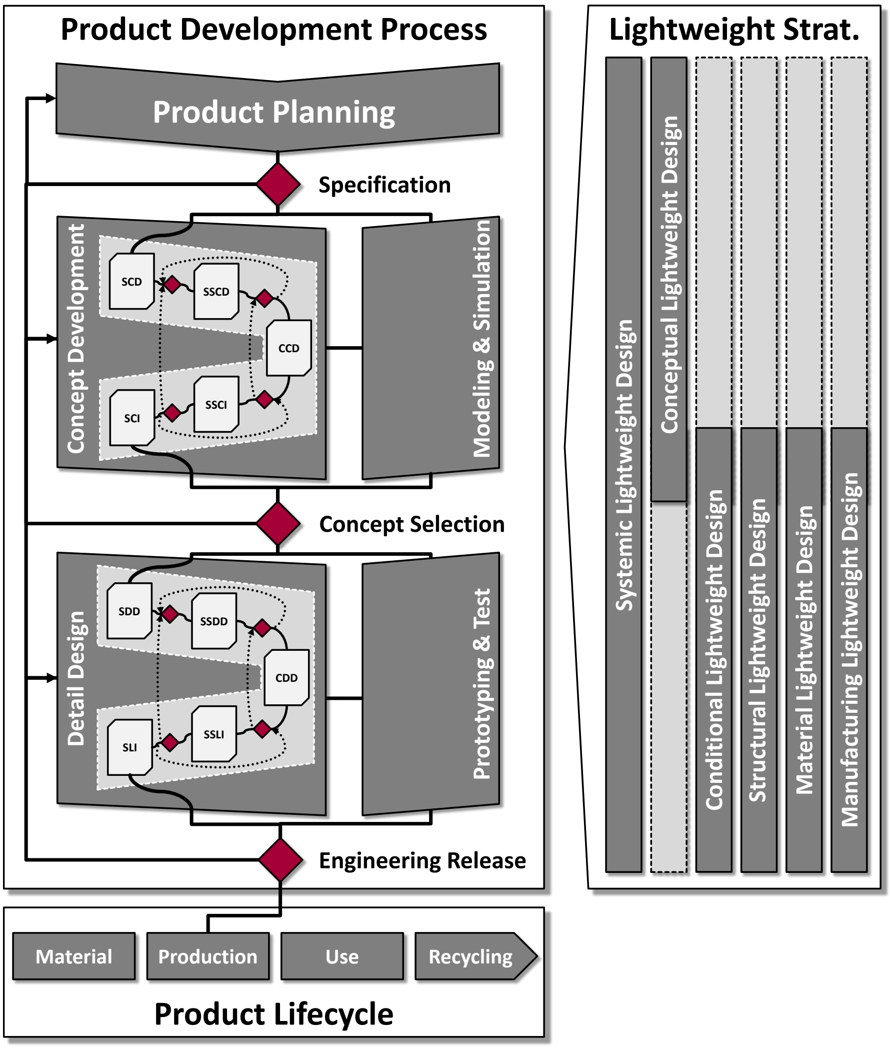

Figure 3. Process Model Considering Weight Properties (for abbreviations see text)

Aim of this process model is the holistic management of weight properties throughout the whole development process starting with the task setting and requirements and finishing with the real product. The approach for managing and monitoring is to introduce analysis gates both between and within the main design process steps product planning and task setting, conceptual design as well as embodiment and detail design.
The stage of conceptual design serves as a first estimation and rough calculation of the weight properties as well as an overview for crosslinks and interdependencies within the system and

subsystems which can result in further weight propagation. After substantiation the system concept in an important analysis gate, the final layout and design of the system and its subsystems is performed in the detail and embodiment design stage which ends with another analysis gate providing a very detailed value of the future weight properties.
Moreover, the different design stages are developed in sense of mechatronic design. Thus, the known process model for mechatronic design (V model) as well as the stages system design, domain-specific design and system integration are reflected within the different steps of conceptual and detail design. It has to be stated that the V models in the stages are similar to the 3-level process model of Bender (2005). It is divided in different levels: system level, subsystem level and component level.

Product Planning Phase

The task in the design phase of product planning is a first definition of a weight target for the future product which has to be achieved at the end of the development process. The data concerning the weight target could be collected in different product analyses, e.g. patent and technology analysis, benchmarking of predecessor or competitive products. Parallel to the definition of the weight target different milestones during the process (analysis gates) are specified in order to monitor and manage the weight properties. Based on the performed product analyses and a collection of requirements from the customer, a requirement list is generated with a quantitative explicit description and determination to importance factors of weight-relevant requirements. Additionally, occurring goal conflicts and interrelations between weight requirements and other product requirements are filtered out.

Conceptual Design Phase

The conceptual design phase generally follows the known process model of mechatronic design (VDI 2206), but is adapted with analysis gates and thus micro-iterations between as well as the possibility for interdependencies detection. In the model of the conceptualization, three different system levels are illustrated: system level, subsystem level and component level. The procedure is shown in detail in Figure 4. During the conceptual design a concept for the entire system and based on this, concepts for subsystems and components are generated. Hence, the focus of this phase is not placed on a domain-specific view with high level of detail but more on the whole system and its subsystems with a lower level of detail.
From the viewpoint of lightweight design, the strategies for systemic lightweight and conceptual lightweight design are applied. Systemic lightweight design is intended to achieve a holistic weight optimization of the system. Core objectives of this method which is displayed across material and product choice are the optimization of the system weight and inertia as well as their positioning or distribution within the system. The conceptual design strategy stands for a systematic optimization of certain structures and modules and their matching to the entire system including layout and design in order to optimizing weight properties.
Based on the results of the planning design phase with an improved requirements list which is especially adapted in terms of weight criteria a preliminary conceptual design on top system level (SCD) is applied. Here, the progress is made as follows (cf. VDI 2206): after the abstraction of the problem the function structure with main functions and their interrelations is designed. The approach for a logical structure follows an extended search for working principles. The concretization of the logical structure results in an embodiment, the physical structure. The monitoring of weight properties occurs after each step following the RFLP approach and at the end of system design stage. For details of methods and tools within the system design stage, see Luedeke and Vielhaber (2013).
Additionally, decomposition and a partitioning of the system main functions to subsystem functions which are consisting of function blocks have to be applied. With their aid, a possibility is given to get to know the weight interdependencies and crosslinks between system and subsystems. During the partitioning activity, care should be taken that the links to each other are not too complex and too numerous. The effects and methods of interdependencies and crosslinks are shown in further detail later. With the help of a systematic application of the occurring lightweight strategies (systemic and conceptual lightweight design), it is capable to identify primary and secondary weight optimization potentials (WOP1/2) in this stage and when changing to the subsystem level. This means that (primary) optimization in system level provides further optimization in the system and subsystem levels (secondary optimization). A review of the weight properties is performed immediately after finishing this design stage.

Based on the distribution in subsystems, subsystem-specific requirements are specified on which the development of the subsystems is based. In principle, the procedure in subsystem conceptual design (SSCD) is identical to the one of the system design. Thus, the function blocks within the various subsystems are refined. The distribution in different subsystem levels might be advantageous when the whole system is very complex and extensive. When generating more subsystem levels the staircase model will change accordingly with an implementation of another level stair. Again, primary and thus secondary weight optimizing potentials can be identified. At the end of each conceptual subsystem design step on each level, analysis referring to the weight properties are performed and compared to previous analysis activities.

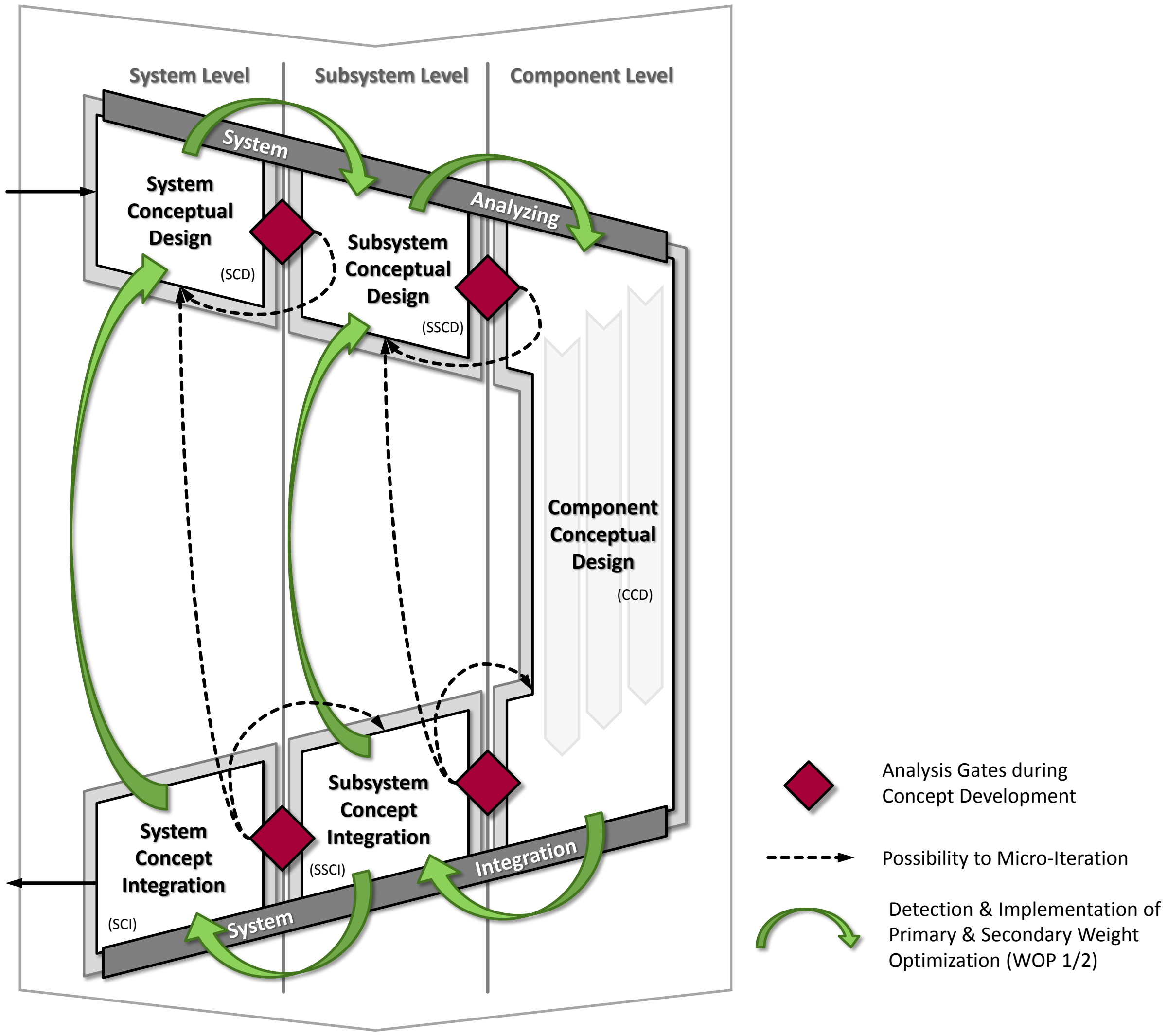

Figure 4. Conceptual Design Phase Showing Weight Optimizing Potentials

On bottom system level in the component conceptual design stage (CCD), the functions of the subsystems are partitioned in the domains involved. The development in the relevant domain follows the rules of established, domain-specific development methodologies which are characterized by their own way of thinking, terminology and experiences. In the single domains, primary as well as secondary weight optimizing potentials due to interrelations within the components can be detected. The weight properties of the specific domain concepts are estimated and roughly calculated at the end of this design step. On basis of the results of the estimation, a fall back to the start of preliminary domain concepts is possible.

With the integration of the domain-specific solutions to the subsystem level (SSCI), interdependencies and crosslinks, relevant for weight properties and distinguished in the design step, between or rather within the subsystems are identifiable and calculable. Thus, it is possible to apply measures for primary and secondary weight improvements which can result in a revised subsystem design stage and/or design cycle for components concepts. Based on the renewed subsystem concepts the system

concept is achieved through another integration of the subsystem (SCI). Again, incompatibilities relevant for the weight properties can be identified and secondary weight optimizations realized.
The result of the conceptual design phase is a solution concept which is parallel to a realistic estimation or rather a preliminary calculation of the weight and the weight-dependent properties like weight distribution, center of gravity and mass moments of inertia which can be clearly and simply illustrated.

Embodiment and Detail Design Phase

The embodiment and detail design phases implement the conceptual product solution from the previous design step to the real physical product. In this stage, the staircase model within the phase known from the conceptual design phase can be found, too. In contrast to the conception phase before, other lightweight strategies parallel to the systemic and conceptual lightweight principles come into action which are mostly related to the physical structure of the product. Here, following strategies and their principles can be named: structural (optimal force distribution), conditional (critical review of all requirements), material (substitution with lighter materials), and manufacturing (review of production processes) lightweight design. For more details, see relevant literature (Schmidt et al., 2001).
Based on the system concept generated in the previous main design stage, the elaboration of the system detailed design (SDD) as well as the final subsystem design (SSDD) depending on the previous system design is performed. The detailed design (CDD) on bottom system level again serves primary (e.g. substitution of materials, structural optimization, etc.) and secondary weight improvement potentials (e.g. weight reduction of a component through weight reduction of another component). Finally, the integration of the domain and component layouts to the subsystem layout (SSLI) as well as their integration to the entire system (SLI) results in detecting secondary weight optimization potentials once again.
The result of the embodiment and detail design stage should be the final product which fulfills the requirements of functionality and the weight target defined in the early design stages.

3.3 Weight Properties throughout the Development Process

Like in Figure 5, the data of the weight properties develop from a very vague status in the early phase of product planning where the weight often is estimated over calculated values in the conceptual and embodiment design to a detailed weighing in the latest phase of the product development to reach the weight target given in the early phases. This progress is called the tunneling effect (Dahm et al., 2005).

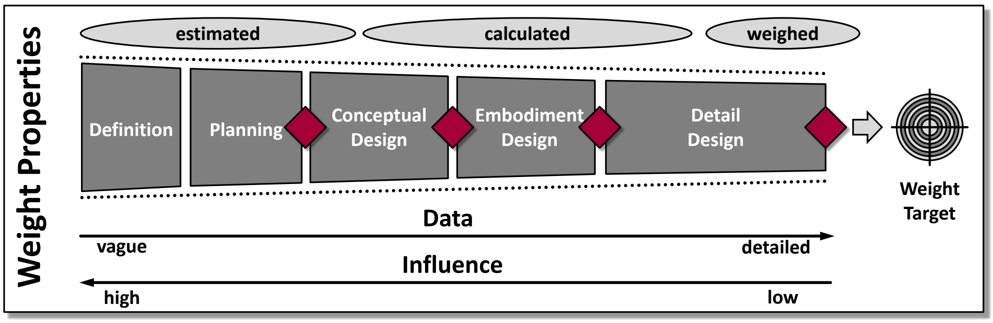

Figure 5. Tunneling Effect of Weight Data, similar to Dahm et al. (2005)

The influence on product properties and the potential for improvement decreases exponentially in contrast to the exponential growing of product knowledge and the degree of product concretization (weight properties data). Thus, the early design phases carry a special significance for weight optimization tasks. It is clear that the early phases demonstrate the greatest potential for influencing the future weight as well as other product properties and at the same time the highest risk during decision stages.

3.4 Analyses and Assessment of Weight Properties

Throughout the design process, there are several analysis points for assessing and monitoring the weight properties. They differ in some points:

– application point of time in design process
– type of analysis (estimation, calculation, weighing, …)

– subject of analysis (requirements, functional structure, logical structure, physical structure, virtual and physical prototypes, …)
– system level (system, subsystem, component)
– result (interdependencies, improvement and risk potential, weight targets and milestones, …)

Table 1 shows an overview of the analysis gates proposed in the process model.

Table 1. Analysis Gates during Design Process

Design Stage	*Design Step*	*Type of Analysis*	*Subject of Analysis*	*System Level*	*Result*
Product Planning	Definition	Estimation	Market & Patent & Predecessor Review	System	weight target and milestones
	Task Clarification	Estimation	Requirement List	System	interdependencies
Conceptual Design	Prel. System Design	Estimation	Functional & Logical Structure	System	interdependencies, WOP 1&2
	Prel. Subsyst. Design	Estimation	Functional & Logical Structure	Subsystem	interdependencies, WOP 1&2
	Prel. Domain Concepts	Estimation, rough Calculation	Functional & Logical & Physical Structure	Component	WOP 1&2
	Subsystem Concepts	Estimation, rough Calculation	Functional & Logical & Physical Structure	Subsystem	interdependencies, WOP 1&2
	System Concepts	Estimation, rough Calculation	Functional & Logical & Physical Structure	System	interdependencies, WOP 1&2
Embodiment & Detail Design	Final System Concept	Estimation, rough Calculation	Physical Structure	System	interdependencies, WOP 1&2
	Final Subsystem Concepts	Estimation, rough Calculation	Physical Structure	Subsystem	interdependencies, WOP 1&2
	Final Domain Concepts	Calculation	Physical Structure	Component	WOP 1&2
	Subsystem Layout	Calculation	Physical Structure	Subsystem	interdependencies, WOP 1&2
	System Layout	Calculation, Weighing	Physical Structure	System	interdependencies, WOP 1&2

3.5 Illustration of Interdependencies in System and Abstraction Level

The illustration of the interdependencies between the different system levels as well as abstraction levels is one of the challenging tasks while considering weight properties in the design process of weight-optimized mechatronic systems. With knowledge of these crosslinks between systems and subsystems or components as well as interrelations in functional, logical, and physical structure, extensive weight propagation throughout the systems can be avoided. Therefore, an assurance of weight properties and their interlinks to the entire system is required as early as possible in the design process. In the model proposed above, the understanding of crosslinks is already performed in the design stage of product planning whereat the requirements list is generated showing weight-relevant requirements and their trade-offs and interlinks. Based on this knowledge, it is possible to detect secondary weight optimization potentials in components and subsystems in the same or a higher system level. They are following primary weight optimization measures which are caused by the classical lightweight design principles (material, structure, conditions, manufacturing). The reason for illustrating the interdependencies is to show how the weight or other weight properties of a specific system part or structure (logical, functional, physical) have an impact on other system parts or structures. Hence, the weight propagation through the system can be depicted. The illustration could be graphical in flow charts or mathematical, comparable with the matrices in Axiomatic Design (Suh, 1998). The results of the illustration are integrated into the design process for identifying the secondary weight optimizing potentials in the design integration steps from the bottom system level to the top system level. In literature, there are some approaches aiming at weight savings by evaluating lightweightedness specifically addressing physical structures (mostly components). For example, the approach of so-called “lazy parts” and “lazy parts indicators” identifies parts (components, assemblies, devices) that add mass to the system but have only little impact on the performance (functionality and behavior) of the system (Namouz, 2010).

4 CONCLUSION AND OUTLOOK

In this contribution, it is shown how an early and holistic consideration of weight properties throughout the design process for weight-optimized mechatronic products can be key for the performance and the handling of these products in all product lifecycle phases. Based on a general process model for product development a design proceeding is proposed which includes the holistic monitoring and management of weight properties in the analysis gates as well as the systematic understanding of interdependencies and crosslinks within the system to be designed. In addition, the needs for illustrating system knowledge and its understanding (interdependencies and interlinks within system structure, logical and functional structure) is depicted. In further research regarding the process view, the analysis gates and the assessment of weight properties as well as the measures resulting from these analyses will be in focus. Furthermore, a graphical and mathematical illustration of system interlinks regarding weight properties will be generated. The systematic consideration and illustration of these interlinks especially supports the detection of secondary weight optimization potentials.

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