Lightweight design and variety: A multi-model optimization approach in product development

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Abstract

The contribution addresses the integration of lightweight design principles into the product development process while managing the challenges posed by increasing product variety. The paper highlights the conflict between the necessity for weight optimization and the proliferation of product variants driven by market trends. It proposes using multi-model optimization (MMO) to resolve this conflict. By implementing MMO, weight reduction can be achieved in components and modules, before and after the modularization process. The paper details how MMO can be applied at different stages of product development. This approach supports economic constraints and improves the overall product structure through iterative optimization of interfaces and modules.

Keywords

lightweight design, multi-model-optimization, product development, modularization

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1. Introduction

The optimization of mechanical products has become a pressing concern in light of the numerous technological innovations that have emerged. Consequently, the systematic integration of lightweight design principles in the design process has become of crucial importance [1]. However, existing megatrends such as individualization, which are influencing today's product development, are counteracting the increasing importance of lightweight design requirements due to the growing number of product variants. The growth in internal variety within companies, as a result of the expansion of product portfolios, has a correspondingly detrimental impact on costs [2]. This causes cost pressure in product development, which can be understood as an economic constraint [3]. The development of modular product architectures represents a viable approach to reducing the internal variety of components without limiting the external variety, as reflected in the product portfolio. Moreover, the approach can contribute to the fulfillment of economic constraints due to the resulting economies of scale. To address the different customer requirements, modular product architectures put a focus on the standardization of interfaces and the oversizing of components to be able to use modules commonly [4]. In contrast, lightweight design strategies tend to prioritize the reduction of the weight of individual product variants, with less attention paid to the product architecture and the variety of products.

This paper presents an approach to address the conflict between weight optimization and variety by suggesting different use cases of multi-model optimization in the product development process.

2. State of the Art

This chapter provides a concise overview of general lightweight design strategies. Furthermore, the impact of variety and modular design on lightweight design is presented, along with the associated challenges. In conclusion, we present a summary of the essential characteristics of MMO and an overview of its operational principles.

2.1. Lightweight design and variety

The concept of lightweight design can be defined as a systematic approach to product development that aims to produce a product with minimal weight while still satisfying the prior specified requirements. This may entail considerations pertaining to the achievement of the desired stiffness of the product. The most prevalent lightweight design strategy is material lightweight design, which utilizes high-performance, low-density materials to substitute heavier materials [5], [6]. Requirements for the materials used in material lightweight design are generally high weight-specific mechanical properties like strength and stiffness, which are present in composite materials like fiber-reinforced polymers or sandwich structures [7]. This is a common initial strategy employed to reduce weight when the system lightweight design approach has already been completed [8]. Another lightweight design strategy that is particularly relevant to this publication is the form lightweight design strategy. Form lightweight design is a strategy that considers the change of design in response to a given load case, with the objective of optimizing the load path through structural modifications to the product [6], [8]. Notably, none of the mentioned design strategies have been developed with the explicit intention of accommodating product variety or considering lightweight design and variety specifically in the product development process.

High product variety is a high-level customer demand in today’s market. In the product development process, the divergent customer requirements that result in the creation of different product variants to satisfy the individual customer needs should be considered as the initial point of reference [9]. To achieve this variety in products while still keeping the internal variety low, modular product architectures can be used [2].

2.2. Modular design and interfaces

Modular product architectures are often used to realize the previously presented needed variety in a product to fulfill the customer's demands. In modular design, the objective is to identify the optimal compromise between integral and differential design, which is then applied to the definition of modules. Through the standardization of interfaces modules can be used commonly between different product configurations to reduce the internal variety [2], [10].

High commonality in modules counteracts lightweight design because the implementation of standardized interfaces frequently results in an oversizing of interfaces [11]. This is due to the necessity of considering the most demanding configuration at the design stage. The fundamental concept of modular products therefore challenges the principles of lightweight design to a certain extent, as modular products prioritize economic performance over product performance [12]. Different existing strategies tackle this conflict. *Gumpinger* proposed a weight optimization after the modularization of the product, where the modularized product configurations are reanalyzed and the potential of weight reduction of a reconfiguration of modules and interfaces is evaluated [11]. Another suggested approach is the combination of lightweight design and variety respecting modularization through data linking in the early development process. This approach is conducted before the modularization and was presented by *Hanna et al.* as modular lightweight design [13], [14].

2.3. Multi-model optimization

Topology or load-path optimization is usually carried out individually for the different variants of a product, considering only the specific product configuration that is examined. The multi-model optimization (MMO) approach can be used to optimize multiple product configurations simultaneously regarding the common design spaces in between them [15]. The MMO framework, implemented in Altair's OptiStruct solver, enables the simultaneous optimization of multiple models, each with distinct objective functions, constraints, and design spaces. The solver permits the optimization of common parts or interlinked design variables across the models. Figure 1 provides a simplified illustration of the advantage of using MMO in comparison to single-model optimization (SMO). It demonstrates how MMO can be used to effectively reduce weight while maintaining component commonality.

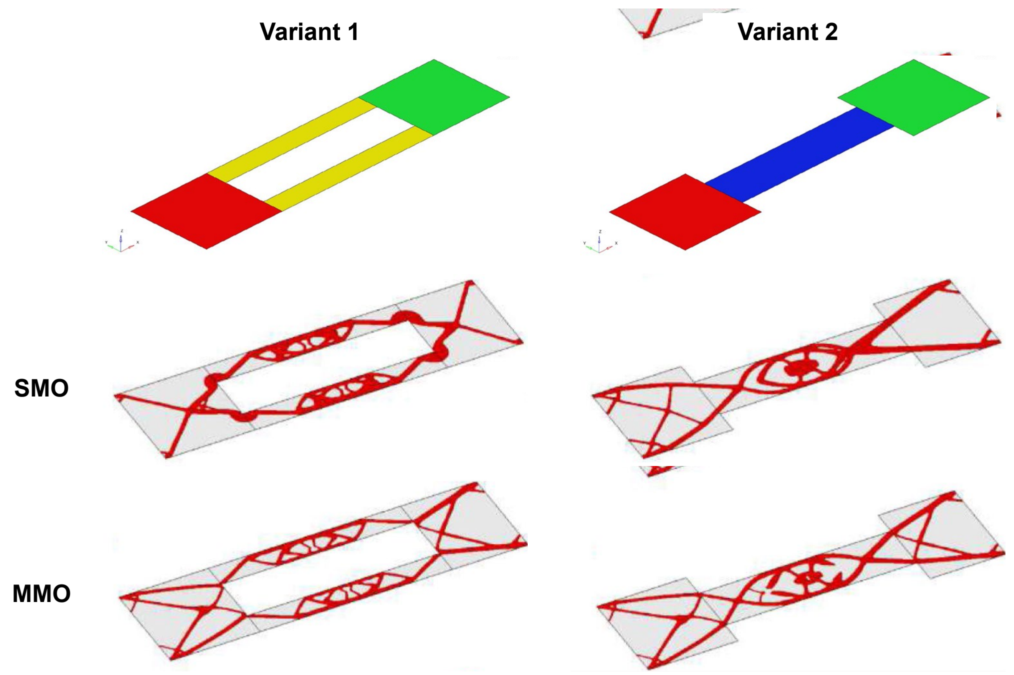

Figure 1: Use case of MMO based on an Example of MMO compared to SMO based on *Zagorski et al.* [15]

Variants one and two are composed of two equivalent surfaces (green and red) and are connected in alternative ways (blue and yellow). In this example, *Zagorski et al.* demonstrated that with MMO, identical elements can be optimized collectively while realizing different load paths due to the distinct configuration [15]. The green and red elements, when optimized with MMO, can be used in both configurations, therefore reducing the number of needed component variants.

The literature contains numerous examples of the application of MMO. For instance, there are numerous publications on the optimization of structures with regard to structural failure [16–18]. In these publications, MMO is also combined with Realiability-based design optimization (RBDO), for example, to consider damage variations in the design [19]. In this particular use case, MMO has been employed to evaluate the potential failure scenarios while simultaneously optimizing for weight across these scenarios. *Jeong et al.* apply MMO to the equivalent static loads method to calculate multiple models simultaneously [20]. In the recent past, MMO was also discussed in the weight optimization of modular product families to consider components in different configurations [14], [21]. The authors propose an approach to utilize MMO to determine which component of a modular product family should be optimized individually or in combination with another component. In this process, the congruent implementation of information exchange between the topology optimization and the product structure is of high importance and could be realized with a custom interface between the finite element method (FEM) software and system models of the product [21].

3. Integration of MMO into Product Development

The product development process can be divided into six distinct phases, as depicted in Figure 2. The initial planning phase incorporates market research and technology assessments to prepare the entire product development process. The concept development phase is oriented towards the generation and assessment of product concepts that are aligned with the previously identified market needs and strategic objectives. In phase two, the selected concept is designed at the system level, including the definition of interfaces and sub-systems. Subsequently, the design is refined in phase three through the incorporation of detailed design and drawings. In the fourth phase, the product is tested with the use of prototypes to ascertain its quality. In the final phase, the manufacturing process is scaled up in preparation for mass production [22].

Figure 2: Product development process after *Ulrich et al.* [22]

This paper addresses the implementation of lightweight design methods within the product development process, specifically in the context of high-variety product families. The authors propose that the Integrated PKT Approach is particularly well-suited to the development of modular product families, and thus serves as a foundation for optimizing product performance while accounting for variety [2]. The following section outlines the five steps of the process. Firstly, a *Requirement Analysis* is conducted to define the goals of the development process. Following the identification of these goals, the *Design for Variety* step is carried out to reduce the number of overall components to a minimum. The resulting components are then grouped into modules in the *Modularization* step, to reduce the overall complexity and cost of the product family, lowering the cost pressure for the producing company. Subsequently, a *Design Evaluation* is conducted to ascertain whether the developed product is consistent with the previously identified requirements. The stage in the process, where the fifth step *Multi-Model Optimization* is carried out represents the core research question addressed in this contribution.

3.1. Early-stage optimization

Placing the *MMO* before the *Modularization* phase is depicted in Figure 3 and creates some advantages for the product development process which must be weighed against the disadvantages. The primary advantage of inserting the step in this order is the potential for identifying common structures before the modules of the product architecture are configured. This creates the opportunity to use MMO for a variety of components, compare the commonality between different optimizations, and decide on this basis which components could be merged into one component for different variants. Therefore, by identifying common structures, the internal variety can be reduced. The identification of common structures can be used in structural optimization as well as an information indicator for the *Modularization*, to configure the modules. Furthermore, the topology optimization of the different components can be carried out together while using the MMO to reduce the needed optimization time. The results of a simultaneous optimization, such as MMO, will, on average, yield a lower weight reduction compared to SMO. However, the additional economic benefits demonstrate a viable compromise between weight reduction and economic performance.

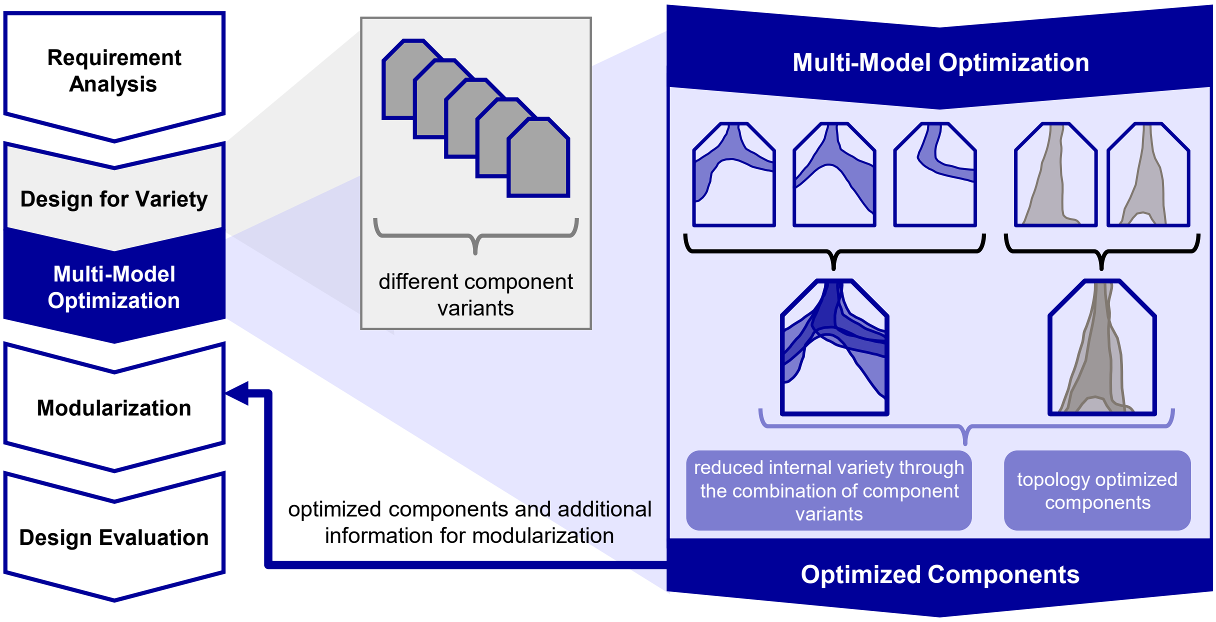

Figure 3: Procedure of MMO in the Integrated PKT Approach before the *Modularization*

The MMO in this case can be used as a tool in the *Design for Variety* step to reduce the internal variety of the product family. One significant tool employed to mitigate internal variety inherent to the Integrated PKT Approach is the Variety Allocation Model (VAM). The VAM provides a visual representation of variant functions and components of a product family and allocates them to the customer-relevant properties. The objective is to achieve a one-to-one allocation by modifying the architectural framework to restrict the number of variants [23]. MMO can be employed to further reduce component variety by combining variant structural components into one and simultaneously incorporating a lightweight design.

Due to the already conducted optimization, the *Modularization* can be carried out with already optimized components reducing the effort to optimize each module configuration. As the modularization procedure is conducted with optimized components, this variation is best suited for new products or product families that have not yet undergone modularization. In cases where the procedure is applied to preexisting modular product families, the modularization must be carried out again, resulting in an iterative development process.

3.2. Late-stage optimization

In comparison to the approach presented in Section 3.1, implementing the MMO after the *Modularization* procedure presents a different set of advantages and disadvantages. This allows for the utilization of MMO for existing product families to optimize separate modules in different product configurations, as shown in Figure 4. The application of MMO in this order presents two main opportunities.

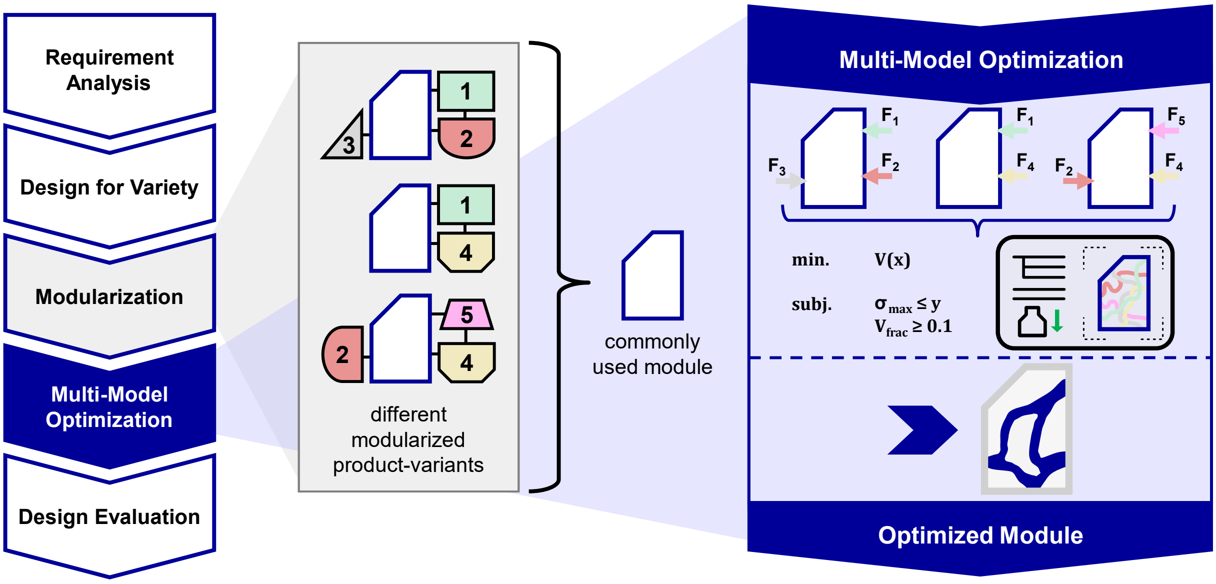

Figure 4: Procedure of MMO in the Integrated PKT Approach after the *Modularization*

Firstly, MMO can be employed to optimize modules while not changing interfaces of the existing commonly used module but simultaneously optimizing the structure considering loads of different product configurations. Once the MMO has been conducted, the product variants can remain unchanged, and the modularization that has already been realized can be maintained with the optimized modules. In this variation, the primary objective is to optimize the weight of modules. Similarly to the strategy proposed in Section 3.1, the internal variety may be reduced due to the combination of multiple modules.

The second opportunity is to utilize the MMO to optimize the modules in consideration of varying product configurations, while also modifying interfaces to achieve the full potential of structural optimization. This necessitates a comprehensive restructuring of the modularized product architecture, which could potentially yield even greater benefits regarding structural optimization. This is because the optimization is not constrained by the given conditions due to the interfaces. Furthermore, in addition to the weight optimization, this variation of the procedure also allows for a weight-oriented interface design, due to the gained information about the optimal placement of interfaces derived from the topology optimization.

The second variation of the procedure can be understood as an iteration of the *Modularization* procedure, while MMO is utilized to optimize the structure as well as the interfaces to achieve better product commonality. Both variations have in common, that the potential for optimization of modules can be identified, similar to the proposed modul lightweight design by *Gumpinger* [11]. The author also considered combining or changing interfaces to reduce the weight of the entire product portfolio. By realizing the MMO regarding interface redesign, the oversizing of interfaces can also be quantified in comparison to the old modules and existing interfaces. The primary disadvantage of utilizing MMO following the *Modularization* is the alteration of the existing product structure, which is a complex and time-consuming endeavor.

3.3. Opportunities and challenges in product development

The two proposed variations of incorporating MMO into the Integrated PKT Approach present different opportunities for product development. Mainly the identification of structures with high commonality, to decide how to carry out the modularization and the optimization of existing components while changing or not changing the current interfaces.

In Figure 5 a flow chart is shown, where the presented opportunities to use MMO are displayed regarding the different approaches. The initial decision that must be made is whether the product under consideration is newly developed or if it is an existing product family to be weight-optimized through the alteration of components and modules. In the context of developing a new product, it is recommended that the MMO is conducted before the *Modularization*. Conversely, for product family overhauls, the MMO should be carried out after the *Modularization*. Optimizing components before modularization is preferable because iterations of modularization are prevented, since product family overhauls can result in a new iterative modularization because with changed interfaces the existing product structure is not congruent with the newly developed modules.

The second decision when using MMO in the product development process is to consider how many variants of a product exist and how many different load cases are given for the different components. The relative advantages of MMO compared to SMO become more evident when the number of variants and load cases increases. This is due to the increasing effort to optimize the components in every variation and for every load case when using SMO. The potential of MMO therefore lies not in the extremes of the load cases but in the in-between load cases to identify and optimize the components concerning commonly occurring loadpaths during the optimization. A more comprehensive, systematic investigation is still necessary to determine the specific product attributes under which individual components and modules can be merged into one component or module. Before trying to use MMO at this step, it should be evaluated if the given conditions suit the employment of MMO or if an SMO is also feasible or even more efficient due to the low quantity of product variants or product configurations.

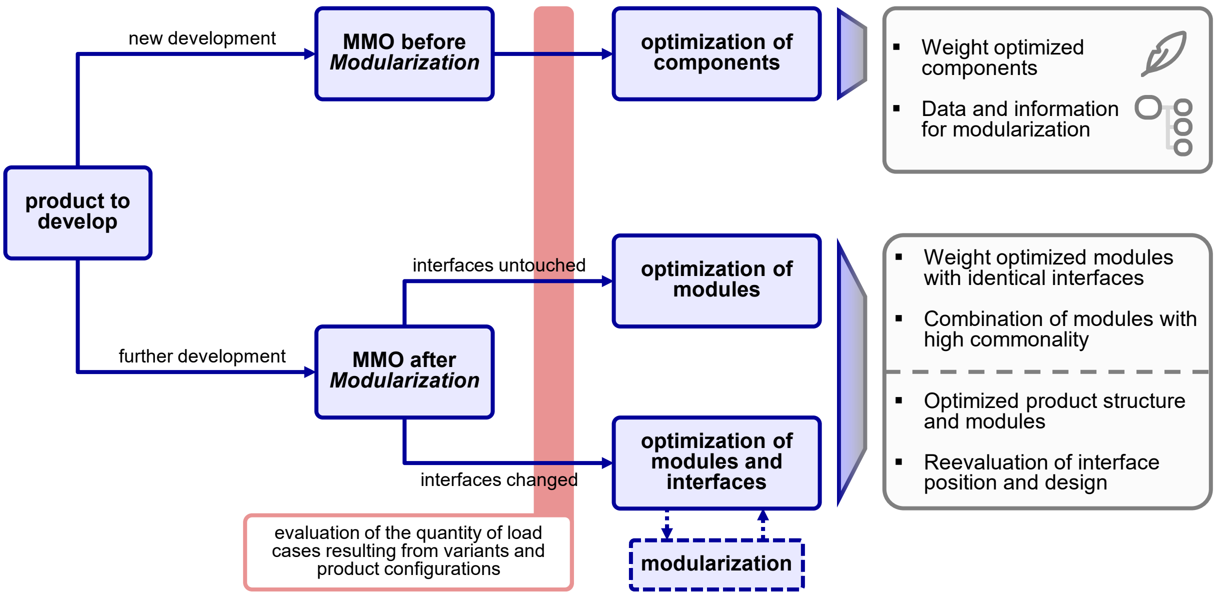

Figure 5: Flowchart of possible use cases of MMO in the Integrated PKT Approach with resulting outcomes

The broadly accessible use case of MMO in product development with a low implementation barrier is the upper path in Figure 5 due to the untouched *Modularization* step. This approach enables the identification of the component's commonalities and the subsequent optimization of its weight. Furthermore, data and information for the subsequent modularization can be obtained.

Following the lower path of the flow chart implies that regardless if the interfaces are untouched or changed the product structure is modified. This follows the modification of modules to achieve weight-optimized modules with identical interfaces and the possible combination of optimized modules due to high commonality after the topology optimization.

When considering changing the interfaces of existing modules the achieved optimization affects the whole product structure and possibly leads to a preferable location and design of the interfaces. The optimization of interfaces and modules using MMO thus results in an iterative modularization process, enabling the configuration of efficient product variants with optimized modules. Therefore, changing interfaces needs to be carefully evaluated and the effort involved needs to be considered.

4. Conclusion

This contribution gives an overview of different possibilities for implementing the approach of MMO into the product development process, specifically the Integrated PKT Approach for the development of high-variety product families. The different stages at which the MMO could be introduced into the development process are illustrated and analyzed. While the early-stage implementation is particularly proposed to reduce the internal variety in addition to the weight reduction before the *Modularization*, the implementation of MMO in later stages of the product development process offers different opportunities. In the later stages interface changes may or may not be considered as a design change for the modules. Maintaining the interface design in the MMO, the modules can be weight-optimized and used in all existing product configurations, if modules with high commonality are identified they could even be combined. A redesign of the interfaces would result in an overall optimized product structure and lead to an iteration of a previously conducted modularization.

The findings highlight the necessity of conducting a thorough analysis of interface alterations, as they exert a considerable influence on the configuration and modularization of the product. In general, additional performance indicators should be defined to ascertain the value of implementing MMO in addressing the current problem.

5. Outlook

Concerning the proposed utilization of MMO in the product development process, the subsequent step will be to perform distinct topology optimizations to evaluate the potential for weight reduction associated with the various approaches. First, the MMO will be considered before the modularization, with later investigations regarding the MMO after the modularization. Another noteworthy aspect is the analysis of the potential for quantifying the oversizing of interfaces and the classification of additional information gained through the optimization procedure in relation to potential influences on modularization. A further investigation is required to determine the conditions under which economic constraints result in the combination of components to form a commonly used component and to identify the specific boundary conditions under which lightweight design is the dominant constraint.

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