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Material Selection Based on a Product and Production Engineering Integration Framework

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Abstract

Material selection is an essential aspect of engineering processes of both products and production systems, and often crucial for the success of the resulting products. In practical engineering, however, material selection is often executed in a hands-on manner and not based on an integrated optimization process taking all relevant product and production engineering aspects into account. This contribution presents a formalized approach to better support material selection decisions. The approach is part of an overall material-oriented development methodology and features a material selection method which takes product, production process and material information into account in an integrated way.

Keywords: Integrated Product and Production Engineering; Material Selection; Material-Oriented Development

1. Introduction

Material selection is an essential aspect of engineering processes of both products and production systems, and often crucial for the success of the resulting products. Material decisions are heavily interlinked with the products' as well as the production systems' properties and characteristics. In practical engineering, however, material selection is often executed in a hands-on manner and not based on an integrated optimization process taking all relevant product and production engineering (PPE) aspects into account. This contribution will present a formalized approach to better support material selection decisions.

PPE describes the phases in the product lifecycle, in which all aspects of an envisioned product are conceptualized, laid out and detailed along with the respective production equipment. In parallel and closely interrelated, the product's material is determined and defined. Thus, product, production and material definition build the three dimensions of product and production engineering. Holistic approaches in this area have therefore to consider all three dimensions and their interrelationships in an integrated way. In previous work, the authors introduced a generic PPE integration framework, which links inputs and outputs (i.e. impacts and requirements) of engineering with the process phases of both domains. Thereby, it provides a generic basis for the development of analysis and synthesis methods for a wide range of integrated PPE aspects.

In this contribution, the integration framework is applied on the specific aspect of material selection. After summarizing its main ideas in section 2, section 3 will give a short overview on material selection. On this basis, section 4 will introduce a general material-oriented development methodology which will then be brought together with the integration framework to form an integrated material selection method in section 5. Finally, section 6 will discuss the findings and conclude.

2. Product and Production Engineering Integration Framework

In order to allow holistic and integrated decisions in product engineering and production engineering taking both domains equally into account as well as considering domain-spanning material aspects, the authors developed a product

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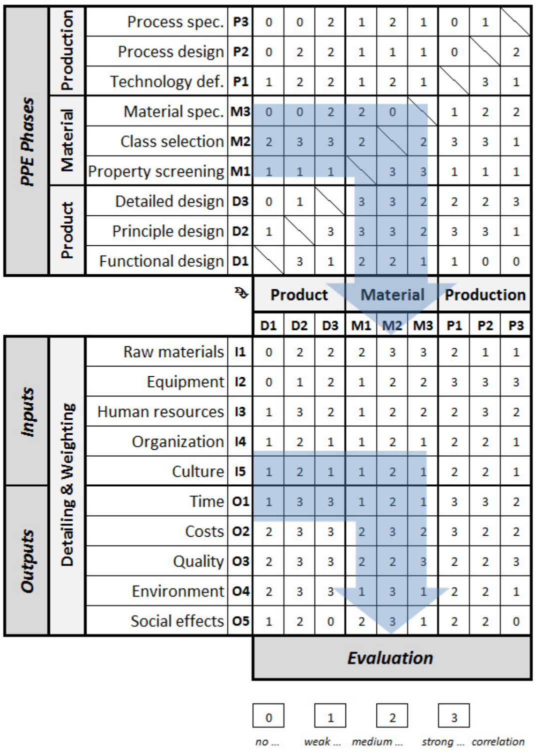
and production engineering (PPE) integration framework which can serve as a basis for a variety of domain-spanning engineering applications [1].

Thus, product definition, production definition and material definition build the three dimension of the framework. For each dimension, the framework defines three maturation phases from a concept via a layout to a detail level, and it evaluates interrelationships between all these nine phases. These interrelationships build the horizontal axis as well as the roof of the House of Quality-like representation of the framework, see figure 1.



				D1	D2	D3	M1	M2	M3	P1	P2	P3
PPE Phases	Production	Process spec.	P3	0	0	2	1	2	1	0	1	
		Process design	P2	0	2	2	1	1	1	0		2
		Technology def.	P1	1	2	2	1	2	1		3	1
	Material	Material spec.	M3	0	0	2	2	0		1	2	2
		Class selection	M2	2	3	3	2		2	3	3	1
		Property screening	M1	1	1	1		3	3	1	1	1
	Product	Detailed design	D3	0	1		3	3	2	2	2	3
		Principle design	D2	1		3	3	3	2	3	3	1
		Functional design	D1		3	1	2	2	1	1	0	0
				Product			Material			Production		
				D1	D2	D3	M1	M2	M3	P1	P2	P3
Inputs	Detailing & Weighting	Raw materials	I1	0	2	2	2	3	3	2	1	1
		Equipment	I2	0	1	2	1	2	2	3	3	3
		Human resources	I3	1	3	2	1	2	2	2	3	2
		Organization	I4	1	2	1	1	2	1	2	2	1
		Culture	I5	1	2	1	1	2	1	2	2	1
Outputs		Time	O1	1	3	3	1	2	1	3	3	2
		Costs	O2	2	3	3	2	3	2	3	2	2
		Quality	O3	2	3	3	2	2	3	2	2	3
		Environment	O4	2	3	3	1	3	1	2	2	1
		Social effects	O5	1	2	0	2	3	1	2	2	0
				Evaluation								

Fig. 1. Product and production engineering integration framework as presented in [1]

Decisions in this environment are on the one hand influenced and constrained by external impacts and boundary conditions. In the integration framework, these inputs have been categorized in raw material, equipment, human resources, organization and culture-related impacts. On the other hand, requirements define the desired outputs of product and production engineering. These outputs have been categorized into time, cost and quality requirements as well as environmental and social effects. Both inputs and outputs build the vertical axis of the framework representation in figure 1. In the main matrix area of the framework, then, inputs and outputs are correlated with the maturation phases from the horizontal axis; strength of the correlations are evaluated on a generic basis, initially.

Applying the integration framework on engineering questions such as material selection would now require to detail and weight both the boundary conditions (inputs) and the requirements (outputs). Then, the correlations have to be re-evaluated, the interrelationships of the PPE phases have to be re-considered, and the material evaluation has to be executed on this information basis. Section 5 will elaborate on this application in further detail.

3. Material Selection Today

Engineering design represents the process of translating a new idea or a market need through a more detailed concept, or rather a technical draft, into an ultimate construction a product can be manufactured from. Therefore, each of these stages require decisions about feasible materials depending on the product itself, commonly dictated by the design, as well as the manufacturing process (form, join and finish).

Nowadays, the variety of available engineering materials placed at the constructor’s disposal is large; according to Moeller [2] approximately 40,000 of metallic and non-metallic each. Thus, without guidance, the selection of the few best suited materials with regard to the respective system or product requirements is difficult and time-consuming, but still insufficiently precise only and furthermore no longer up-to-date. Due to this fact, there is an urgent need for a systematic approach of a material-oriented product development process.

The scientific literature, however, contains numerous approaches, methods and procedures for a systematic material selection. Indeed, these closely resemble the common problem-solving cycle, but are still different in terms of their priorities. Thus, Grosch [3], Ehrlenspiel et al. [4] and Fischer [5] first provided the link between the traditional product development process and an overall systematic approach to material selection, highlighting material-relevant decisive fields.

An internationally accepted and well-known standard for material selection is represented by Ashby [6], see figure 2.

Fig. 2. Four main steps of the material selection guideline by Ashby: translation, screening, ranking, supporting information [6]

Although this guideline provides a basic methodology of a suitable choice of material, that collates material-related requirements, followed by a screening and a subsequent ranking process up to the final material selection, there is primarily a more detailed procedure for the fundamental pre-selection of material groups.

By using the appropriate computer-based material data (Cambridge Engineering Selector / Granta Design), a detailed material selection within the eligible material classes can be determined based on the particular required material specifications and the resulting property charts (figure 3).

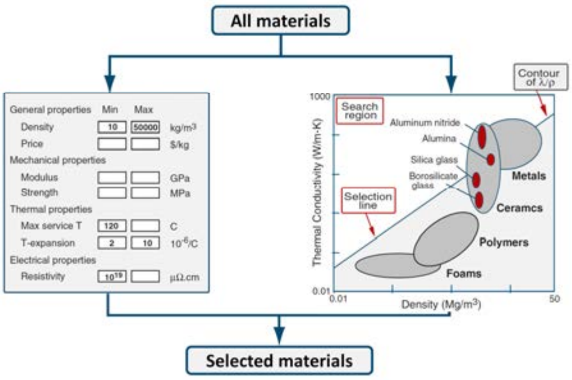


Fig. 3. Computer-aided material selection using the CES software [6]

In his approach, Ashby also targets to bring product-related material information closer together with relevant process information. This attempt as well as the similar approach by Farag [7] is however limited to the proposal of suitable production processes for previously selected materials, or vice-versa, and thereby does not provide sufficient support for truly integrated product and process-based decisions.

Based on the aforementioned approaches, in particular regarding the represented guideline by Ashby, Reuter summarizes all these considerations into one ‘standardized’ approach for a systematic material selection integrated into the general product development process. Referring to the classical phases, the task clarification as well as the conceptual, embodiment, and detail design (VDI guideline 2221 / 2222-1), this approach is also classified into four material-relevant stages [8]:

- determination of material properties (*task clarification*) and derivation of a specific material requirement profile
- pre-selection of suitable materials (*conceptual design*) including a procedure of individual material or entire class exclusions
- fine-selection of remaining materials (*embodiment design*) based on a more detailed comparison of necessary but also targeted system requirements and respective material properties, followed by a ranking process with determined assessment criteria
- specification (selection of the most appropriate material options) and validation of the demanded product requirements (*detail design*) by material experiments closely connected to design geometry

As a result, a systematic material decision-making can be achieved with the help of individual instruments for the actual process step, such as the ABC analysis (task clarification) or browsing different material database systems (solution seeking), as well as the resulting process documents (outputs).

In summary, there are different approaches to describe a systematic strategy of finding the best suited material for the particular design. Thereby, however, all these approaches are not targeted sufficiently towards the entire manufacture / product or the overall technical system, but rather the various components. Against this background, and by taking into consideration that manufacturing aspects with many new technologies (for instance multi-material construction techniques) have not yet or just inadequately been supported by the present procedures, there is an urgent need for a material-oriented product development methodology based on both the product design and its production process.

4. Material-Oriented Development Methodology

Due to the continuously increasing introduction of high- and super high-strength steel as well as the partial usage of different aluminium alloys and composites within the industrial product development over the last years, considerable progress in material-oriented lightweight design has already been made. Thus, the singular steel, aluminium and FRC (fiber-reinforced composite) design is replaced by a multi-material construction method. Consequently, many choices have to be made when designing in multi-material systems, which on the one hand increase the design freedom whilst they make the process more complex at the same time.

However, to achieve the full potential, hybrid concepts - targeted on the right material in the right place in consideration of the optimum cost, sustainability and quality - require a holistic approach including a significantly stronger integration of the respective conceivable production process besides the common material selection primarily based on the developed design (figure 4).

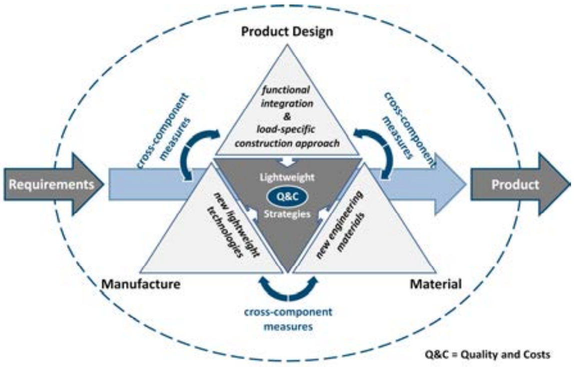


Fig. 4. Triangle of the lightweight design framework

Thereby, a key role is particularly attributed to the joining process within the barely introduced cross-component lightweight and material-oriented design (LMOD) methodology depicted below. This fact is derived from the various new challenges and requirements entailed by the trend towards multi-material construction techniques. Despite the related areas of concern, e.g. predominantly different mechanical and/or physical properties of adjacent components, the multi-material compliant integrity of the structure has to be realized to fulfil the designated functionality at appropriate strength and stiffness. Accordingly, newly developed lightweight materials and constructions can only be successfully implemented if there are tailored solutions in respect of generally possible but also cost-efficient and reliable joining technologies. Consequently, new hybrid joint technologies are presently being investigated [9, 10].

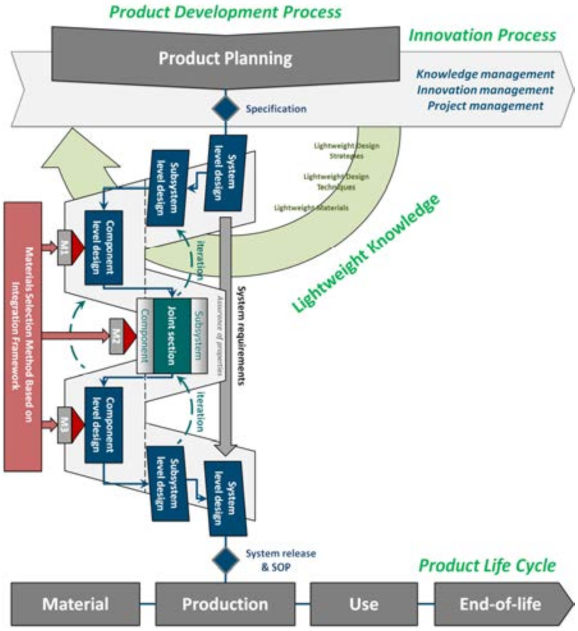


Fig. 5. Cross-component lightweight and material-oriented design (LMOD) methodology

The depicted cross-component procedure in figure 5 portrays a double V-shaped or W-shaped product development process centered by the joint section design and is integrated within the entire product life cycle (bottom horizontal line). Based on the 1993 as the VDI 2221 published directive (a meanwhile widely accepted approach for developing technical systems and products) [11], the design process is initiated by the pre-phase of product planning. The resulting product specification represents the origin of the following systematically focused double V-shaped model. Classified into the three main levels 'system', 'subsystem' and 'component level design' (according to VDI 2206 [12]), this procedure aims at a simultaneous top-down as well as a bottom-up approach partly influenced by appropriate lightweight knowledge.

Starting with the first wing of the upper V-shaped model, the respective boundary conditions must be clarified just as the adequate functional analysis has to be conducted for the three main levels. As a result, the pre-design, or rather the functional design, can be developed in conjunction with the actual definition of (main) joints in terms of type and position for both the 'system' and 'subsystem level design'.

At the 'component level design' (bottom level) the functional design underlies a first *screening* process (M1) of generally possible and permitted *properties* of favorable material classes. By taking into consideration the previously selected limitations with the complying technology definition in mind, the design process of the central task - the joint section design - starts to conceptualize and optimize the junctions between each component and subsystem as well as the subsystems and the entire system. Within the scope of this step (M2) a *class selection* should be targeted on the basis of the pre-optimized joint layout. In comparison to other lightweight approaches [13,14], this offers a further penetration of feasible potentials in lightweight design, particularly with regard to (cross-component) multi-material systems.

In the final step of the inner procedure (M3), a shape (CAO) and topology optimization (SKO) is applied at both respective joints and related components. Verified by material modelling with FEM simulation and combined with a further specified process design, the final *material specification* can be determined based on this detailed design.

Finally, each component is being interlinked with the integration through the specific component joint. A subsequent multiple-body simulation as well as a prototype manufacturing provides a further vertical integration to the 'system level design'. The successful development of a pilot series permits the system release.

5. Materials Selection Method Based on the Integration Framework

In this section, the integration framework from section 2 will now be put into the context of the material-oriented development methodology from section 4. Thus, a material selection method will be presented that holistically takes the product and production engineering information from the integration framework into account.

The method runs through the integration framework in three cycles, one for each maturation step, see figure 6.

5.1. First Cycle: Material Screening

This cycle starts in the very conceptual phase, depicted as M1 in figure 5. Only initial boundary conditions are set and initial requirements are defined. Material selection in this phase means to do a pre-screening based on main target properties of the material to be selected. To do so, the generic inputs and outputs in the integration matrix are detailed and/or replaced by the initial boundary conditions and requirements, which are weighted and thereby lead to a clear prioritization of material screening criteria. In parallel, evaluating the inputs and outputs from a product and process point of view, the matrix leads to an initial functional design and technology definition, accordingly.

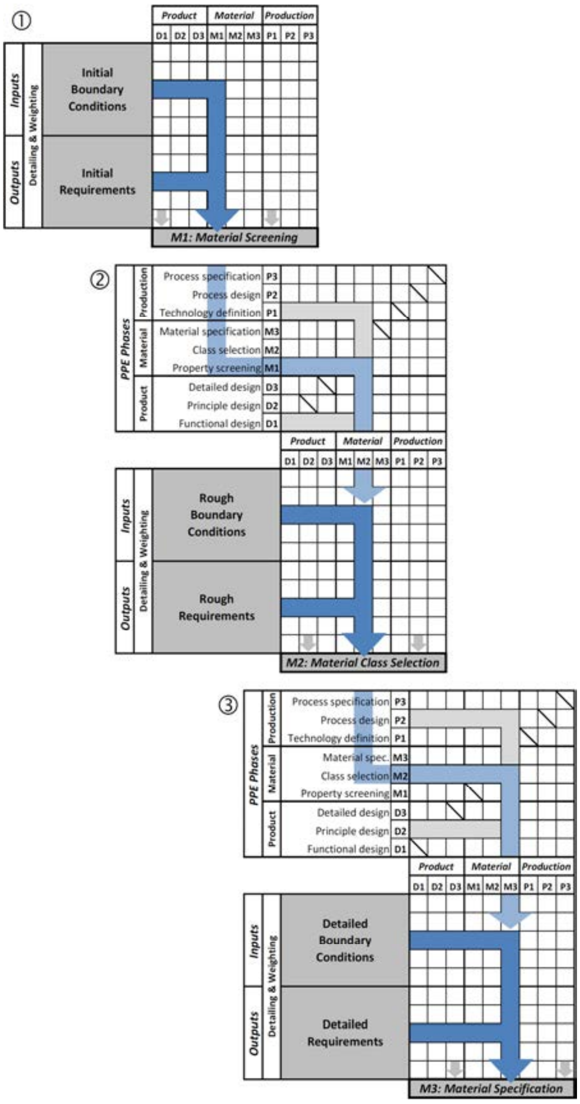


Fig. 6. Product and production engineering integration framework applied on material selection

Thus after this cycle, an integrated rough concept for the product, the production and the material design has been determined.

5.2. Second Cycle: Material Class Selection

The second cycle enriches the information from the first cycle in two ways. First, the boundary conditions and requirements get further detailed and deliver more input to be evaluated in the framework matrix. Second, due to the screening result from the first cycle, the relationships between the material, the product and the production maturation steps from the upper part of the framework matrix, can be evaluated, too.

Thus, enough information is gathered to come to a sound material class selection, which takes product, process and material aspects into account, simultaneously. In parallel, the functional product design from the first cycle gets materialized to a principle product design featuring also definitions of component interfaces and joints, as well as the technology definition from the first cycle is detailed towards a process design on the production side, thereby finishing phase M2 in the methodology from section 4.

5.3. Third Cycle: Material Specification

The third cycle generally resembles the second one. Now, boundary conditions and requirements are getting fully detailed and finalized, so that the material selection can be brought further to a final material selection well-fitting to the detailed product design and production process specification developed simultaneously.

Through this method, when completing phase M3 in the methodology from section 4 and thereby reaching the upward system integration wing of the product development V-model, it is assured, that material selection has been done closely interlinked with product and contemporaneously production design – systematically along all maturation steps of the development process.

6. Discussion and Conclusion

With the material selection method from section 5 the presented approach offers support for material decisions that take the relevant product, production process and material aspects into account in a truly integrated way.

The approach integrates this method into an overall material-oriented development methodology, see section 4, which supports the handling of material information as well as material-related decisions for both components and component-spanning joints from the early conceptual development phase till the final detailing of the product and the respective production system. Especially joints play a key and even further growing role in multi-material product designs and the respective production processes, what is getting the standard with respect to further increasing lightweight and efficiency targets.

Compared with existing approaches as described, e. g. in section 3, the concept presented here stands out especially regarding the integrated view on product, production process and material information and decisions. The application on material selection shows the power of the underlying PPE integration framework presented earlier by the authors, see section 2.

The development of both the proposed methodology and the developed method is however still ongoing. The material-oriented development methodology with its special focus on joints will be elaborated on in further detail in follow-up work, e. g. [15]. The material selection method which in the frame of this contribution could only be presented on a more conceptual level will be further detailed on a concrete example and supported by a software prototype covering the matrix of the PPE integration framework.

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