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Procedia CIRP 109 (2022) 520–525

www.elsevier.com/locate/procedia

32nd CIRP Design Conference

SyProLei – A systematic product development process to exploit lightweight potentials while considering costs and CO2 emissions

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Abstract

In lightweight design, developers are used to face the conflicting objectives of functional fulfillment, economic performance, and sustainability. Against this background, however, a clearly structured approach for the satisfied use of specific lightweight engineering methods within the product development is still missing. Thus, this contribution deals with the fundamental conception and first implementation of a systematic development methodology covering the disciplines of mechanics, electrics/electronics and software just like the focus on an integrated view on product, production and material aspects. To ensure an application-specific manifestation of the product development process for three exemplary use cases from small and medium-sized enterprises but also large corporations in the area of prosthetics, bike construction and plant engineering, the individually developed methods and tools are first generalized in order to make them adaptable to a wide variety of industries. As a result, one lightweight-specific method or tool (e.g., function mass analysis, "PPM solution correlator" or "2D layout & weight drafting") is introduced in more detail for all stages of the technically extended RFL(T)P approach derived from model-based systems engineering (MBSE).

Keywords: lightweight design; product development process; engineering methods; system engineering

1. Introduction and Motivation

Lightweight design is often seen as one of the key technologies and essential drivers of resource and energy efficiency. A prime example is the intelligent material selection and/or the topological optimization to reduce or minimize the moving mass of assemblies (e.g., not only for mobility solutions, but also consumer products as well as mechanical, plant and apparatus engineering), which particularly ensure a decreased cycle time by improved machine dynamics (or ergonomics) as well as a lower energy consumption in normal operation [1]. However, lightweighting is often only compared with the conflict regarding primary cost and energy expenditures within the material extraction and manufacturing production phase of the product life cycle.

To ensure an overall system-efficient lightweight design, a systematic product development process is needed to guide the engineer throughout the individual development phases by using specific methods and tools addressing an integrated and multi-criteria optimization of product, production, and material. For this reason, the research project "SyProLei" was funded to set up a digital systematic lightweight development framework based on model-based systems engineering (MBSE). After presenting the actual state of the art (section 2)

10.1016/j.procir.2022.05.288

and introducing the new systemic lightweight development process (section 3), section 4 applies selected lightweight-specific methods to the collaborating companies in the field of of prosthetics, bicycles and plant engineering. By giving a discussion and outlook in the end (section 5), the presented approach is critically being reviewed.

2. State of the Art in Literature

Starting with the fundamentals of product design, almost all systematic development processes are based on various perspectives and basic models (e.g., VDI 2221, VDI 2206, or INCOSE Systems Engineering). Although new procedures more and more integrate agile frameworks like LeSS, SAFe or Nexus, the majority of the many approaches, however, still do not aim at an early integrated selection of product, production and material. But exactly this is absolutely necessary in the context of a systemic lightweight design.

Against this background, and apart from the even larger number of specific lightweight methods usually applied on component level to achieve different optimization goals, there are only some approaches explicitly covering the topic of a methodological lightweight development process. Two of these are the approaches by Klein [2] and Krause [3] that basically follow the four phases of product development (task clarification, conceptual, embodiment and detail design) but additionally integrate specific lightweight expertise along with the individual steps of the procedure. Moreover, and compared to their predecessors, Ellenrieder et al. [4] consider an instant separation of component and system level collaterally allocating concrete lightweight design strategies inside their tactical lightweight design phase. Combined with different lightweight design techniques and the traditional use of design catalogs, the multifarious selection of best solution principles (e.g., by multiple assessment criteria) or even whole solution combinations (e.g., by morphological chart) is facilitated regarding individual functions. Striving for the inherent inclusion of component design, material as well as manufacturing and process selection already at the beginning of the evaluation of solution principles, Hufenbach's and Helms' interactive approach to the design of lightweight FRP structures [5] only lacks of a multi-criteria decision-making as well as a further systemic way of thinking.

Nevertheless, in industry and the ever-increasing model-based engineering the V-model plays a key role and gains in importance, despite its mainly only outwardly appearing waterfall-like process flow. Here, the system view (starting from system analysis to its detailing and system integration) is emphasized particularly to enable a continuous traceability, for example, regarding a change request needed to be verified and validated throughout the whole system design. Accordingly, these advantages regarding a simultaneous division into system, subsystem and component level as well as the representation of different domain and/or discipline-specific aspects per development stage should also be used for the following introduction of the systematic lightweight product development process as a first part of the overall "SyProLei" vision.

3. Systematic Lightweight Product Development Process

Based on the aforementioned deficits identified in the state of the art, the following section presents a systematic lightweight development methodology extending the focus of Kaspar et al. [6, 7] concerning an integrated and multi-criteria optimization of product, production, and material. No longer primarily focused on mechanically driven products, the developed process model for efficient lightweighting additionally covers the disciplines of electrics/electronics as well as control logic/software. Thus, and in addition to the renewed view on the mechanical, electric and software elements of the product, the affiliated domains of material and production (including manufacturing and joining) are explicitly highlighted across all development stages, see Fig. 1.

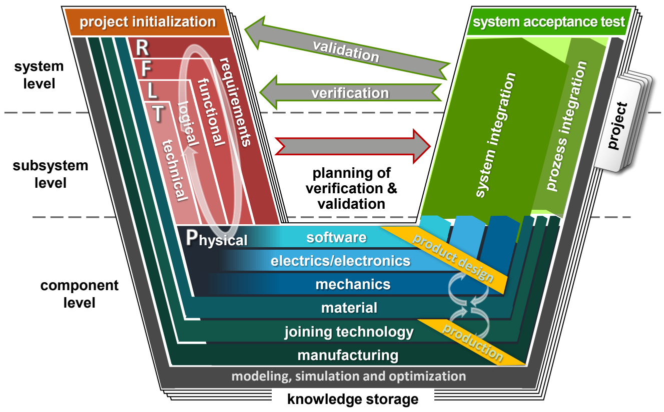

Fig. 1. Systematic lightweight product development process [8]

Originating from the product initialization and system analysis with its first definition of technical, economic and ecological targets (e.g., permissible and industry-related lightweight costs), the procedure basically follows the scheme of the V-model [9] with an increasing level of detail from top to bottom. In doing so, the RFLP approach derived from model-based systems engineering is used to develop a consistently traceable model across all different views (requirements "R", functional "F", logical "L" and physical "P"), first for the system decomposition into individual components and second for their gradual integration back to subsystems and the final technical system facing the aspects of verification and validation (V&V). Although this approach is well established, an intermediate technical view ("T") is added between "L" and "P" to enable a smooth and more comprehensively accompanied elaboration of complex products with less intermediate uncertainties in decision-making on the basis of multidisciplinary modeling methods.

Depending on an initial stakeholder analysis as well as recorded use cases and use case scenarios leading to the definition of the lightweight-oriented target system, the influences between the individual disciplines (mechanic, electric/electronic and software) and domains (product, production and material) can already be identified at the early stage of the categorized elicitation of interrelated requirements ("R") being steadily added, adjusted or removed throughout the product development process. For example, a renewed customer request of having an individually adjustable drive comfort also for amphibious journeys would call for an electronically controlled spring-damping system, which set up not only specific material requirements (e.g., full corrosion resistance) to fulfill the changed environmental conditions, but also necessitates a different design with, amongst others, material-dependently manufacturable wall thicknesses in terms of changed maximum forces.

Afterwards, the determined requirements represent the baseline of the functional view ("F") comprising the preparation of the functional structure and its inner (white box) and outer (black box) elements. The development of the functional modeling strategically guiding later design activities basically uses the standardized set of function-related terminologies as listed in [10], although the formally evolved function representation is slightly refined to systematically pursue a minimal functional design for lightweight optimization. By using various methods (e.g., functional mass analysis [11, 12]), the effects of the individual functions on weight, costs and ecological aspects can be determined, which helps to reconsider the subsequent choice of weight and cost-intensive operation principles per function and also to adapt the structure in terms of a potential functional integration. Having already addressed the operation principles or rather the principle solutions ("L") of a respective function, the logical element does not have any physical properties at this point, but first manufacturing and joining processes as well as material families are to be excluded based on the previously stated boundary conditions and empirical knowledge in order to limit the hitherto widened solution space. Thus, in the example of compensating vehicle movements to provide an adequate drive comfort for passengers the function can primarily be addressed by a mass-spring-damper system and an anti-roll bar as individual components of a specifically selected wheel suspension principle, see Fig. 2.

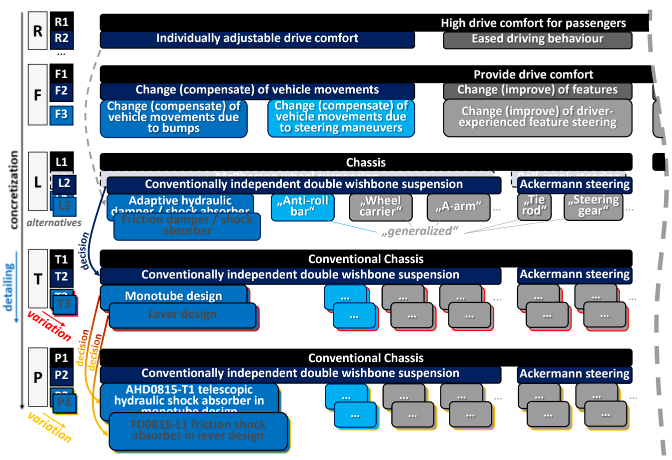

Fig. 2. Successive detailing process for the R, F, L, T and P view

As a result of several industrial observations with regard to an unusual big and after all not systematically supported development leap between "L" and "P", the technical view ("T") supplements the logical element by first physical properties as well as generalized design proposals based on the determined installation space as well as fundamental thoughts on bearings and operating forces, and thus comes up with different technical concepts. In the example of the focused mass-spring-damper system, a hydraulic shock absorber in a monotube or double-tube design or a friction damper in a lever or monotube design is available for selection.

Subdividing the steadily concretized procedure from "R" to "P" into different abstraction layers according to the SPES methodology [13], here at the "L2" layer and its subsystem view an evaluated decision is made regarding which alternative will exclusively be considered at the subsequent "T2" layer. For the decision at the "L2" layer, all refined options of the underlying abstraction layer of "L3" are included based on their technical, economic and ecological capabilities. The same procedure will then be continued at the "T3" layer and its inclusion of "T4" variants providing a fundamental decision-making for the followed-up observations at the final physical view. More details of this enhanced methodology will be given in an upcoming contribution decidedly coving the newly introduced "T" view.

Against this background of applying a first profound and target-oriented multi-criteria decision-making on different variations of technical concepts provisionally leading to a reduced amount of detailed considerations right at the start of the physical system design, in the "P" view the draft undergoes a specific detailing in the three disciplines of structural mechanics, electric/electronic and software. Owing to the detailed preselection at the "T" view, this concretization can notably focus on the material, manufacturing and joining specification, which mostly leads to a valued time and thus also cost reduction in the product development process. In doing so, a detailed design, material type and manufacturing as well as joining process is the output, whereby a permanent use of different modeling, simulation and optimization approaches (e.g., mathematical modeling of material composites, FEA, and topology optimization) guide the complete development process. This corresponds to the (model-based) systems engineering idea in which the development results are repeatedly mapped in mutually linked models, so that a continuous optimization in several iterations leads to a traceable, efficient and systematic product development.

As a result, the systematic lightweight product development process is concluded with a system and process integration. Here, on the one hand, the functionalities of the individual systems get repeatedly checked as a whole (by system tests and system integration tests (viz. fault conditions in the interfaces and in the interaction between integrated components) [14, 15]) based on the initially planned V&V criteria. As extension to the conventionally product-centered view (mechanic, electric and software) on V&V, the processability and complications along with the material selection are specifically traced and evaluated. On the other hand, the results are analyzed in order to detect potential possibilities for further projects and to incorporate this as empirical knowledge into the follow-up projects (e.g., findings from energy-based simulations of specific production plant designs).

Instead of having just a lot of tacit know-how being not always available in the right place or time within an organization, exactly this collection and provision of knowledge built up over many projects and years is identified as a key factor for a systemic lightweight design due to the manifold correlations to all the aforementioned aspects in each domain of the mentioned disciplines. This includes, for example, information retrieved from a design, material and production database, which not only needs to be accessible in the specific phase of the tool chain, but also can be stored in a structured manner enabling a steadily improved knowledge space for the future development of lightweight systems.

Having already addressed the underlying topic of a preferably consistent tool chain consisting of existing software as well as new lightweight-specific solutions, the following methods and their software environment are suggested to be considered for a systemic lightweight design, see Fig. 3. To ensure consistent data formats to avoid common data discontinuities between each stage, the "SyProLei" project pursues an adequate linking of the requirements management system, the system modeling and the CAx and simulation software as well as common production planning programs.

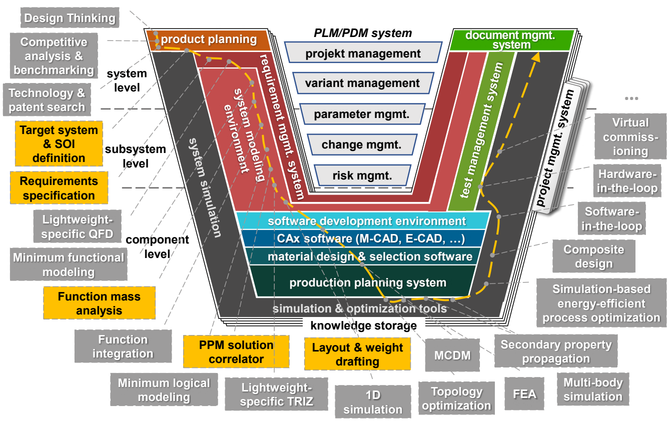

Fig. 3. Methods and tool environment of the "SyProLei" framework

4. Methods Used within the "SyProLei" Framework

Covering some examples of the comprehensively listed methods and tools from Fig. 3, this section presents one selected method (already highlighted in yellow) per previously discussed viewpoint. In doing so, the individual topics will first be theoretically discussed and then applied to one of the three case studies of the "SyProLei" project (lightweight portal robot with more energy-efficient drives, lightweight prosthetic leg providing an increased sense of mobility, or lightweight bicycle trailer encouraging the use of bicycles for private activities) to immediately support the practical understanding and showing the universal applicability in various industries.

Beginning with the product initialization, here the definition of the target system as well as the present system of interest (SOI) needed to be optimized (e.g., regarding an improved stiffness, decrease of CO2 emissions or increase of usability) is focused first due to the strictly limited, but mostly very time-consuming optimization process. In the presented approach the target system is defined in an interactive process which is guided with a multiple compartment template starting to record the boundary conditions as well as the strategic product orientation (e.g., planned lot size and industrial sector). Afterwards the main project requirements in general (e.g., evaluation of new concepts) and with regard to lightweight design are formulated, which derives the even later being relevant target values also concerning the performance-driven information on permitted additional costs per saved kilogram. Giving a clear advice which goals has to be achieved in each of the four domains of product, material and manufacturing as well as joining, the systematically guided description of the SOI defines the scope of the considered system components (i.e., system context) as well as the parts of the supply chain being integrated, for example, in the life cycle costing analysis. For the use case of a lightweight bicycle trailer, Fig. 4 exemplarily shows an excerpt of target values (e.g., max. weight of 17 kg, total costs up to 400 €, given DIY repairability, short development time of max. 0.5 years) inside the stated SOI, which are further specified with efficiency values like product mass per payload or raw material volume per product volume for an improved evaluation basis.

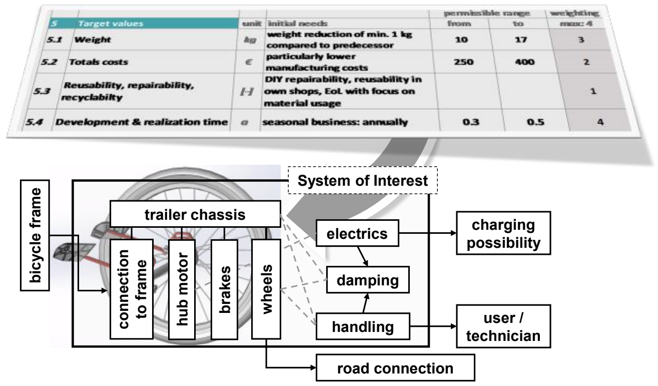

Fig. 4. Excerpt of target system and SOI definition (example: bicycle trailer)

Having set this frame, the requirements can be recorded and classified according to the individual stakeholders and use case scenarios. Divided into demands and wishes to basically display the responsibility for reaching the weight, cost or performance goals for the target system, the rubrics of relevancies (e.g., regarding lightweight design) are added into the modified requirements list to state a first hint how high each functional or non-functional requirement contributes to each aspect. As shown in Fig. 3, the requirements cover the whole process initiating the iterative extension towards a clear allocation of the requirements to the design, production and material domain after the definition of the functional, logical and technical elements has been done. This information is used to have a considerably improved selection of the best logical and technical concepts based on a full traceability to the original requirements.

Table 1. Excerpt from requirements classification (example: bicycle trailer)

stake-holder	use case	description	prioriti-zation	LW design relevance	Mat
user	driving	dosed braking must be possible	must	high	✗
user	driving	stable connection to the bicycle	must	high	✓
user	assembly	final assembly must be possible for the customer	must	middle	(✓)
certifi-cation	driving	max. weight of entire system 60 kg	must	high	✓
market-ing	buying	stable appearance of the system	should	high	✓

In case of the lightweight bicycle trailer in Table 1, three stakeholders are exemplarily listed having an intended use (e.g., the functional requirement of a dosed braking and a stable connection to the bicycle when driving on a flat street). While progressing the development process every functional requirement is translated into adequate functions and so-called verification criteria containing precise information for the persistent pursuance of V&V on the right side of the V model.

Based on this already initiated shift to the functional view, the Extended Target Weighing Approach of Albers et al. [12] is used to identify lightweight potentials regarding the target values of mass, costs and CO2 emissions on functional level. To perform the extended function mass analysis, the method follows upon the requirements specification and the derivation of hierarchically ordered product functions. With view to the target values, the relative weights, costs and CO2 emissions for every product function can first be identified from the percentual requirement fulfillment of each function by using an elaborated template. Subsequently, the functions are compared in a pairwise scheme within the SOI to determine their relevance for the overall product function. From the system perspective the functions are then gradually mapped against the assembled components yielding in a quantified relation of the product function to the components, also thanks to an interim "T" view. Finally, the relative mass, costs and CO2 emissions are plotted in a bar chart for each product function considering the determined order of the functional importance from the least important functions to the highest. A regression line based on the relative importance of each function covers an estimation of the function-dependent lightweight potential.

In the example of a gripper within the system context of a portal robot the product functions with the highest lightweight and environmental optimization potential are those where the bar of mass and CO2 emissions are above the regression line and the costs are below, see Fig. 5. Consequently, the method provides no absolute values but merely represents a recommendation for further design optimizations. Thus, the product function "transmit holding force" has a lightweight potential in terms of mass, whereby additional costs can be tolerated, just like slight increases of CO2 emissions.

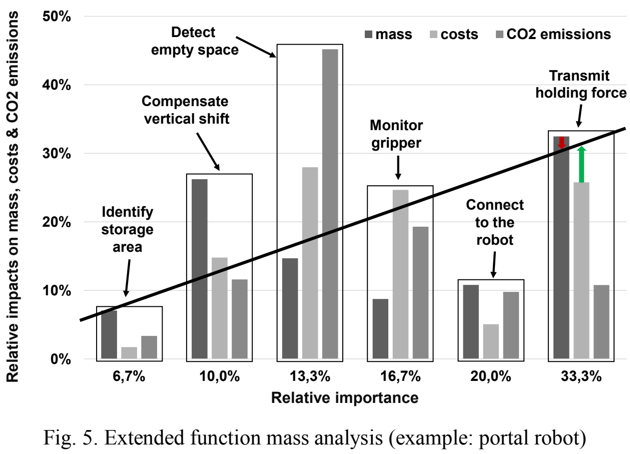

Fig. 5. Extended function mass analysis (example: portal robot)

Having that functional optimization issue in mind and moving further in the product development process, the logical view bears the potential to analysis first correlations between the domains of design, material and production, even though in the early phases the information for the material and process selection is very vague but still useful to create new solution concepts for an efficient lightweight design. Thus, the newly presented method of the "product-production-material (PPM) solution correlator" builds up on a knowledge-based approach to connect standardized, preferably solution-neutral functions to first principle solutions by considering typical technical realizations (best practices) from past reference products or other industries. Lastly having associated specific requirements to individual functions, generally required material and process properties are derived in such a way as to enable first material classes (referenced to the principle solution) and process families (referenced to the underlying knowledge-based technical realizations). Merged to a mass, cost and CO2 emission weighted selection of individually best material-process combinations per requirement, the usually product-driven engineering mindset is directly supported with information about the other domains and their potential impact to product design. In doing so, Table 2 exemplarily displays the consequences for the material and process selection for the previously addressed function to transmit holding forces and its assigned requirements, which can also lead to certain contradictions calling for a certain prioritization.

Table 2. Excerpt from PPM solution correlator (example: portal robot)

Requirement	Design function	Solution principle	Technical realization	Reference product	
no damage to handling object	transmit holding forces	form-fitted gripping jaw	bionic gripper	Festo trunk gripper	..
		force-locking gripping jaw	parallel gripper	FIPA 2-finger parallel gripper	..
holding force of 30 N		…	…	…	

	Material properties	Favorite material	Process function	Favorite process	PPM
..	low hardness	polymers > metals	3D forming	3D printing > injection molding	1) polymer 3D printing 2) …
..			hollow structure forming	extrusion	1) thermoplastic extrusion 2) …
	…	…	…	…	…

After limiting the preselection of PPM options by means of a specific multi-criteria decision-making approach (see Kaspar et al. [16]), the technical view covers, amongst others, an internally developed "2D layout and weight drafting" method. Acknowledging the importance of quick sketches and drafts in product development, the digital sketch tool does not just support a simple concept shaping, but also ensures a systematic variation of its individual component arrangement by evaluating the underlying physical information such as weight and loads for a rough calculation of the center of gravity and the moment of inertia. In addition, interconnections needed for a material, energy and/or signal flow can decidedly be modeled, and thus the system layout can be optimized concerning their length (i.e., additional weight by pipes and wiring) and the potential rethinking of a consolidation of technical elements (e.g., central power supply or decentral battery units). Consequently, the engineers are empowered to compile design comparisons prior to a direct modeling in CAD usually calling for a more detailed expert knowledge and a costly and, in this way, often limited availability of specific software licenses in industry.

As a result of this early evaluation of lightweight potentials, Fig. 6 shows an example of the analysis of moving masses preferably placing heavy components like energy storage in the close surrounding of the clamping (shaft connection) or near the rotation axis of the prosthetic leg. Leading to different, mostly improved moments of inertia, the resulting lower acceleration forces necessitate a just smaller dimensioned activator, lighter bearing and supporting structure thanks to secondary effects which ensure a lower energy consumption and higher wearing comfort during operation in return.

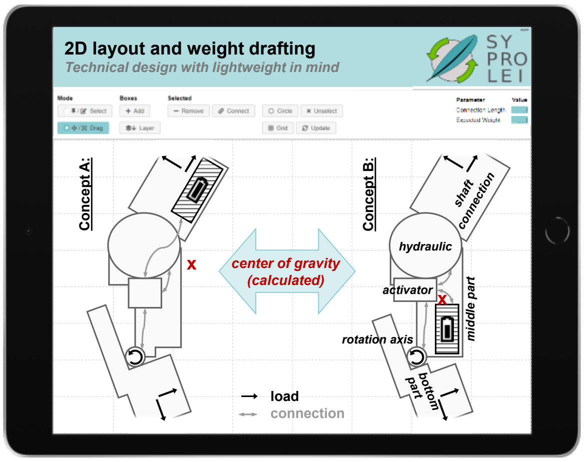

Fig. 6. Technical concept comparison by the 2D layout and weight drafting method (example: prosthesis of lower extremity)

With the idea of an even deeper potential analysis of secondary effects and their derived suggestions on a technically, economically and ecologically ideal system design (see Kaspar's et al. secondary property change propagation approach in [17]), the model-based fundamentals primarily addressed here are concluded leading to the domain-specific detailing in the physical view before progressing to the subsequent stages of a component simulation and testing, a system integration, verification and validation as well as a system qualification, as described in section 3.

5. Discussion and Outlook

Having stated the needs for a revised lightweight design methodology, first a systematic lightweight product development process was presented followed by individual methods to basically support the systems engineer's decisions in the early phases of development. Using digital tools throughout the whole development process, an interconnected and continuous tool chain including a smooth and consistent data exchange without any media discontinuity is guaranteed in future. This allows a more indispensable traceability of various types of change propagation at any time even with view to predictive maintenance. Given the fact that a totally digital and synchronized application of the introduced methods is still missing, a next step is the actual implementation within a joint ALM-PLM collaboration system (e.g., Teamcenter). Besides this fully targeted digital process chain with a certain neutrality of the data formats, the central build of an extensive knowledge store based on previous or similar projects delivers empirical values and experiences for the product, production and material domain being used for both detailed recommendations or conceptual proposals. This could anticipate risk and cost concerns, a lack of specialists and organizational issues that have the highest negative impact on innovation. In the end, however, a holistic evaluation method for an early multi-criteria optimization throughout the whole product life cycle need to be further elaborated for a sustainable lightweighting.

Acknowledgements

The authors thank the "Technologietransfer-Programm Leichtbau (TTP LB)" of the Federal Ministry for Economic Affairs and Climate Action (BMWK) for supporting their research within their project "SyProLei" (03LB2007H).

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