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Lightweight design of a gripping system using a holistic systematic development process - A case study

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Abstract

Lightweight design is a key driver for resource and energy efficiency and thus essential on the road to climate neutrality. A systematic and holistic development process can significantly leverage the potential of lightweight design in industries like machinery and plant engineering. This paper describes the application of a novel systematic lightweight design process for the development of a gripping system, considering design, material and manufacturing. Based on the state of the art in gripping system development, the novel systematic lightweight development process is applied to the case study of a gripping system.

Keywords: Lightweight design; Model-based systems engineering; Product development; Gripping system; Case study

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1. Introduction and motivation

Lightweight design and the associated goal of weight reduction have always been a motivation for researchers and engineers. Common use cases are to make several means of transport more efficient and faster, to improve the handling of products and to permit new designs. Apart from further application-specific utilization benefits, functional improvements and enhancements, however, advantages and thus reasons to develop and use lightweight solutions can also be of an economic, ecological, political or social nature. On the other hand lightweight design often requires changes in manufacturing strategies and leads to a conflict in decision making [1].

In the field of plant engineering for example the handling process is non-productive but often necessary. Reducing the weight of a gripping system by 10 % the annual energy consumption of a robot could be reduced by around 1.4 %, without effects of the potential use of a weaker robot [2]. A reason is that even the general elaboration of lightweight advantages is limited due to a lack of knowledge or evaluation methods in lightweight design.

To deal with all these aspects in future, the research project "SyProLei" is funded setting up a digital systematic lightweight development framework based on model-based systems engineering (MBSE). Focusing on an integrated and multi-criteria optimization of material production, manufacturing and the product usage, the recently elaborated lightweight product development process will now be practically applied to the aforementioned industrial sector of plant engineering. After presenting the actual state of the art in the development of gripping systems (section 2) and shortly recapitulating the procedure of the novel lightweight design approach (section 3), all theoretically described methods and tools are continuously

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performed to develop a weight-reduced gripping system with accepted additional costs and CO2 emission (section 4). By giving a discussion (section 5), the presented approach is critically being reviewed against its first end-to-end practice.

2. State of the art – gripping system development

Since the rise of automatization in the 1990s, the importance of gripper selection and design increases. As described in [2] the weight of the gripping system has an impact on the energy-efficiency of the handling system, which consists of the gripping system, a handling device and additional periphery elements. The structure of a gripping system itself consists of the gripping unit, the active elements and the adapter flange [3]. As the part directly in contact with the handling object the gripping unit has high impact on the quality of the grasp. Thus, several methods have been developed to assist engineers in the selection of gripping units and the design of their elements.

Pham and Yeo [4] defined five main factors which impacts the gripper selection. The handling object represents the constraints regarding geometry, weight, material, surface quality and temperature. The task describes the performance requirements on the gripper and has a high impact on the needed gripping force. The environment impacts the selection with the temperature and humidity. The compatibility of the interfaces of handling device and gripper could lead to additional adapter plates. Additionally, the load capacity of handling device limits the permissible weight of the gripping unit. In [5] a learning expert system is presented using a two-step selection method. Based on user inputs regarding part, environment and process, first a feasible working principle is selected. In a second step an existing solution with the chosen working principle is selected from a database. Despite this systematic procedure lightweight specific evaluation parameters still missed.

Agrawal et al. [6] classify grippers by their working principle, gripping force and weight. The classification serves as a basis for a requirements-based selection with the help of a multi-criteria optimization algorithm.

Consequently, the common approaches do not mention needed adjustments of the grippers to the specific tasks [7]. In addition, the methods support the selection of existing grippers and do not support the development of innovative, lighter grippers. In [8] a systematic development approach for light grippers for textile handling is presented. Based on the CAD-Model of the textile and force and part deflection simulation the needed amount and configuration of the vacuum grippers is calculated. This results in gripping systems adapted to the application. The focus here is on the pneumatically gripping units and mechanical ones are not mentioned. In [9] a similar model-based approach is presented to reduce the safety factors in gripping system development by using more accurate gripping process models. Through the reduced requirements lighter gripping systems are developed.

To sum up, an approach supporting the engineer in designing a lightweight design gripping system is missing over the whole process and considering the effects on other parts of the handling system. As a result, the focus is often on costs and the benefits of lightweight construction are recognized.

3. Novel systematic lightweight design approach

Based on the aforementioned state of the art, the methodological development of gripping systems calls for a procedure to systematically develop technically, economic and ecological efficient solutions. Primarily aiming on a weight-optimized gripping system, Fig. 1 highlights the baseline of the recently developed systematic lightweight product development process. Concerning an integrated and multi-criteria optimization, not only the mechanical aspects regarding product design, production, and material but also the disciplines of electrics/electronics as well as software are equally covered within the decision-making.

Originating from the product initialization and system analysis with a first definition of technical, economic and ecological targets, the procedure basically follows the scheme of the well-known V-model [9] with an increasing level of detail from top to bottom. In doing so, an extended RFL(T)P approach derived from MBSE is used to develop a consistently traceable model across all different views (requirements “R”, functional “F”, logical “L”, technical “T” and physical “P”). With this approach the engineer is supported firstly in decomposing a system into individual components and secondly in integrating them gradually back to the individual subsystems and the final system facing all the aspects of verification and validation (V&V) [10].

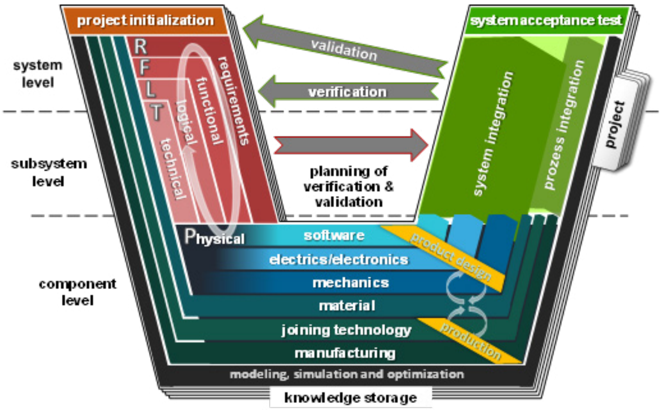


Fig. 1. Systematic lightweight product development process [11].

In terms of the early phases of product development and the application of MBSE, the presented approach takes the advantage of the guided procedure of ARCADIA (Architecture Analysis & Design Integrated Approach) [12] to identify and verify the architecture of complex systems. Here, the MBSE method for systems, hardware and software architectural design builds up on a sequential view on an operational analysis, the functional and non-functional need as well as the logical and physical architecture, see Fig. 2.

The operational analysis of ARCADIA can be aligned with the “F” view of the presented approach. In the example of the successively pursed gripping system, the capability of the handling system could be the transport of an object. This can be divided into the subjected functional needs, for example, hold object and move object. Based on these needs, the logical components are defined (e.g. gripping system, industrial robot).

Subsequently, the functional needs get refined and the resulting needs due to the selected principle are described. Thus, different viewpoints can be highlighted in term of mass, costs or sustainability. Finally, the physical architecture describes the system in full detail, which is further evolved by CAx-models.

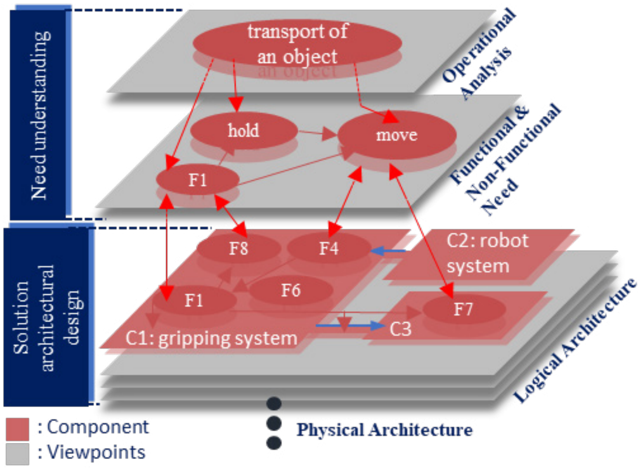


Fig. 2. Schematic example of the ARCADIA Methodology according to [12].

4. Application of systematic lightweight design approach

4.1. Description of the use case

The case study in this paper is the development of a gripping system. The handling system including the gripping system transports heavy, large tools. This requires high forces and large gripping systems. The focus on known solutions and importance of the safety leads to a heavy solution. This results in handling system with high energy consumption as well as a high material usage in the system components due to high loads. With an optimized gripping system this could be reduced but the more expensive lighter solution is often not compared with their potential for a more efficient system.

4.2. Project initialization

As shown in Fig. 3, the product development starts with the definition of the system of interest (SOI) as part of the project initialization, and serves to focus the development task more precisely so that of specific development goals in the target system for a narrowed system.

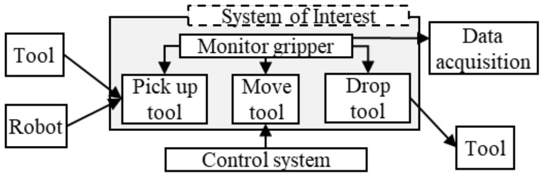
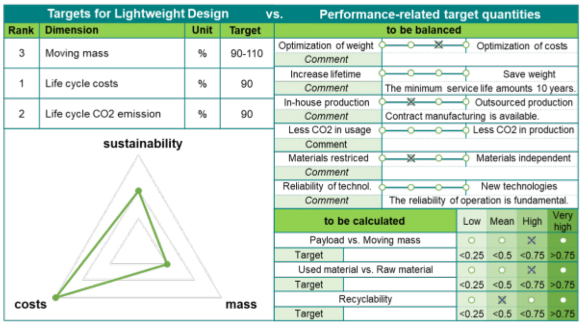


Fig. 3. Excerpt of the system of interest (SOI) for a gripping system.

Within the “SyProLei” framework, the target system contains specific objectives for the dimensions of lightweight design, costs and sustainability and are instantly verified by the admission of performance-related variables, so that the integrity of the product development is improved and all boundary conditions as well as the strategic product orientation are gathered in a single document, see Fig. 4.



Targets for Lightweight Design vs. Performance-related target quantities

Rank	Dimension	Unit	Target
3	Moving mass	%	90-110
1	Life cycle costs	%	90
2	Life cycle CO2 emission	%	90

to be balanced		
Optimization of weight	○—○—✕—○	Optimization of costs
Comment		
Increase lifetime	○—○—○—○	Save weight
Comment	The minimum service life amounts 10 years.	
In-house production	○—✕—○—○	Outsourced production
Comment	Contract manufacturing is available.	
Less CO2 in usage	○—○—○—○	Less CO2 in production
Comment		
Materials restriced	○—✕—○—○	Materials independent
Comment		
Reliability of technol.	○—○—○—○	New technologies
Comment	The reliability of operation is fundamental.	

to be calculated		Low	Mean	High	Very high
Payload vs. Moving mass		○	○	✕	●
Target		<0.25	<0.5	<0.75	>0.75
Used material vs. Raw material		○	○	✕	●
Target		<0.25	<0.5	<0.75	>0.75
Recyclability		○	✕	○	●
Target		<0.25	<0.5	<0.75	>0.75

Fig. 4. Excerpt of the lightweight target system for a gripping system.

4.3. Requirements engineering

After defining the SOI and setting the boundaries for the development in the target system the initial requirements the gripping system need to be defined. For this purpose, a classification of the requirements was developed as already shown in [11].

To support the requirements engineering use case specific for gripping system, a questionnaire was developed. With the questionnaire the engineer is forced to set sharp values for the selection of designs later in the process and the focus is set on the relevant ones. The initial non-functional requirements and the mentioned classification are shown in Table 1. Additionally, the requirements are classified in functional and non-functional requirements.

Table 1. Non-functional requirements in the classification.

ID	stake-holder	use case	description	prioriti-zation	LW design relevance	Mat
1	user	handling	gripping on inside cylindrical surface or on plane phase	must	less	✗
2	user	handling	handling an object with 35 kg	must	high	✗
3	user	handling	maximum acceleration is 10 m/s^2	must	high	✗
4	user	handling	temperature resistant between 10°C and 40°C	must	middle	✓
5	user	handling	resistant against oil and dust	must	middle	✓
6	service	handling	lifetime up to 30.000 h with 60 handling operations	must	high	✓
7	user	handling	Hold object without energy	must	less	✗

In [13] the gripping system design process starts with the analysis of possible gripping positions. The surfaces are analyzed regarding their accessibility and assigned to the principles: magneto adhesive, pneumatic or mechanical. Magneto adhesive and pneumatically gripping principles require plane surfaces which can be accessed from the top.

Mechanical gripping principles require at least two parallel surfaces or a cylindrical object geometry. An evaluation of the surfaces regarding lightweight design potential is not done yet but could be interesting in the future.

The shown requirements and their classification represent the starting point for the development process. Here, the prioritization and the assignment to stakeholders and use cases support the traceability. If a requirement needs to be discussed the relevant stakeholder can easily get identified.

The lightweight design relevance of the requirements gives a hint on requirements with high impact on the weight. In the use case especially the requirements effecting the gripping force and the lifetime of the gripper have a high impact. Due to longer lifetime or higher forces larger dimensions are needed leading to heavier solutions. Requirements allocated to materials need to be regarded in the selection of the material.

With going parallel through the other stages of the process the solution gets more detailed. The same happens with the requirements. After analyzing the functional requirements and identifying different working principles for a gripper like mechanical, pneumatic or magneto adhesive the needed gripping forces are calculated based on the requirements in Table 1. For a better understanding of the process and the critical cases a method was developed to model the handling process and calculating the forces needed. In [14] this is taken into account in a later stage of the development.

After identifying a suitable concept the requirements can be extended by production-related and additional material-related requirements to consider them from the beginning of the detailing phase.

4.4. Functional and logical design

After the requirements stage follows the functional design and afterwards the logical design. But as already described in section 3 and section 4.2 the process is not linear with a continual iteration loop between “R” and “T” view. The “F” and “L” view are described in one section because of the iteration between these two phases.

In the first iteration all as functional classified requirements are depicted in the functional structure. During “F” the gripping system is described as part of the whole handling system to support decision making later. Fig. 5 shows the functional and logical structure of the gripping system.

The functions are allocated to the logical elements in a different degree of detail for a mechanical gripping unit. Before the decision to use a mechanical principle the functional structures of pneumatic and magneto adhesive working principles also need to be modelled. The process between “F” and “L” is a zig-zagging between the views. In level 1 of “F” the functions of the system are described. In level 1 of “L” a logical component is selected which fulfills the functions. Afterwards in level 2 of “F” the functions are further detailed and a logical component is selected. As an example, a gripping unit as a complete system on level 3 fulfills the function "generate holding force". The functional structure of a pneumatic or magnetic working principle is easier but realizing the holding force without energy requires additional components. Therefore, the mechanical one is selected.

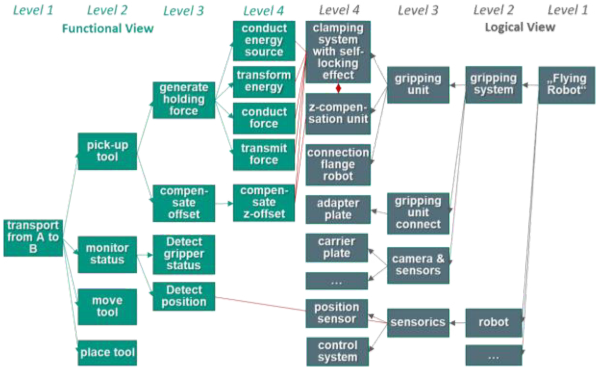


Fig. 5. Description of a handling system focused on the gripping system.

At the next level, the function “generate holding force" can be divided into the sub-functions "conduct energy", "convert energy", "conduct force" and "transfer force" and these sub-functions can in turn be assigned to logical components. This is followed by the selection of a solution for the functions of the mechanical gripping unit. The other functions are also further detailed but not visualized due to readability.

Currently a clamping system, which is actuated pneumatically, grasps the handling object on the inside and pulls it in a conus which is the counterpart to the conus at the handling object with a self-locking effect. From this follows the requirement of a force for detaching the handling object. Due to Newton’s Third Law of motion during detaching a force acts in the opposite direction. To avoid damage on the handling device a compensation of this force is needed, which leads to the function “compensate z-offset” and the allocated components. For analyzing the impact of the functions regarding mass, costs and CO2 emission the Extended Target Weighting Approach (ETWA) [15] can be used.

For this purpose, firstly, the relative importance of the identified sub-functions to fulfill the overall product function is estimated using a pairwise scheme. This is supported by the systematic approach which clearly shows the needed functions to fulfill the main function of the SOI and the functions are resulting from solutions.

Secondly, they are assigned to mass, costs and CO2 emissions as a sustainability indicator by allocating the components from the physical level to each sub-function. This allows the sub-functions to be plotted in a bar chart in increasing order of their importance from left to right, and at the same time their attributed relative fraction of the total product mass, costs and CO2 emissions to be charted above them. By adding the regression line with a slope based on the importance of the sub-functions, the sub-functions that have the highest optimization potential can be identified as those where the bar of mass, costs and CO2 emissions are above the line. The ETWA for the gripping system is shown in Fig. 6 and indicates the highest lightweight potential for the function "compensate z-offset".

If the “z-compensation unit” is removed, this results in a weight reduction of 12.3 kg compared with the existing architecture. Considering the target of 10 % less weight the new gripping unit is allowed to have a mass of 17.3 kg. Additionally, capacities of cost and sustainability can be shifted to other components.

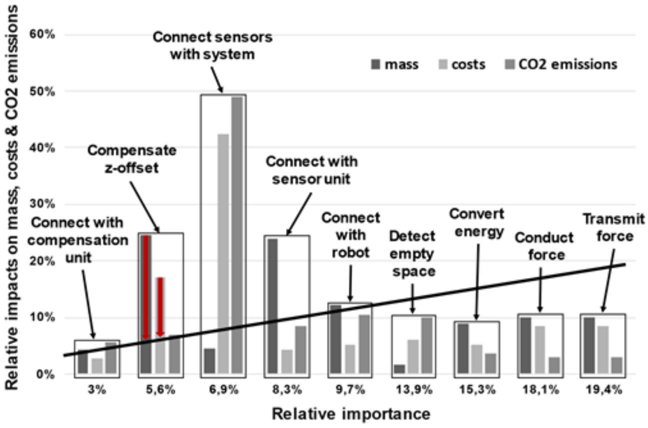


Fig. 6. Visualization of the results of the extended target weight approach.

To support the engineer in finding new technical solutions the method of the product-production-material-solution correlation method (PPM-solution correlator) was shortly presented in [11] and is shown here to specify the transmission from logical to technical design. As an example, the function “connect with robot” is used because the weight in the ETWA is a bit too high, but there is a potential for cost savings. The function has non-functional requirements assigned like temperature resistance, oil resistance and absorbing the forces. These are translated in material properties like specific stiffness, oil resistance and temperature resistance. The material classes ferrous-metals, non-ferrous metals, elastomer, plastic, ceramics, glasses, composites and natural materials are ranked regarding their suitability on the material properties and the evaluation factors cost, mass and CO2 emission. From previous development the requirement of manufacturing a 3D solid is known. The three best materials are selected and it is evaluated how they can be manufactured. The manufacturing processes are evaluated regarding mass, cost and CO2emissions, too.

The best manufacturing processes together with the assigned materials are given as an idea for further development. In the presented case it is mold casting of ferrous materials or non-ferrous materials. However, this is not a final process or material selection. Making the decision for a design concept requires further specification of the concepts.

4.5. Technical design

Based on this first elaboration of more detailed solution principles, the mutual influences within the previously discussed SOI as well as the overarching impacts on the whole plant system can additionally be analyzed and/or reviewed by a separate, matrix-based method called “secondary property change propagation” (SPCP) [16]. Using this managed monitoring of change propagation during the pre-development phase, all secondary effects regarding the primarily selected technical, economic and ecological aspects of the target system can easily be detected and compared owing to different possible primary changes on a specific subsystem in the system architecture. Ideally, this leads to reduced time for the subsequent detailed physical design process. 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, Fig. 7 investigates the two possible scenarios of the outlined gripper system and their effect to the whole system context to demonstrate the analytical capabilities of the method in a hands-on manner.

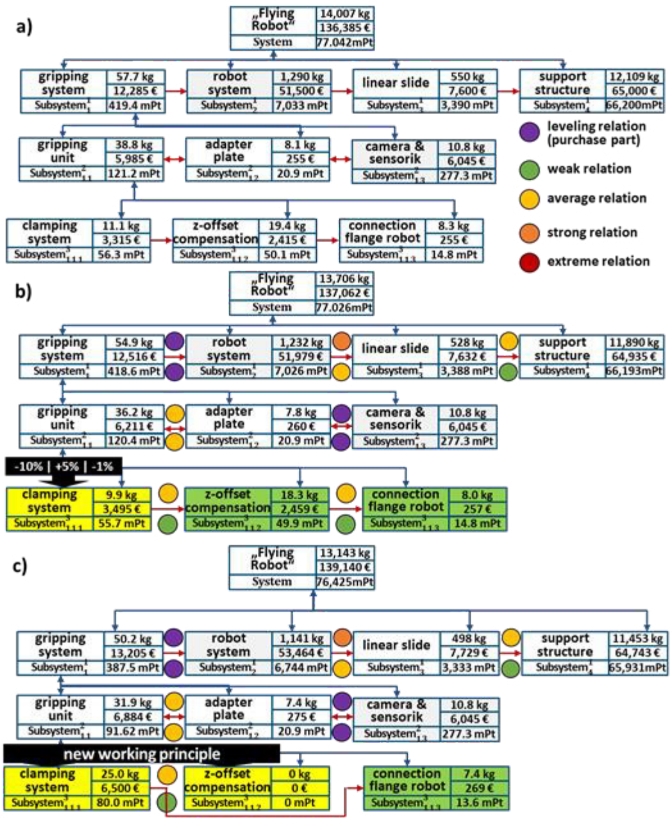


Fig. 7. SPCP method: (a) original system; (b) first option; (c) second option.

As shown in Fig. 7, the focus certainly is on the gripping system itself but changes here have further impacts on the overall system. Thus, option 1 comes up with a pure design improvement of the “clamping system” and its secondary effects on the “z-offset compensation” and the “connection flange robot” compared to option 2 with an actual change of the working principle and its complete elimination of a previously needed “z-offset compensation”. Originating from the primary change (yellow box) and its secondary effects to the directly coupled neighboring elements (green boxes) the summed-up changes in one system level lead to a similar procedure of property changes in the superior subsystem derived from analytically determined influence matrices. In the end, a nearly cost-neutral primary mass reduction of only 10 % in option 1 (secondary effects: -300 kg, +497 €) bears less overall lightweight potentials than option 2 (secondary effects: -863 kg, +1,985 €) due to the further mass savings by its no longer required “z-offset compensation”.

5. Discussion

The project initialization with the target system leads to a clear understanding of the targets of the development project and is the basis for every decision during the development process. The classification of requirements and the usage of a questionnaire to collect the requirements supports to get rid of historical grown requirements. Very important here is also the breakdown of the requirements to the functions and the logical, technical and physical components. After the identification of improvement potentials with the ETWA it is also possible to set production requirements to reduce the weight considering CO2 emissions and costs.

Through the systematic approach in the “F” view and the “L” view analyzing the functions and logical components on different levels of detail a deeper understanding of the product can be achieved and importance of functions can be identified very easily. To improve the decision making for working principles considering information like weight which is specified in later stages databases need to be created to analyze the concepts from different viewpoints. While the costs are easy to determine for an existing product it is difficult to determine the CO2 emissions. Furthermore, the database would support the engineer in building up the system while using standardized building blocks. The PPM-correlator gives ideas to improve weight, cost and sustainability. With the presented “secondary property change propagation” the impact of different measures on the whole system can be determined. But here also the quality of the data especially regarding the production need to be improved. This calls for possibilities to inherently select materials and production processes based on a multi-criteria decision-making method, see [17]. For that matter, the previously selected PPM solutions are analyzed in more detail, for example, to determine specific material types serving as a basis for the subsequent simulation environment of the physical detailing phase. In terms of the preferred gripping system made of ferrous or non-ferrous cast materials, EN-GJS-400-18LT exceeds all competitor regarding its performance in dynamic stress, low notch sensitivity and good elongation values.

6. Conclusion and Outlook

The paper has shown the development of a gripping system up to the technical design stage with a holistic systematic development process. It has been shown how the systematic approach can support in developing lighter products with acceptable cost and CO2 emissions. The generated description of the system in the “T” view need to be connected in a digital workflow with the physical layer where the components are finally detailed. Setting up the process in a development environment like “Siemens Teamcenter” enables the possibility to connect the different aspects. Still great potential is in the process and system integration. Especially, in the field of handling systems better simulation tools for V&V can lead to lighter products. Increasing the understanding of the impact of lightweight design on different lifecycle phases will support in bringing more expensive lightweight solutions to the market.

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