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Seamless Function-Oriented Mechanical System Architectures and Models

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Abstract: One major challenge of today's product development is to master the constantly increasing product complexity driven by the interactions between different disciplines, like mechanical, electrical and software engineering. An approach to master this complexity is function-oriented model-based systems engineering (MBSE). In order to guide the developer through the process of transferring requirements into a final product design, MBSE methods are essential. However, especially in mechanics, function-oriented product development is challenging, as functionality is largely determined by the physical effects that occur in the contacts of physical components. Currently, function-oriented MBSE methods enable either the modeling of contacts or of structures as part of physical components. To create seamless function-oriented mechanical system architectures, a holistic method for modeling contacts, structures and their dependencies is needed. Therefore, this paper presents an extension of the *motego* method to model structures, by which the seamless parametric modeling of function-oriented mechanical system architectures from requirements to the physical product is enabled.

Keywords: function-oriented; model-based systems engineering; product model; mechanical systems; modeling

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1. Introduction

The objective of product development is to translate the customer's expectations regarding the product's behavior and functions into a manufacturable product. Today, one of the key success factors for the competitiveness and innovative strength of a company lies in mastering this translation process, despite the continuously increasing level of product complexity [1–4]. This complexity is mainly driven by growing physical and logical interactions (especially on the product layer) due to the high integration of different disciplines of mechatronic products, like mechanical, electrical and software engineering [5–10]. Whereas software engineering realizes product functions by immaterial software code, mechanical components have to be developed and manufactured based on physical laws to achieve the desired physical product behavior [11]. In mechanics, the physical product behavior is mainly influenced by physical effects which occur in a contact area of two mechanical components [12–14]. Therefore, the design of the contact geometry and the choice of interacting materials are crucial factors in the development of mechanical subsystems.

Recent research in model-based systems engineering (MBSE) [15,16] has provided approaches to describe mechanical subsystems as part of complex mechatronic products, e.g., in [17–22]. The core idea of these approaches is the establishment of a discipline-neutral functional architecture that serves as a consistent basis for discipline-specific development methods [23]. For the function-oriented development of mechanical subsystems, the formalized modeling of contacts (e.g., the shaft and hub surface of a shaft–hub-connection) [5] and the virtual validation of functional requirements via the linking of domain models [24–26]

represent a decisive basis. As mechanical subsystems (e.g., the shaft and gear wheel) consist of contacts and their connecting structure, it is also necessary to test entire components. Furthermore, to manufacture the functionally developed components and to manage them within distribution, the product description up to the bill of materials (BoM) is required as well. Thus, the following five criteria are relevant to enable the seamless function-oriented modeling of mechanical system architectures:

1. Based on a function-oriented system architecture.
2. Linking domain models for function validation.
3. The formalized modeling of physical contacts.
4. The formalized modeling of physical structures.
5. The formalized modeling of relations between physical contacts and structures.

However, no current MBSE modeling method combines all five previously mentioned criteria (cf. Section 2). Therefore, the objective of this paper is an approach for the function-oriented modeling of mechanical system architectures. The paper is structured as follows: Section 2 provides an overview of current approaches to model system architectures, with a particular view of modeling contacts and structures. Subsequently, Section 4 is derived from the state of the art, and the research questions of this paper are defined. The main section presents a modeling method for the function-oriented modeling of mechanical system architectures, including the definition of the structure elements, the integration of domain models into the structure elements and the arranging of the components at the product level. Finally, Sections 6 and 7 conclude this paper. The developed modeling approach is illustrated by its application to the example of a centrifugal pump.

2. State of the Art

MBSE is the formalized application of modeling to support requirements in engineering as well as the development and validation of (technical) systems over the entire product lifecycle [27]. By creating an interdisciplinary system model as its key element, MBSE centrally manages all domain models and the information of product development and links them [27–30]. The system thus represents a formalized representation of the product [27–30]. To model system models, textual and graphical modeling languages are used. In many industries, the graphical general-purpose modeling languages Systems Modeling Language (SysML) of the Object Management Group, which is based on the Unified Modeling Language (UML), has become established [8,31,32]. For in-depth information about further languages, as well as the advanced language profiles being used, such as MODELICA and KARMA, and an overview of the development of the MBSE and its application in industrial practice, please refer to the survey papers [8,16,33].

In the following section, state-of-the-art approaches to model discipline-neutral system architectures are analyzed, with the focus on mechanical engineering. The approaches are analyzed with regard to the five criteria listed within the introduction. Therefore, the following five subsections each briefly explain the regarded criterion before the state-of-the-art approaches are analyzed subsequently.

2.1. Analyzed Criterion: Based on a Function-Oriented System Architecture

A promising approach to master the complexity of mechatronic products caused by interactions between mechanics, electrics and software is the function-oriented application of MBSE. In function-oriented product development, the function architecture is built as the central element that structures all interactions by the functional decomposition of the product [11]. Functions describe the product's behavior without specifying how the behavior is realized, which allows all technical disciplines to provide alternative technical solutions for the same function [5]. Therefore, a function's solution-neutrally defines the transformation of functional flows that enter and leave a function. Within design methodology, the differentiation of functional flows as energy, material or signal flows is established. However, among the current function-oriented methods to model MBSE system models, such as *Digital Function Modeling in DC43* [34], *FAS4M* [35], *Functional*

Product Description [2]/*mecpro*^{2} [36], *Integrated Product Model for Conceptual Design* [37], *MagicGrid* [38], the *motego* method [5], *OpenSE/OpenMBEE* [39] and *SYSMOD* [40], the modeling of functions, and especially the consideration of functional flows, differs:

- Usage of functional flows is not specified [34].
- Focus on the modeling of signal flows [38,39].
- The modeling of all three established functional flows (energy, material and signal) is provided [2,5,35–37,40].

In mechanical system architectures, as discussed in this paper, functions are realized through physical components and their interaction. These interactions are mainly described by the exchange of energy. Therefore, products in mechanical engineering cannot be modeled via methods that are limited to the consideration of signal flows.

2.2. Analyzed Criterion: Linking Domain Models of Product Development for Function Validation

An MBSE system model is a descriptive representation of a product to be developed. However, in order to develop the product in accordance to the requirements and to validate the fulfilment of the requirements, the behavior of the product needs to be described. For this description of the product behavior, domain models must be linked to the system model and connected to all parameters of the other constitutes of the system elements [5]. Domain models are simulation models which abstractly describe a particular real system and which are used to predict the physical behavior of a product [25]. By linking domain models to the system model, e.g., with the methods *MagicGrid* [38], *motego* [5] and *OpenSE/OpenMBEE* [39], MBSE enables the virtual validation of requirements as well as the identification of the optimal combination of technical solutions for the product concept. Several approaches to establish interfaces between MBSE system models and domain models have been developed. An overview of the exchange of parameters of SysML-based system models and domain models are provided by [41–43]. As examples, the approach according to [44] for the transformation of system models with *MODELICA* simulation models, and the approach according to [45] for the automatic generation of analysis models, are mentioned in [26]. A more detailed overview on the integration and coupling of simulation models is provided within [26], which also presents a model signature for the integration of simulation models into system models.

Depending on the product development phase, it is usually necessary to use domain models of different fidelity levels ("To which accuracy are the physical quantities calculated for the represented systems?") for the same purpose. To enable the simulation of the appropriate domain model, the modeling method has to allow the efficient exchange of domain models. The only approach that sufficiently fulfils those requirements is the modeling method for the integration of domain models in the *SolutionElements* of the *motego* method according to [25].

2.3. Analyzed Criterion: Formalized Modeling of Physical Contacts

Within mechanical engineering, the interaction between two components occurs via physical contact. The listed state-of-the-art modeling approaches can be divided into the following categories to describe the contacts:

- Description of physical contacts not explicitly considered [2,34–39,46–49].
- Description via a connector between single active surfaces of two different structures [40,47,50–52].
- Description through sketches [35,53].
- Description of single active surfaces and the energy flows between them [37].

Besides the ability to model the geometry of contacts, the modeling of its physical effects is essential for the description of the physical behavior and necessary for the model-based validation of mechanical system architectures. Only the approaches *FAS4M* and *System Sketcher* provide a method to model the physical effects occurring within contacts [35,53]. However, the active surfaces of contacts are not described parametrically,

but via sketches. Thus, the influence of the contact geometry on function fulfilment is not formalized and can therefore not be tested.

Among the methods shown in Table 1, only *FAS4M* and *motego* provide an approach to model contacts with their active surfaces and the occurring effects. In contrast to the SysML dependency generalization in *motego*, *FAS4M* uses the less formal SysML dependency trace to connect functions and contacts [35]. As a result, within the *FAS4M* approach, the functional flows energy, material and signal are not inherited by the contacts, and thus are not available for the design and testing of the contacts.

Table 1. Qualitative overview of the analyzed state-of-the-art approaches to model cross-discipline system architectures.

		Analyzed Criteria				
Approach	**References**	**Based on a Function-Oriented System Architecture**	**Linking to Domain Models of Product Dev. for Function Validation**	**Formalized Modeling of Physical Contacts**	**Formalized Modeling of Physical Structures**	**Formalized Modeling of Relations btw. Physical Contacts and Structures**
Functional Product Description/*mecpro*^{2}	[2,36]	◑	–	–	●	–
motego	[5]	●	●	●	–	–
Digital Function Modeling in DC43	[34]	◕	–	–	●	–
FAS4M and System Sketcher	[35,53]	◔	–	◑	◔	◑
Integrated Product Model for Conceptual Design	[37]	◑	–	◑	●	◑
MagicGrid	[38]	●	◕	–	●	–
Open SE/OpenMBEE	[39]	◔	●	–	●	–
SYSMOD	[40]	◑	–	◔	●	◑
Mechatronic Modeller	[46]	◔	–	–	◑	–
SPES	[47,49]	◔	–	–	●	–
STRATA	[48]	–	–	–	●	–
C&C^2–A	[50–52,54]	◔	◔	◔	●	◕

Explanation: – not considered; ◔ slightly considered; ◑ partly considered; ◕ largely considered; ● fully considered.

2.4. Analyzed Criterion: Formalized Modeling of Physical Structures

The design of mechanical subsystems not only contains interacting surfaces, but also a connecting structure of these surfaces with each other that is characterized by geometric and material properties. In the approaches *C&C*^{2}*-Approach* [50–52,54], *Digital Function Modeling in DC43* [34], *Functional Product Description* [2]/*mecpro*^{2} [36], *Integrated Product Model for Conceptual Design* [37], *MagicGrid* [38], *Mechatronic Modeller* [46], *OpenSE/OpenMBEE* [39], *SPES* [47,49], *STRATA* [48] and *SYSMOD* [40], structures are modeled using SysML blocks with parameters, respectively UML classes with attributes. The parameter-based modeling of structures offers the potential to seamlessly link not only the whole SysML block with respect to the UML class, but also specific parameters (e.g., mass and strength) to the requirements and models. This linking enables the efficient testing and design of structures, as the fulfilment of requirements can be validated at early-development stages. *FAS4M* and *Systems Sketcher*, in contrast, describe structures via sketches [35,53], resulting in high efforts for the testing and designing of structures according to the requirements, while the *motego* method, according to [5], does not provide the modeling of structures.

2.5. Analyzed Criterion: Formalized Modeling of Relations between Physical Contacts and Structures

To seamlessly achieve the described mechanical system architectures, the formalized modeling of relations between contacts and structures is essential. The analyzed approaches shown in Table 1 can be divided into the following two categories regarding the relation between contacts and structures:

- *FAS4M* uses the SysML dependency *trace* to model the dependencies between the contacts with their active surface set and structures [35].
- The other listed state-of-the-art approaches link individual active surfaces to structures, either as the parts or as ports of structures. Of these, the *C&C*^{2}*-A* [50–52,54] is to be pointed out, because linking active surfaces with structures via ports seems to build a suitable basis, since the ports can be linked to active surfaces within the contact elements, as, for instance, the *SolutionElement* of the *motego* method, according to [5]. However, the *C&C*^{2}*-A* does not allow a parametric description of contacts, as the contacts are not specifically modeled, but realized through connectors between two active surfaces.

The modeling of active surfaces as *parts* only allows the description of individual active surfaces, but not how the active surfaces are connected and interact with each other. The modeling with *trace* dependencies instead does not enable the transfer of parameters between the contacts and structures, but rather describes that they are related.

Table 1 provides a qualitative overview of the findings generated by the analysis of the state-of-the-art approaches *C&C*^{2}*-A* [50–52,54], *Digital Function Modeling in DC43* [34], *FAS4M* [35] and *System Sketcher* [53], *Functional Product Description* [2]/*mecpro*^{2} [36], *Integrated Product Model for Conceptual Design* [37], *MagicGrid* [38], *Mechatronic Modeller* [46], *motego* [5], *OpenSE*/*OpenMBEE* [39], *SPES* [47,49], *STRATA* [48] and *SYSMOD* [40].

Existing modeling methods either focus on the formalization of only one development artefact (contacts or structures) or lack possibilities for linking domain models with the modeling of technical solutions, so that contacts and structures cannot be tested within the system model. Hence, the objective of this paper is to elaborate a method for the function-oriented modeling of mechanical structures on the basis of contacts, test them by linking domain models and enable the arrangement of components on the product layer according to structuring criteria, such as assembly.

When elaborating a new modeling method that focuses only on a part of the product development process, it is reasonable to integrate the method into a suitable broader framework, if possible. The *motego* method, according to [5], represents such a promising framework (cf. Table 1). Therefore, the *motego* method is explained in the following section, and the current limitations of the method are outlined using the example of a *centrifugal pump*.

3. The *motego* Method

The *motego* method (short for *Model–Test–Go*, formerly referred to as the *MSE Architecture*) [55] represents an MBSE method for the seamless, function-oriented development of mechatronic systems [5]. Therefore, the *motego* method provides approaches for modeling *Requirements*, *Functions* and *Solutions*, as well as their parametric linking (highlighted in red, orange and blue colors in in Figure 1). Requirements are linked to a functional decomposition of the product, which describes the behavior of a product solution-neutrally by the changes in the functional flows [5]. How these changes in functional flows are realized is concretized on the *Solution* layer via the *SolutionElements* and the superordinate *SystemSolutions*. The *SystemSolutions*, in turn, can consist of several *SolutionElements* [5]. For more information about the *motego* method to build MBSE system models, please refer to [5]. Like in this paper, the *motego* method is constantly being expanded. For example, a method-specific SysML language profile exists to apply the function-oriented modeling with *motego* [56]. In order to list just an excerpt of further work related to the *motego* method, we refer to the following publications: [24–26,55,57].

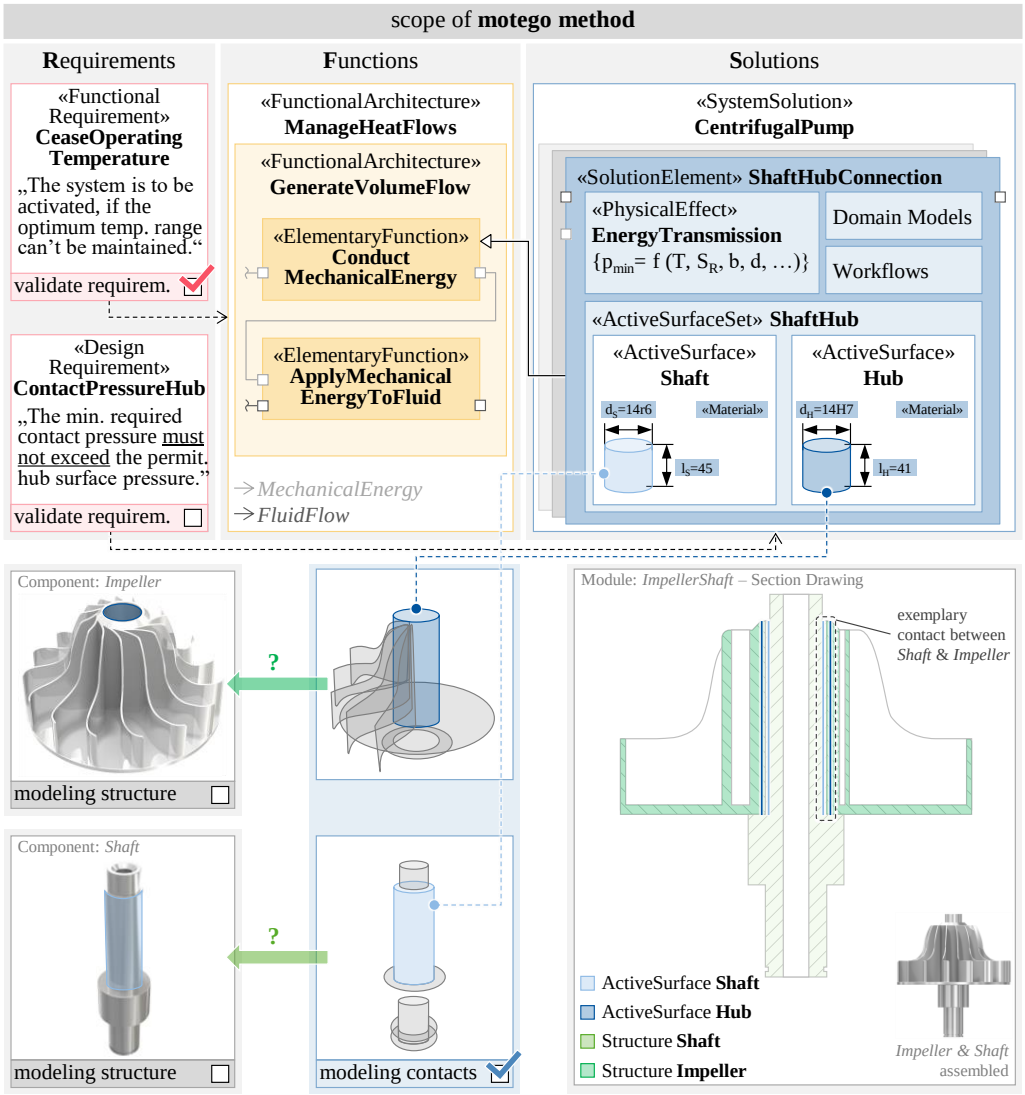


Figure 1. Scope of the *motego* method for the function-oriented modeling of mechanical system architectures, according to [5], and its gap regarding structures.

In mechanical subsystems, functions are realized through interactions at contact surfaces [58]. Within the *motego* method, these contact surfaces are referred to as *ActiveSurfaces* [5]. Two *ActiveSurfaces* that are in contact with each other form an *ActiveSurfaceSet*. The *ActiveSurfaceSet*, in turn, is modeled as a part of the *SolutionElement*, which is linked to the functions with the SysML dependency *generalization*, as shown in [5]. In combination with the *PhysicalEffect* as part of the *SolutionElement*, this linking enables the virtual validation of the functional requirements, as well as design requirements, that are related to the contacts modeled via *SolutionElements* in early-development stages [5].

However, this limitation of the *motego* scope, according to [5], to validate contact-based design requirements does not allow the entire testing of, e.g., strength requirements. For example, it is not sufficient to only consider the *ActiveSurfaces* for an FEM analysis that is used in a model chain to test the strength. Instead, the connecting structure between *ActiveSurfaces* needs to be considered as well (green highlight in Figure 1) within the product development. To enable the entirely seamless product development from the requirements of the physical product, the *motego* method needs to be extended by a modeling method for structures. Such an extension needs to formalize the relations between physical contacts and structures. For this formalization, the modeling method has to contain mechanisms to assign the *ActiveSurfaces* to structures, as well as the description of the dependencies

between the active surface parameters and the structure parameters. In addition, the linking of structures to requirements has to be ensured, and the fulfilment of these structure-related requirements has to be verifiable.

Another aspect is the processability of the development results by the departments following in the value chain, such as purchasing, logistics, manufacturing and assembly. *Enterprise Resource Planning* (ERP) and *Product Data Management* (PDM) systems are established in companies for the cooperation of people which are involved in the product development. The ERP and PDM systems support the management of geometry data, as well as the planning of material procurement and manufacturing steps. While the *motego* method is used to consistently build the architectures of functions and contacts with respective solutions in product development, the ERP and PDM systems typically capture the architectures of the components. An example is the BoM, which hierarchically structures a product in the assembly sequence. In order for functional architectures and product structures, such as the BoM, to exist in parallel and synchrony, it is important that functionally developed structures can be rearranged at the product layer according to structuring criteria, such as assembly.

4. Research Need

In summary, the *motego* method is able to map mechanical solution concepts in a function-oriented way and link domain models to them. However, *motego* lacks a method for the function-oriented modeling of mechanical structures. This leads to the following three research questions of this paper:

1. How can structures be defined so that they can be assigned to functions?
2. How can domain models be integrated to enable the design and validation of structures according to the requirements?
3. How can the defined structures be arranged at the product layer to synchronize them with data management systems?

As justified before, the modeling approach to be developed is intended to be an extension of the *SolutionElements* within the *motego* method [5]. The approach is presented in the following section by addressing each research question within a separate subsection.

5. Function-Oriented Modeling of Mechanical System Architectures

This section presents the method to model structures within *motego*. The presented modeling approaches are applied to an exemplary *centrifugal pump* to continue the example presented in [5,11].

5.1. Definition of Structure Elements Based on Function-Oriented Contacts

The modeling of mechanical components with the *motego* method, according to [5], is limited to the contacts, which are represented by *SolutionElements*. The *SolutionElement* contains the *ActiveSurfaceSet* with a parametric description of the geometry and the material properties of two contacting *ActiveSurfaces*, as well as the *PhysicalEffect* as the first simplified behavior description. In addition, the validation and optimization of the contacts can be performed through *DomainModels* and *Workflows* [5,25,26]. Regarding mechanical system architectures, the two *ActiveSurfaces* finally have to be provided by two structures. In consequence, *motego* has to be extended by a modeling method for structures. As Figure 2 shows for the exemplary *centrifugal pump*, the structures, referred to as *StructureElements* (green highlight in Figure 2), extend the *motego* solutions. The modeling of *StructureElements* and their connection to *ActiveSurfaces* is described in the following subsection using a metamodel (cf. Section 5.1.1), and subsequently applied to the example of the centrifugal pump (cf. Section 5.1.2).

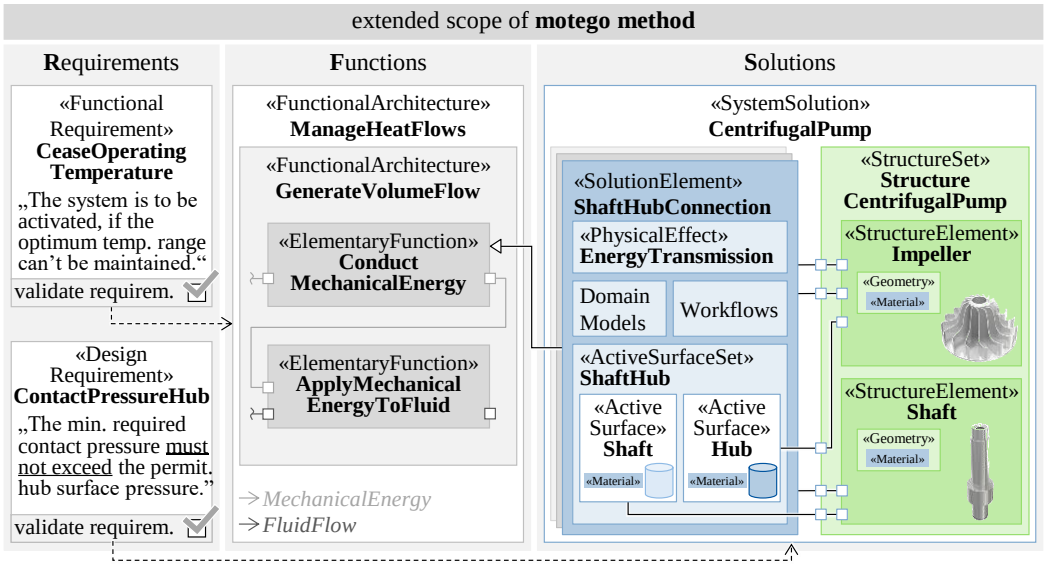


Figure 2. Definition of function-oriented *StructureElements* within the *motego* method.

5.1.1. Metamodel for Modeling Structure Elements

Within the *motego* method, according to [5], *SystemSolutions* can be decomposed into other *SystemSolutions* or *SolutionElements*. To follow this hierarchical decomposition, the extension of the *motego* method not only has to include the *StructureElement* as the representation of components, but also the superordinate *StructureSet*. This *StructureSet*, in turn, can consist of several *StructureElements* (green highlight in Figure 3). To enable the seamless creation of *StructureElements* from *ActiveSurfaces*, it has to be defined which *ActiveSurfaces* are realized by which *StructureElement*. A component typically realizes *ActiveSurfaces* from different solutions. Therefore, all relevant *ActiveSurfaces* of the subordinate solutions are assigned to the *StructureSet* as the physical interfaces of the structures via the SysML element *full port* (blue highlight in Figure 3). Subsequently, the *full ports* of the *StructureSet* have to be connected to the respective *full ports* of the *StructureElements*.

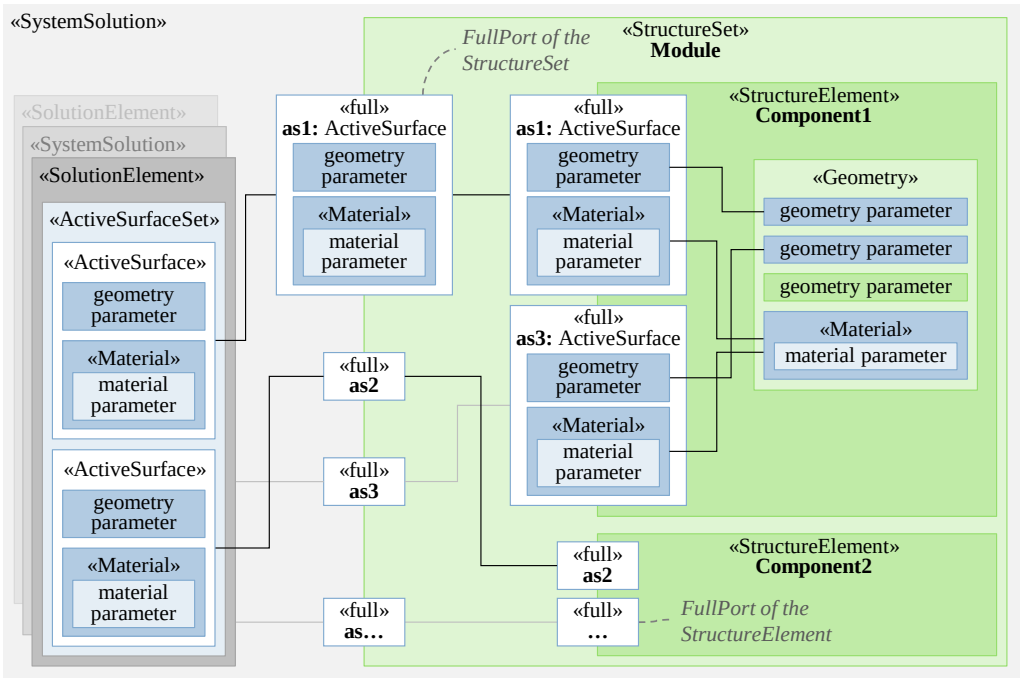


Figure 3. Metamodel of *StructureElements* based on function-oriented *SolutionElements*.

For the function-oriented development of *StructuralElements*, not only the *ActiveSurfaces* have to be assigned to these, but also the dependencies between the parameters of the *ActiveSurfaces* among each other and with the connecting structure have to be modeled. To define these dependencies, it is necessary to describe the structures parametrically. Comparable to *ActiveSurfaces* [5], the parametric description of *StructureElements* is based on *geometry* and *material*. In addition, the geometry parameters of the structure itself are added to the *StructureElement* to fully define its geometry. To ensure consistency between the geometry and material parameters of the *ActiveSurfaces* and *StructureElements*, the relations of the parameters have to be defined. Since the *ActiveSurfaces* are assigned to the *StructureElements* via *full ports*, bidirectional parametric links are implemented. Thus, the geometry parameters and the material of the *ActiveSurfaces* are passed to the *StructureElement* that physically has to fulfil them (cf. Figure 3).

5.1.2. Exemplary Application of the Structure Element Metamodel

In the following, the described metamodel is applied to an exemplary centrifugal pump. For the development of the pump structure, the structure set *StructureCentrifugalPump* is created (light-green highlight in Figure 4) and the *ActiveSurfaces* of the solution elements *ShaftHubConnection* and *CentrifugalPumpWheel* are assigned as *full ports*. Subsequently, the structure elements *Impeller* and *Housing* are created within the *StructureSet*. The application in Figure 4 shows the assignment of the active surfaces *Hub* and *Wheel* to the *Impeller*. The *full ports* of the *StructureSet* and the *StructureElement* are finally linked with connectors. By this assignment, the *Impeller* contains the active surface *Hub* of the *ShaftHubConnection* and the active surface *Wheel* of the solution element *CentrifugalPumpWheel*.

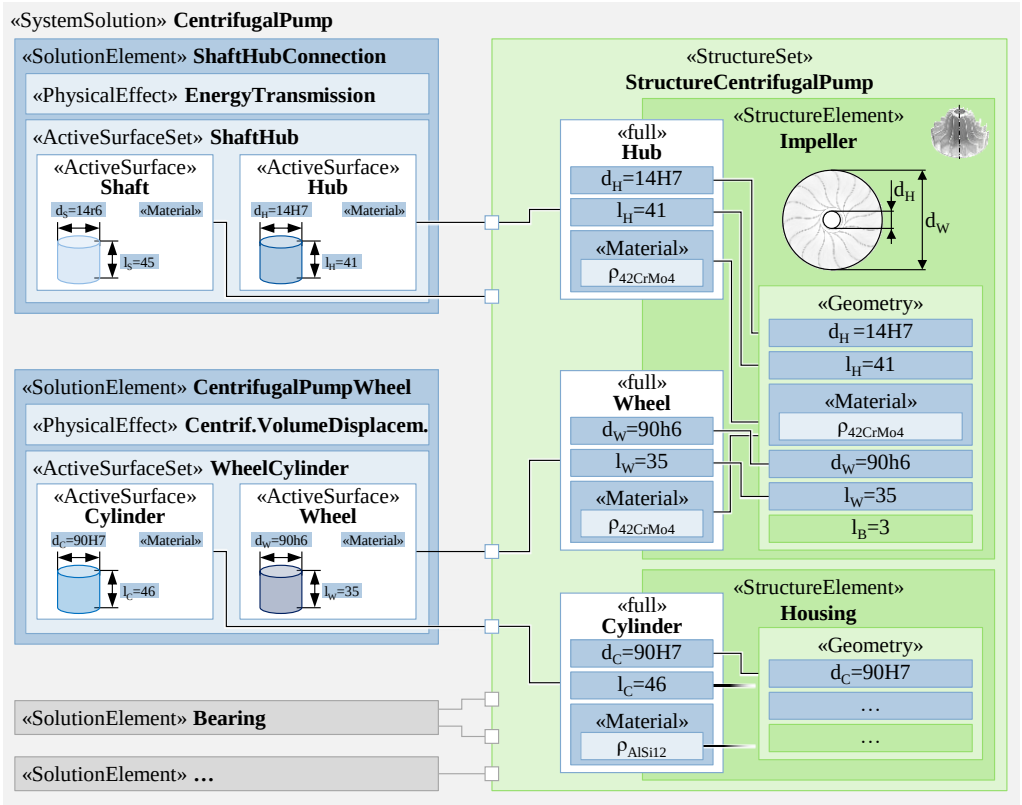


Figure 4. Function-oriented definition of the structure element *Impeller* based on the *ShaftHubConnection* and the *CentrifugalPumpWheel*.

One challenge in corporate practice is to provide all collaborating developers with current and valid data, and to inform them transparently about changes. In the example described, the *CentrifugalPumpWheel* could be designed by a simulation expert with a focus

on fluid engineering optimization, while the component *Impeller* is designed by a design engineer to be suitable for casting. Both employees pursue important goals to ensure that the final product is functional and can be manufactured. At the same time, both access the same geometric parameters and calculate or reuse them. Due to the complexity described above, current mechatronic products have a high number of physical and logical interfaces where a high number of parameters are commonly used and must always kept consistent. This task has so far been ensured by the swarm intelligence of well-practiced employees and established company processes, but requires model-based support for sustainable knowledge storage and to master more complex products. The modeling proposed here inherently ensures that, for example, if the *CentrifugalPumpWheel* is changed by the fluid expert, an impending conflict can be detected in a model-based manner. This conflict can subsequently be resolved, e.g., by a note to the responsible expert or by the automated execution of a generative design process for the *Impeller*. In reality, an initial change can potentially trigger high impacts on a wide variety of parts of the system. The modeling method described enables these change effects to be transparently identified and evaluated a priori in the future on the basis of the parameter linkage.

In the modeling method presented, *StructureElements* are defined on the basis of *ActiveSurfaces*. Thus, with regard to the system architecture of the *motego* method shown in Figure 1, a parametric link from requirements via functions and solutions up to the *StructureElements* is created. This seamless parametric description provides a basis for testing the design requirements that are related to the structures. However, the validation of such design requirements requires integrated domain models.

5.2. Integration of Domain Models into Structure Elements

Domain models are defined as simulation models that describe a specific real system behavior in an abstract form for a specific purpose, such as a finite element simulation for the deformation calculation [5]. Usually, domain models are not used as stand-alone models, but are interconnected via their input and output parameters [24,25]. SPÜTZ ET AL. describe an approach for the *motego* method that contains engineering models, production models and controlling models to test and design technical solutions with respect to the requirements [25]. Within this paper, the metamodel according to [25] is adapted for the integration of domain models into the *motego* system model to be used for the validation of the requirements associated with the *StructureElements*.

5.2.1. Exemplary Application of the SPÜTZ ET AL. Metamodel

In the following, the different categories of domain models and their respective integration into the MBSE system model of the product to be developed are described.

Engineering Models: Engineering models describe a certain scope (e.g., contact, bearing, drive train and the whole vehicle) of the system under development concerning a specific purpose (e.g., strength, noise vibration harshness and heat exchange) with a specific model fidelity (e.g., characteristic curves, analytical equations and numerical approximations). Engineering models with the scope of a single contact of an *ActiveSurfaceSet* are integrated into the *SolutionElements* and can calculate the physical behavior of the contact based on the parameters that are defined in the *SolutionElement* and its ports. If an engineering model represents a broader scope (e.g., multiple contacts and certain components), the engineering model is integrated into the respective *SystemSolution* that fully contains this broader scope (cf. Figure 5). Since the behavior of structures always occurs through the interaction via *ActiveSurfaces* with at least one other structure, engineering models are not integrated within *StructureElements* but rather into the superordinate *SystemSolution*.

Production Models: Production models describe the process steps to manufacture *StructureElements* and assemble them. The production process includes the production planning, the manufacturing of *StructuralElements* using specific production machines (e.g., a CNC milling machine, a grinding machine or an FDM 3D printer) and the assembly of the *StructuralElements* to *Modules* and the overall product. The production machines are not

part of the technical system to be developed but are used for manufacturing or assembling the *StructuralElements* of this system. Thus, production models are not part of the MBSE system model of the system to be developed. Instead, the references are integrated into the system model as interfaces that enable access to the production models, and therefore plan and validate the manufacturing and assembly of the *StructuralElements*.

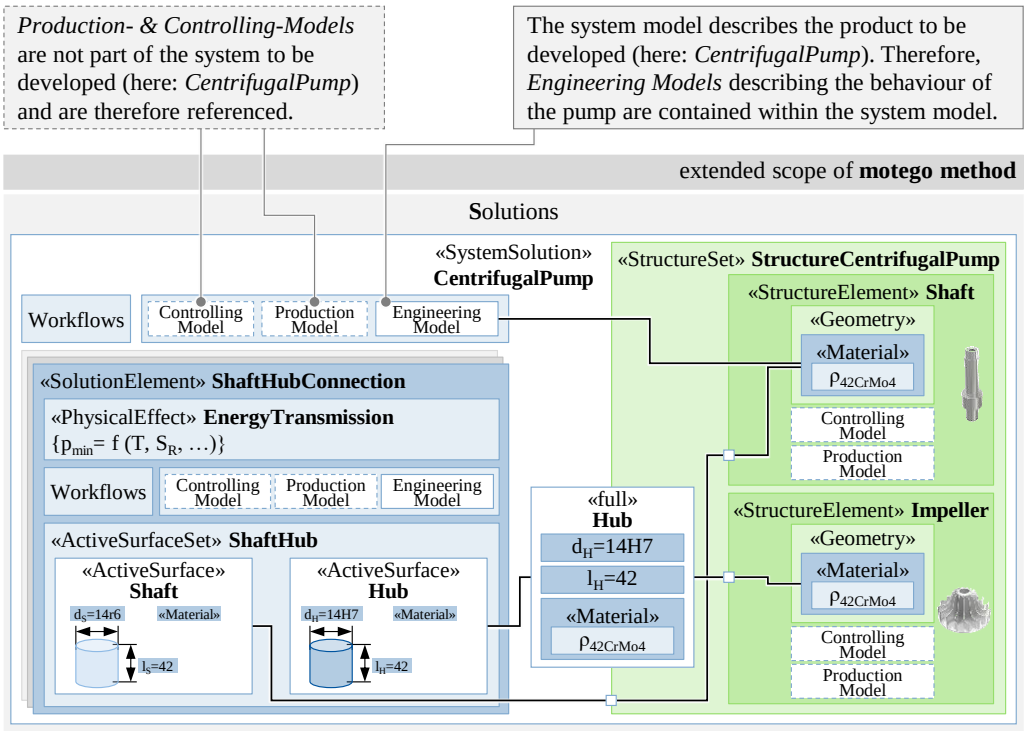


Figure 5. Integration of *DomainModels* in the *SystemSolution* and *StructureElements* using the example of a *centrifugal pump*.

Controlling Models: Controlling models are used to estimate and calculate the costs arising from the development of a product over the material costs up to the production. Like in production models, controlling models are not part of the system to be developed. So, instead of the controlling model itself, the references to access the model are integrated into the system model.

The execution of these interconnected model networks, and thus the order of the models, is controlled by workflows [57]. These workflows are modeled as SysML behavior elements, like *activities* and *interactions* within the *StructureElement* or the superordinate *SystemSolution*, which contains the domain models to be controlled by the workflow [57].

5.2.2. Exemplary Application of the Domain Model Metamodel

The previously elaborated metamodel to integrate domain models is applied to the example of the *centrifugal pump* in the following subsection and illustrated by an exemplary engineering model.

Engineering Models: To describe the integration of engineering models associated with *StructureElements*, the *ShaftHubConnection* between the *Shaft* and the *Impeller* (cf. Figure 5) of the *centrifugal pump* is regarded in detail. The *ShaftHubConnection* represents a cylinder press fitting, which is realized by joining two *StructrualElements* each with overmeasured *ActiveSurfaces*. The overmeasure fitting is defined by the dimensions of the two active surfaces (and their tolerances) in contact with each other (cf. Figures 4–6). Fitting both *StructrualElements* by force creates a consistent pressure throughout the contact that results in an adhesive force which is capable of transmitting constant, alternating and impact torques, as well as longitudinal loads. The *ShaftHubConnection* of the exemplary *centrifugal pump* has to transmit torque from the *Shaft* to the *Impeller* to finally generate a volumetric

flow of a fluid. Figure 6 exemplarily shows the integration of an engineering model for the verification of the permissible contact pressure for the structure element *Hub* (according to a calculation process described in [59]). For its calculation, the engineering model needs input data from certain parameters of the solution element *ShaftHubConnection* and the structure elements *Shaft* and *Impeller*. With the *FactorOfAdhesiveSafety* and the *FactorOfApplication*, two input values are also defined via requirements (highlighted in red color in Figure 6). For this purpose, the engineering model checks whether the minimum required contact pressure is lower than the permitted surface pressure of the structure element Hub. If this is the case, the *Boolean ValidPressure* as the output value of the model is set to true.

If the requirement is not fulfilled and the resulting pressure is too high, the hub can be damaged. The pressure depends on the load case, the materials of the fitted *StructuralElements* and the geometries. Thus, the wall thicknesses of the *StructuralElements* have a decisive influence on the behavior. In order to reduce the mass of the accelerated *StructureElements*, the *Shaft* has a continuous inner drilling. Since this drilling is not in contact with another *StructureElement*, its geometry is not defined by an *ActiveSurface*. The influence of the *StructureElement Shaft* on the *ShaftHubConnection* illustrates the necessity to model both the *SolutionElements* and *StructureElements* in a harmonized and interrelated manner, and to integrate domain models into those specific model elements that provide the best access to relevant parameters, as well as the broadest solution reuse.

The collaboration of the presented modeling approaches enables the development and optimization of the mechanical system architecture up to the final design. This modeling enables the identification of a valid overall product design by taking all parameters, their specific restrictions and multidimensional dependencies into account.

5.3. Arranging Structure Elements at the Product Layer

Within manufacturing companies, the PDM and ERP systems have become established as the central interfaces to control the data and processes of product development through the distribution of information across all participating departments. The PDM and ERP systems typically capture the architectures of components (equivalent to the *StructureElements*), like the BoM, instead of the functional architectures as the basis of product development within the *motego* method. The BoM structures the components of a product hierarchically in terms of the sequence of the assembly during production. In addition to information about the components and their setup in the modules, the BoM serves to control the supply chain, work preparation and production. [60]

To combine and synchronize the function-oriented application of the MBSE and the managing of the product orders with the established PDM and ERP systems using the BoM, components that have been developed based on functions need to be rearrangeable according to structuring criteria, such as assembly or controlling. Therefore, we propose the extension of the *motego* method by a *Product* layer within the scope of this paper (cf. Figure 7). The product layer follows as the fourth layer after the *Requirements*, *Functions* and *Solutions*. In order to enable the arrangement of the previously introduced *StructureElements* with regard to the different phases of a product lifecycle, the *motego* method is extended by the stereotype *Module* (cf. Figure 7). *StructureElements* can be assigned to a *Module* via the SysML dependency *directed composition*. This dependency expresses that a *Module* is composed of the associated *StructureElements*. Figure 7 shows the application of this modeling approach by using the *centrifugal pump*. Within the example, the product *ElectricPumpAssembly* is structured into preassembled modules respecting the final assembly sequence. Therefore, the module *CentrifugalPumpWheel* consists of the structure elements *Housing*, *Impeller* and *Shaft*, whereas the module *ElectricMotor* contains the *Rotor* and the *Stator*. In general, a *Module* can consist of further subordinate *Modules* or *StructureElements*. The BoM can be derived directly from the architecture of *Modules* and *StructureElements* which is generated by the sequence of assembly.

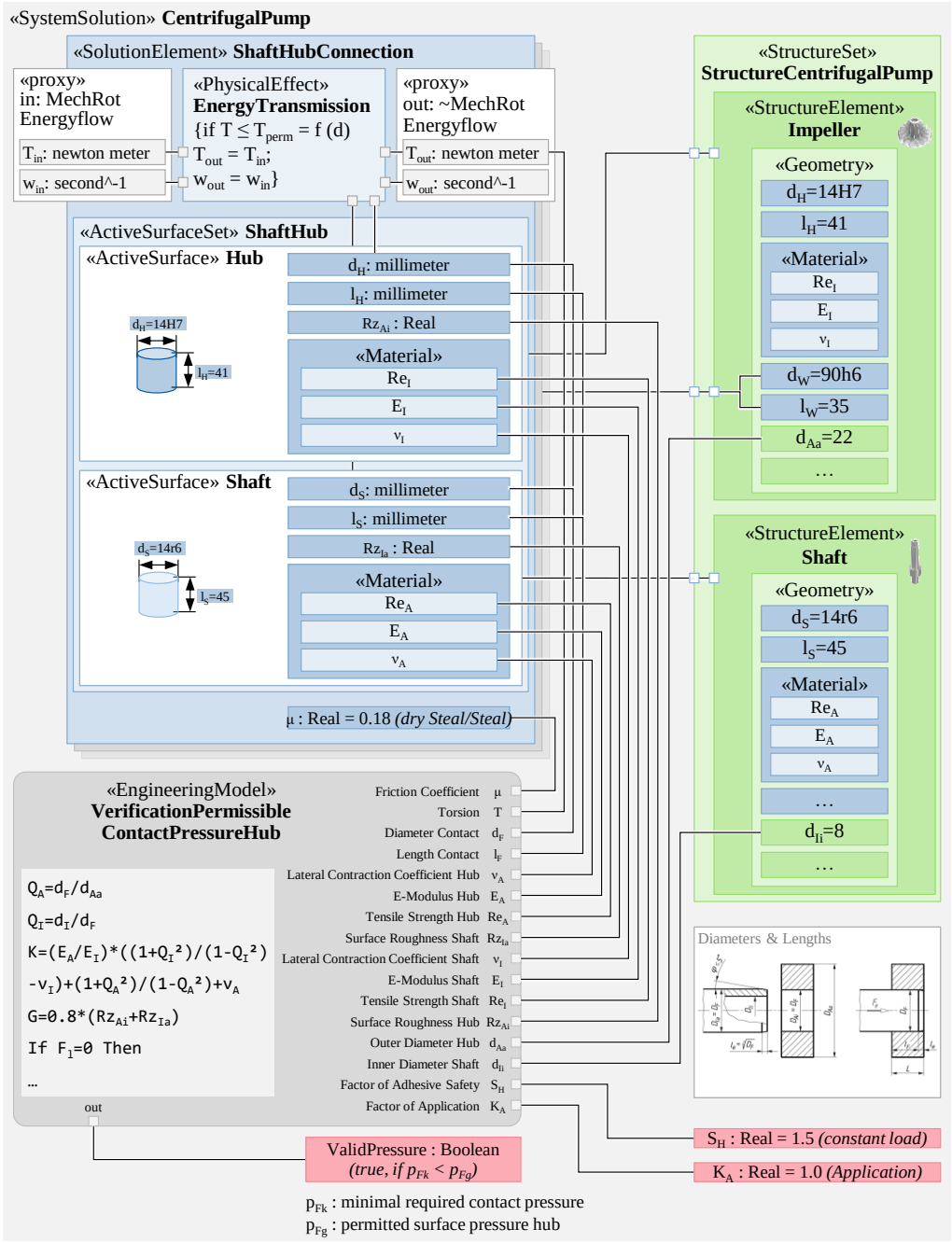
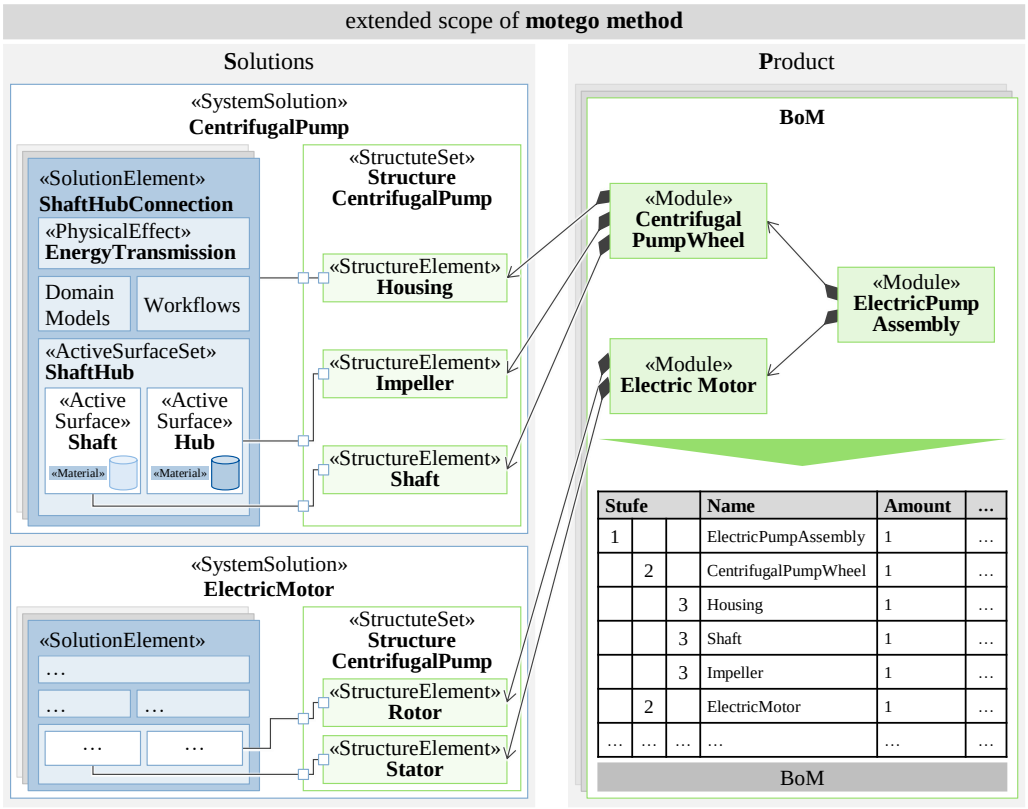


Figure 6. Integration of an engineering model for the verification of the *Permissible Contact Pressure* in a *ShaftHubConnection* of the exemplary *centrifugal pump*.

With the extension of the *motego* method by the *Modules* and the *Product* layer, functionally oriented developed structures can be arranged according to all criteria of the product lifecycle phases, like manufacturing, assembly, procurement, distribution, service and recycling. The arranging of the *StructureElements* represents the link to the BoM as the leading document of the current PDM and ERP systems, and thus to established product development processes. Despite the logical foundation of this contribution, one important future challenge will be the seamless coupling of MBSE system models with the PDM and ERP systems via software interfaces.



Stufe			Name	Amount	…
1			ElectricPumpAssembly	1	…
	2		CentrifugalPumpWheel	1	…
		3	Housing	1	…
		3	Shaft	1	…
		3	Impeller	1	…
	2		ElectricMotor	1	…
…	…	…	…	…	…

Figure 7. Arranging *Modules* at the *Product* layer for the example of the *BoM*.

6. Discussion

The contribution of this paper is the extension of the *motego* method, according to [5], by a modeling method for structures (the extension is highlighted by color in Figure 8). The added value created by extending the *motego* method is illustrated for the application example of a centrifugal pump. In terms of mechanical engineering, the *motego* method, according to [5], has been limited to the modeling of physical contacts (*ActiveSurfaces*), such as the *Shaft* and the *Hub* of the solution element *ShaftHubConnection*, as shown in Figure 8. Therefore, the *ActiveSurfaces* could already be defined parametrically (e.g., in terms of their dimensions and materials), according to [5], but it has not been possible to validate whether the required contact pressure of the shaft–hub connection is satisfied. This can be illustrated by the example of the wall thickness of the *Shaft*, which affects the resulting contact pressure: a continuous drilling within the *Shaft* to reduce the rotating mass could be considered and would affect the wall thickness. However, as the surface of this continuous drilling is not in contact with another structural element, its dimensions cannot be specified via an *ActiveSurface* (cf. Figure 6). Therefore, the *motego* extension presented in this paper enables the modeling of structures as well as the definition of which contacts shall be realized by a structure.

Through the integration of simulation models into the presented framework, mechanical system architectures can be efficiently tested and optimized with regard to requirement and function fulfilment. As a result, product failures, such as critical material stresses leading to the damage of the *Shaft*, can be identified and eliminated in earlier development stages.

However, a major drawback of the presented modeling method remains the initial modeling effort. To justify the modeling efforts in practice, the method is currently mainly applicable to products whose parts are reused over several product generations or whose complexity could otherwise only be mastered at great expense. Initial approaches to overcome this limitation may be the reuse of existing modeled system elements from solution libraries, as shown in [5]. In addition to reuse, another approach to reduce the

modeling time is to accelerate the development process, e.g., by the method-specific SysML profiles for common modeling tools [56]. Furthermore, the presented approach is currently limited to MBSE modeling environments. As product development is followed by further steps, like purchasing, logistics, manufacturing and assembly, in which the PDM and ERP systems are used, the required interfaces and processes to link MBSE environments have to be examined.

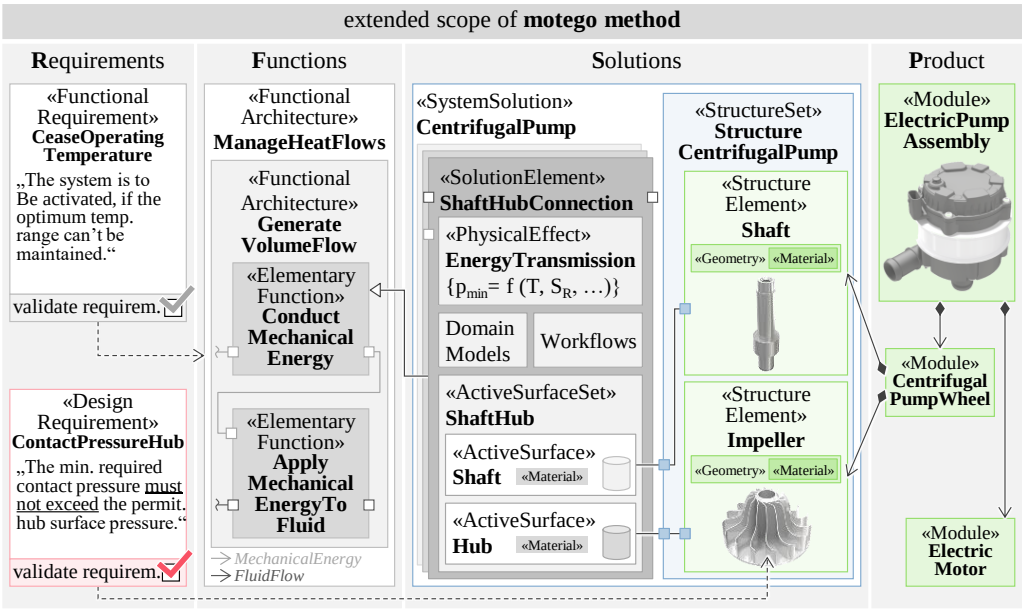


Figure 8. The *motego* method for the function-oriented modeling of mechanical system architectures, according to [5], with its extension.

7. Conclusions and Outlook

The function-oriented application of MBSE represents a promising approach to master the increasing complexity in today's product development [61]. In particular, for mechanical engineering, function-oriented product development is challenging due to the methodological break resulting from the realization of functions through components. The extension of the *motego* method presented in this paper represents an approach to bridge this methodological break, thus enabling the seamless modeling of mechanical system architectures from requirements to physical products.

However, the initial modeling effort due to the high degree of formalization of the development artefacts currently limits the practical application of the method and requires further research. In the future, the presented method to model mechanical system architectures may represent an initial step for the automation of generative engineering on the basis of requirements. For instance, structure elements may be designed automatically based on assigned active surfaces and the transmission paths of forces between these active surfaces. Thus, the use of generative design for designing the final physical product continues the idea of model-based product development. By combining function-oriented, model-based system engineering with these design methods, complete consistency can be created from the requirements to the final design. This consistency provides the basis, for instance, for efficient design adaptations in the case of requirement changes or the automation of development processes.

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