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Integration of Production and Cost Models in Model-Based Product Development

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Abstract

Companies in mechanical engineering are facing an increasingly high cost pressure in international competition. Therefore, in addition to the given technical functionality, cost oriented product design is becoming a dominating factor for the success of a product on the market. For the cost-oriented product design, knowledge from the field of production and controlling is highly relevant. This contribution shows how this knowledge can be formalized and linked to the product model of the engineering department in a model-based product development. This enables engineering departments to access non-domain specific but cost-relevant knowledge at an early stage in the development process. As a result, the product design can already be determined cost-oriented in the engineering department.

Keywords

Model-Based Systems Engineering, Domain Models, Cost Calculation, Production, Knowledge Transfer

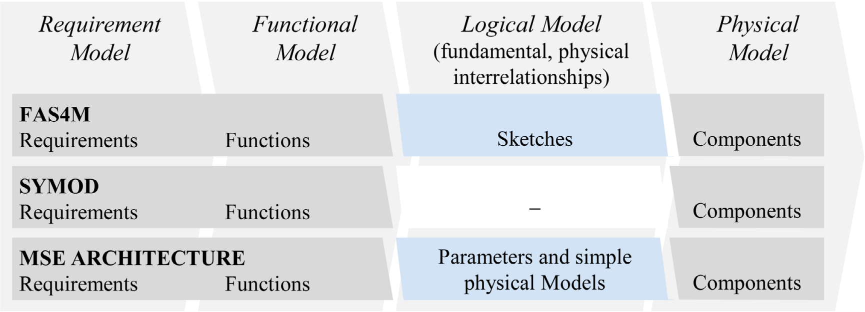
1. Introduction

Mechanical engineering companies are facing increasing cost pressure due to international competition (Verband Deutscher Maschinen- und Anlagenbauer, 2018; Friedli & Schuh, 2012). This environmental change is particularly relevant for manufacturing companies in the classical mechanical engineering sector, with a high degree of new and customized designs (Friedli & Schuh, 2012). For the success of products on the market, cost-oriented design is becoming a dominant factor in addition to the given technical functionality (Ehrlenspiel et al., 2014). In addition, the change towards international competition implies that market needs can no longer be satisfied by products with pre-engineered parts (Anderson & Pine, 1998). This leads to customized products as well as components and consequently to adjustments in the production of these. Thus, cost calculation is usually only possible after the product has been fully designed. The problem associated with this situation is that the greatest potential for influencing product costs lies in the engineering department. Approximately 70% of the product costs are determined in this department (Ehrlenspiel et al., 2014; Eigner & Stelzer, 2009). In contrast, the originators of the main costs are in manufacturing and purchasing. These departments together cause about 69% of the product costs (Verein Deutscher Ingenieure, 1987; Verband Deutscher Maschinen- und Anlagenbauer, 2006). Consequently, the knowledge about the product cost origin lies in these departments and is usually not available at an early stage for new and adapted designs in the engineering department (Ehrlenspiel et al., 2014). As a result, the engineering department cannot evaluate during the product design, whether the product target costs are met (Ehrlenspiel et al., 2014; Eigner & Stelzer, 2009). Late cost calculation makes iterations between product development and manufacturing or purchasing likely. This essential problem must be solved by externalizing cost-relevant knowledge through modeling and making it available across departments (Ehrlenspiel et al., 2014). A promising approach is model-based system engineering (MBSE).

2. Model-Based Systems Engineering

Current MBSE approaches focus on the use of formalized modeling to support product development (Eigner, Roubanov, & Zafirov, 2014). This enables the management of increasing product and functional complexity in the development process (Eigner, Roubanov & Zafirov, 2014). MBSE methods such as SYSMOD (Weilkiens, 2016) and FAS4M (Moeser et al., 2016) as well as the MSE ARCHITECTURE (Zerwas et al., 2021) focus on a function-based product development. Differences between the MBSE approaches lie especially in the way of linking development results and the modeling of fundamental, physical interrelationships (see **Figure 1**).

The FAS4M (Moeser et al., 2016) method focuses on modeling the fundamental, physical interrelationships via sketches. The linking of these sketches with development results, such as functions, is done via the abstract systems



	Requirement Model	*Functional Model*	*Logical Model* (fundamental, physical interrelationships)	*Physical Model*
FAS4M	Requirements	Functions	Sketches	Components
SYMOD	Requirements	Functions	–	Components
MSE ARCHITECTURE	Requirements	Functions	Parameters and simple physical Models	Components

Figure 1. Comparison of the MBSE methods FAS4M, SYSMOD and MSE ARCHITECTURE in terms of mapping the fundamental physical properties within the logical model.

modeling language (SysML) relation *trace*. SYSMOD (Weilkiens, 2016) focuses on the direct function-oriented description of the physical realization without describing the basic, physical interrelations. Thus, the methods FAS4M and SYSMOD do not allow a description of the basic, physical realization via parameters and models. For this reason, the approaches are not suitable for the connection with cost-relevant knowledge in the early development phases. The MSE ARCHITECTURE (Zerwas et al., 2021) with the language profile SysML4FMArch (Drave et al., 2020) focuses on the continuous linking of requirements via functions and principle solutions up to the product. The formalized, functional description of the principle solution via parameters and simple physical models allows the description of basic physical interrelations (Zerwas et al., 2021). Thus, early function-based testing and product design is enabled (Höpfner et al., 2021). The central component of the approach is the solution element, in which the principle solution is linked to all models and workflows of the necessary domains, to describe its behavior. The engineering models and workflows also enable the design and testing of the principle solution with respect to further purposes, such as lifetime.

3. Research Needs and Methods for the Integration of Production and Controlling Models into the MSE ARCHITECTURE

Using the MSE ARCHITECTURE, the function-oriented development of products can already be described (Zerwas et al., 2021). However, there is currently a lack of concrete approaches for a function-oriented development considering cost relevant knowledge. Within the scope of this thesis, such an approach is developed by means of a methodical procedure for the integration of production and controlling domain models into the function-oriented MSE ARCHITECTURE. With the help of the models, the production costs already become apparent in the development process and can be compared with the target costs. The procedure consists of the following steps:

1) Building the system model of the product according to the MSE ARCHITECTURE.

2) Extending the MSE ARCHITECTURE metamodel by production and controlling models.

3) Identifying and formalizing relevant production and controlling models.

4) Integrating relevant production and controlling models into the MSE ARCHITECTURE.

The steps of this procedure are presented in the following using a product example. The example is based on the industrial practice of a middle-sized company with a portfolio of conveyor chains.

3.1. Building the System Model of the Product According to the MSE ARCHITECTURE

The relevance of the production and controlling models for product cost determination mainly depends on the product geometry. For this reason, the principle product design is required. In the MSE ARCHITECTURE the principle geometric design is described within the active surfaces of the solution element. For the conveyor chain product example, a part of the MSE ARCHITECTURE is shown in Figure 2. Initial point of the development is customer-specific, functional requirements, such as the maximum tensile force of the chain. The functional requirements are transferred into a functional product description *Conduct Force between Solids*. This is realized by the solution elements *Clearance-Contact* and *PressContact*, which are represented through the active surface set and the physical effect of the solution element. The solution element links the principle solution view with various domain models.

The function-oriented design of the active surface geometry parameters is performed using models from the domain engineering and design workflows in the solution element and the superordinate element—the system solution.

With the help of the function-oriented description in the solutions, products can already be developed and designed in a functional optimized way. The function-oriented design of the solution elements with engineering models is not critical for the success of products, such as the conveyor chain. In order to succeed in competition, the target costs from the requirements must be met for a given functionality. For this purpose, the product costs must already be apparent during development. Consequently, the MSE ARCHITECTURE metamodel must be extended by models that enable cost calculation. These models are located in the domains Production and Controlling.

3.2. Extending the MSE ARCHITECTURE Metamodel by Production and Controlling Models

To enable the extension of the MSE ARCHITECTURE by production and

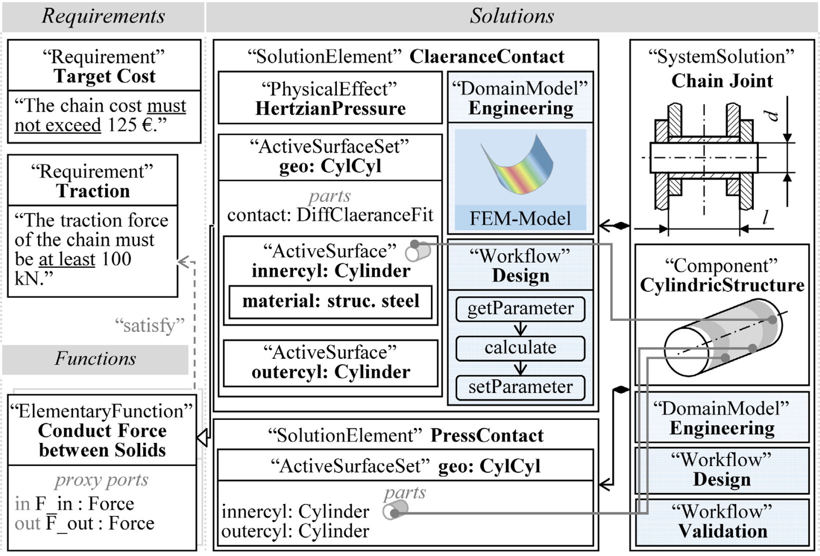


Figure 2. Function-oriented modeling of a chain joint according to the MSE ARCHITECTURE according to Jacobs et al. (2022).

controlling domain models, the metamodel of the system solution and the solution element has to be extended. Through the extension is explicitly defined at which point of the MSE ARCHITECTURE the domain models are integrated. The metamodel of the system solution and the solution element already includes the engineering domain models. The models of the domains production and controlling have to be integrated at the same point. This extension of the MSE ARCHITECTURE metamodel is shown in Figure 3 for the solution element.

The production domain models are used in the MSE ARCHITECTURE to plan and optimize the production of the geometry. This production planning is based on the geometry from the principle view of the solution. By planning the production of the geometry, the determination of relevant controlling models and the input parameters for these models is enabled. Purpose of the controlling models is to determine the production costs of the geometry. The structuring of the engineering, production and controlling models within the system solution metamodel is designed similar to the solution element. Only the explicit content of the models differs.

Extending the MSE ARCHITECTURE metamodel by production and controlling models provides a framework for the inclusion of cost-relevant knowledge at an early stage of product development. Depending on the application, the relevant domain models for the production of geometry in the solutions must be identified and integrated.

3.3. Identification and Formalization of Relevant Production and Controlling Models

How the identification and architecture-compliant formalization of production and controlling is carried out, is explained on the conveyor chain example in the following. The main focus is the functionally relevant part of the chain—the system solution chain joint.

3.3.1. Identification of the Relevant Production Models

The identification of the relevant production models is based on the production planning for the geometries of the system solution. In the running example of

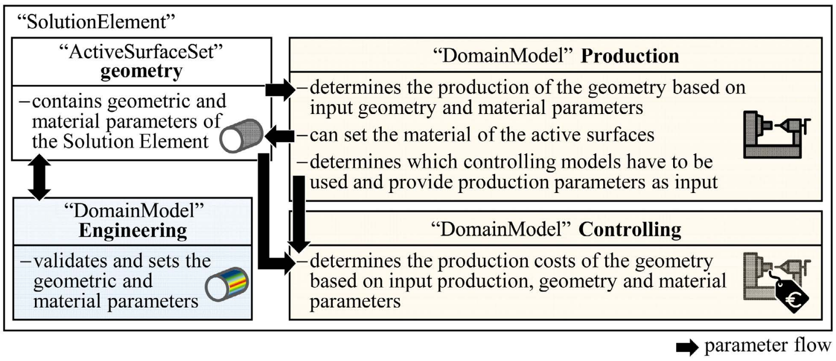


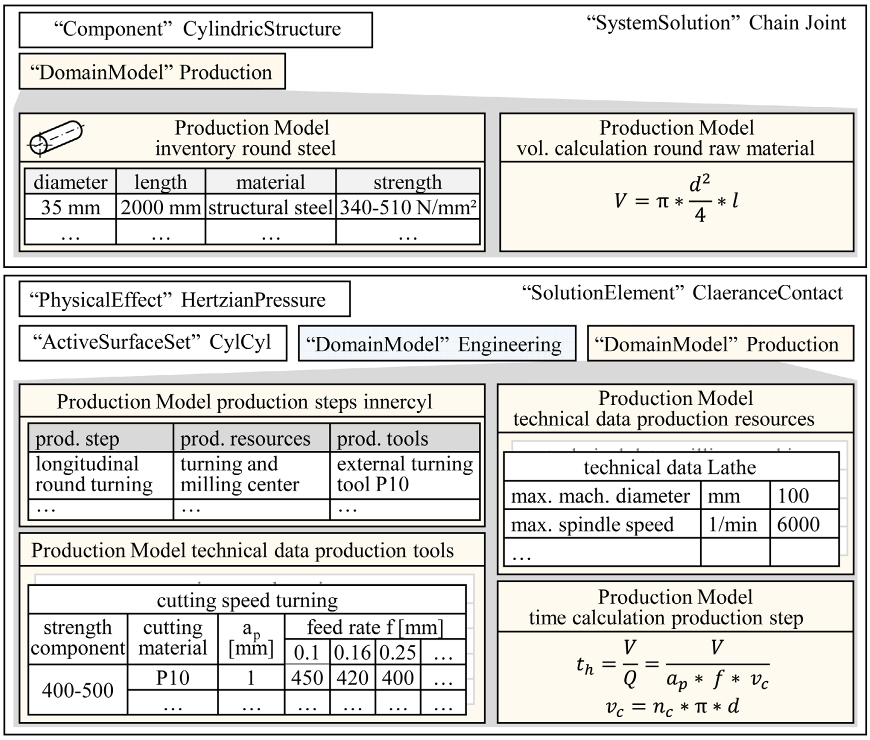
Figure 3. Extending MSE ARCHITECTURE meta model according to Jacobs et al. (2022) by Production and Controlling Models.

the chain joint, the relevant production models for the geometries *Cylinder* and *CylindricStructure* are shown in **Figure 4**.

Relevant production models can be delimited in the first step by defining the production process of the active surfaces. In the running example the *Cylinder* surfaces are usually produced by round turning processes. This production process requires the use of a round steel as the raw material for the component *CylindricStructure* (see **Figure 4**, below). Relevant information related to this raw material include the available inventory and the calculation of the production parameter *volume*. The geometry parameters, such as the diameter of the active surfaces and the permitted surface pressure, directly influence the permitted dimensions and the material of the raw material.

The production models relevant for the *Cylinder* geometry are already constrained by the definition of the production process and raw material. In the running example, the specified models determine the selection of the longitudinal round turning production step (see **Figure 4**, below). In addition to the production step, the production resources and the associated tools are relevant for determining the production time t_h. The input parameters for calculating the production time depend directly on the raw material and tool production parameters as well as the active surface geometry parameter.

By identifying relevant information from the production domain, knowledge from production can already be made available to the engineering department for production planning of the geometries. Using the identified models, the



diameter	length	material	strength
35 mm	2000 mm	structural steel	340-510 N/mm²
…	…	…	…

$$V = \pi * \frac{d^2}{4} * l$$

prod. step	prod. resources	prod. tools
longitudinal round turning	turning and milling center	external turning tool P10
…	…	…

technical data Lathe		
max. mach. diameter	mm	100
max. spindle speed	1/min	6000
…		

cutting speed turning						
strength component	cutting material	a_p [mm]	feed rate f [mm]			
			0.1	0.16	0.25	…
400-500	P10	1	450	420	400	…
	…	…	…	…	…	…

$$t_h = \frac{V}{Q} = \frac{V}{a_p * f * v_c}$$

$$v_c = n_c * \pi * d$$

Figure 4. Relevant production models for the "SystemSolution" Chain Joint (in reference to Paucksch et al., 2008, Dietrich, 2016).

relevant production models can be selected from various data sources, when the geometry parameters are changed. Thereby, the design of the geometries can already be adapted according to production requirements.

3.3.2. Formalization of the Production Models

In order to be easily accessible in model-based development, the models must be formalized compatible with the MSE ARCHITECTURE. The formalization of the previously identified production models is based on the modeling language SysML. Basically, the models are divided into three sections—production processes, production resources and raw materials (**Figure 5**). The respective sections are structured in the classes production processes and steps, machine (groups) and tools as well as raw materials and the subordinate classes shape and material. The classification of the previously identified round turning production process, the longitudinal round turning production step and the round steel in this class is shown in **Figure 5** for the running example.

The *longitudinal round turning* production step supplements the *round turning* production process with a production model for calculating the production time and with ports as an interface to the geometry parameters of the solution element. The modeling and classification of the production resources is carried out parallel to the classification of the production processes. The class *lathe* is assigned to the various machines of this type. By extending the model of the lathe, the turning and milling center owns the calculation constraint for calculating the material removal rate depending on the selected tool. A linking element is used to assign the production steps to the production resources. This linking

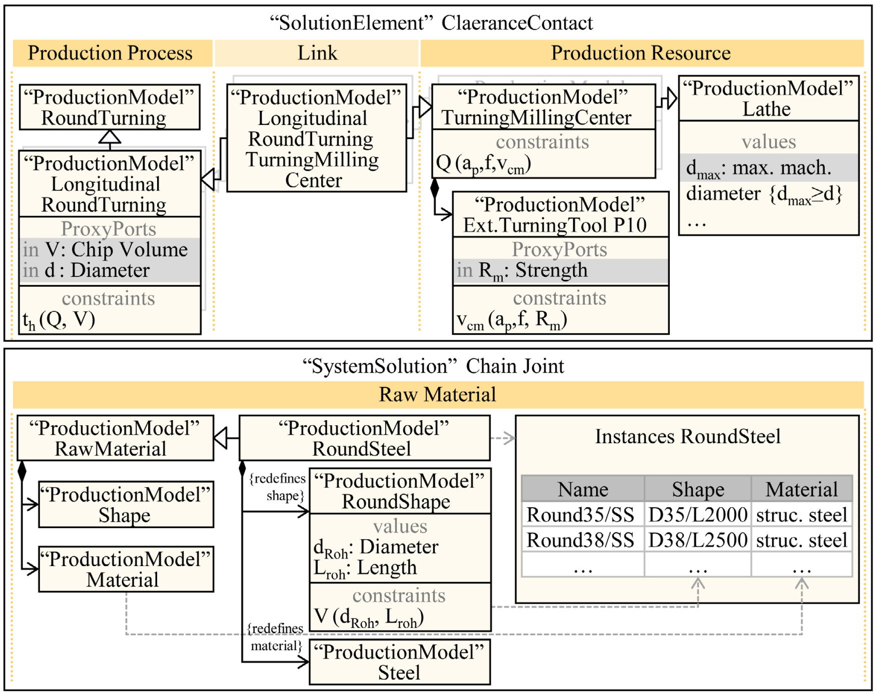


Figure 5. Formalization of the production models for the "SystemSolution" Chain Joint.

element inherits the properties of the production resource and the assigned production step. Therefore, the properties of the production steps with regard to the individual resource can be modeled, new production resources can be integrated, and properties of the production resources can be adapted easily. Additional advantage of modeling in a class structure is that a single point of truth (SPOT) is created and the maintenance effort is reduced.

The formalization of the identified raw materials is carried out analogously via the definition of common relationships in a superordinate class *raw material* and the refinement of these. The specialized class *round steel* refines the superordinate class, by defining the material *steel* and the raw material form *round shape*. The inventory associated to the round steel is mapped via instance tables.

Advantages arise already in the systematic provision of the identified information in the engineering department. Through the formal description of the interrelationships, it is immediately visible which production steps, production resources and raw materials are currently available and suitable for the application. Using this information, the design of the products can already be adapted to production restrictions in the engineering department, which avoids iterations and thus increases efficiency in the development process.

3.3.3. Identification of the Relevant Controlling Models

With the help of the identified production models, raw materials and production steps can already be selected in the engineering department and thus the production parameters can be estimated manually. In order to determine the manufacturing costs, controlling models are also necessary. These models determine the product costs based on geometry and production parameters. Only by considering these models, the product costs can be calculated and compared with the target costs.

In development, the manufacturing costs of the product are particularly relevant. These result from the production and material costs. Inputs for the determination of the production cost include the volume of the raw material and the production time, whereas the volume of the raw material provides the input for calculating the material costs of the component. The production time supplies the necessary input for the calculation of the production costs of the solution element. **Figure 6** presents the relevant models for the production and material cost calculation of the running example are indicated.

The production costs of the geometry arise from the costs of the individual production steps. For the *Cylinder*, these are only the production costs of the longitudinal round turning production step. According to Paucksch et al. (2008), the production costs for machining production steps consist of the primary time cost K_1, the fixed cost of the production resources and staff K_2 and the tool (change) cost K_3 (see **Figure 6**, left). Partial costs can be influenced in different amounts by changing production parameters, such as production time, adapting material parameters and selecting production resources. The material cost of the component result from the direct material cost K_{ME} and the overhead material cost K_{MG} (see **Figure 6**, right). These costs only depend on the production parameters of the raw material via the fixed overhead rate g_M and the relative material cost k_V.

Generally, this identification method can be used to identify the controlling models beyond metal-cutting processes, such as additive manufacturing. However, the production and material costs vary according to the selected production process and the raw material. Identifying the production and resulting controlling models already provides the engineering department with relevant production and controlling knowledge. This permits geometries to be designed in line with production and cost requirements.

3.3.4. Formalization of the Controlling Models

In order to make the controlling models easily accessible in model-based development processes, they also need to be formalized. In Analogy to the formalization of the production models, the identified controlling models are formalized in three sections - production processes, production resources and raw materials (**Figure 7**).

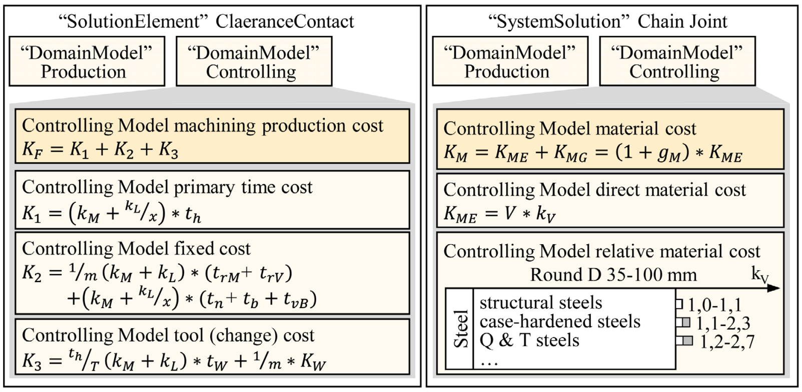


Figure 6. Relevant controlling models for the "SystemSolution" Chain Joint (in reference to Pauksch et al., 2008, Ehrlenspiel et al., 2014).

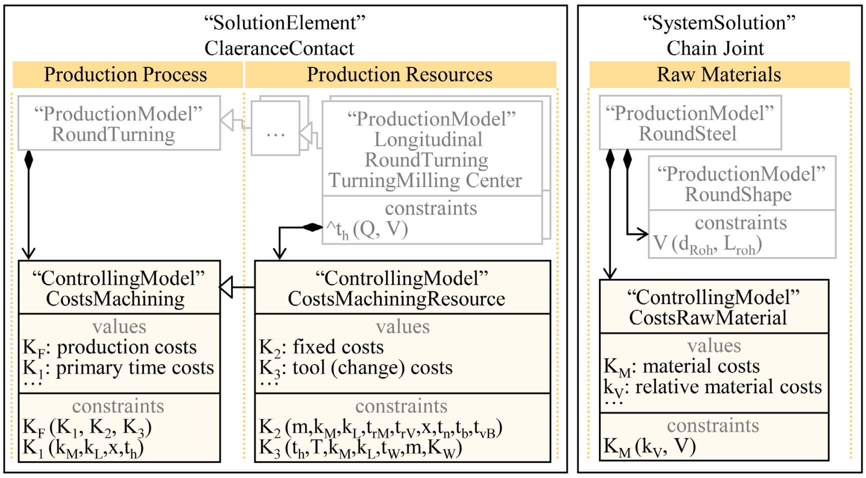


Figure 7. Formalization of the controlling models for the "SystemSolution" Chain Joint.

Identified models are assigned to the respective sections. The assignment condition is, that the controlling models are assigned to the production models through which they are mainly caused. For example, tool (change) costs K_3 are mainly caused by the production resource and the associated production step and are therefore allocated to them. Advantages of this modeling arise in particular from the clear allocation of the individual controlling models to the cost-generating production models. The allocation also enables simple parameter value transfer to the respective controlling models.

By identifying and formalizing the relevant models, costs can already be calculated by selecting the models and manually entering the input parameters of the geometry. Thus, cost-relevant knowledge can be made available to the engineering department in a simple, formal and flexible adaptable form.

3.4. Integrating Production and Controlling Models into the MSE ARCHITECTURE

In order to achieve seamless value transfer and consistency, the models need to be integrated into the function-oriented product description analog to the defined MES ARCHITECTURE metamodel. The integration takes place within the system solution and the subordinate solution elements. **Figure 8** shows the integration of the previously formalized models into the system solution chain joint.

Within the solution element, the production models and the associated controlling models of each active surface are modeled collectively in the production plan. In the running example, the production plan of the active surfaces *Cylinder* consists of the production model *LongitudinalRoundTurning TurningMillingCenter* and the associated controlling model *CostsMachiningResource*. The geometry parameters are linked via the interfaces which are defined for the

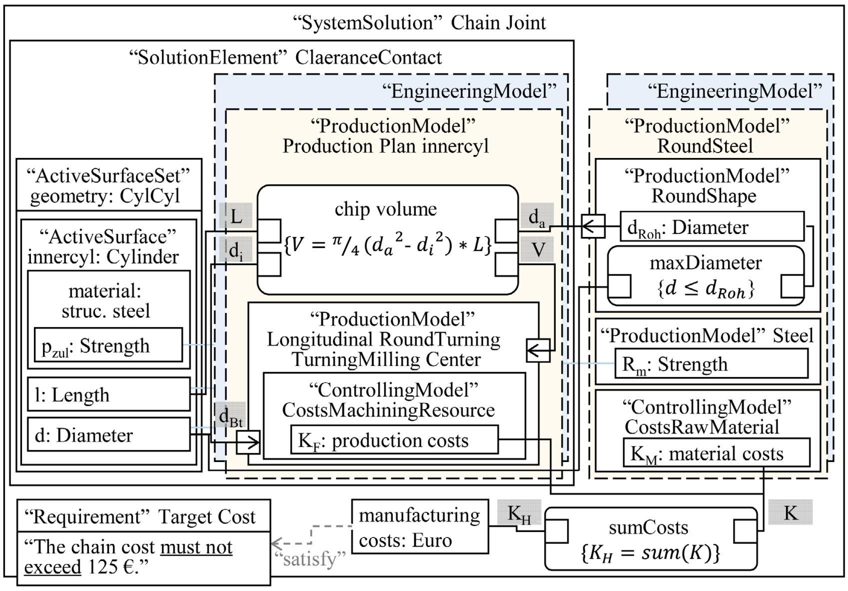


Figure 8. Integrating production and controlling models into the MSE ARCHITECTURE for the "SystemSolution" Chain Joint.

models. The domain models of the system solution are connected via the production model *Round Steel*. This model contains the production models *RoundShape* and *Steel* as well as the controlling model *CostRawMaterial*.

Through the integration of the domain models into the system solution, seamless parametric linkage of the controlling and production models to the digital product description is possible and thus an automated, direct provision of cost information during concept development. This enables a direct comparison of the manufacturing costs with the target costs defined in the requirements. As a result, the product design can be adapted and optimized earlier and faster based on current information. Potential cost reductions located in the development department can thus be exploited.

4. Conclusion

Especially for companies that are facing international competition, the consideration of costs early in the development process is an issue of great concern. Therefore, the goal of the presented approach is to provide cost-relevant knowledge in product development. Based on the geometries of the solution element and the system solution, the relevant models could be identified. The provision of knowledge was made possible by linking production and controlling models to the MSE ARCHITECTURE. With the help of the language SysML and extending the language profile SysML4FMArch, the models could be formalized and integrated into the MSE ARCHITECTURE. As a result, the approach allows to provide cost information of the current design already within the development. Based on this information, the developer is directly informed whether the target costs are met. When the target costs are not met, countermeasures can be taken early in the process, thus avoiding iterations. A further advantage is, that according to Ehrlenspiel et al. (2014), the production costs can be reduced by 10 to 30 percent through the collaborative cost optimization by engineering, production and controlling. The costs can be reduced even further, if the product concepts are adapted in the MSE ARCHITECTURE *solutions*.

Disadvantage of considering controlling and production domains in addition to the engineering domain within the product development is that the complexity of the system model increases with the number of models. To address this deficit, a necessary next step is to develop an approach which reduces the complexity of integrating a large number of models into the system model. The partially automated control of the production and controlling models as well as the optimization of the geometry parameters with regard to the costs should also be strived for. This could exploit potentials for cost reduction in development and lead to a permanent reduction in product costs.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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