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Support of Future-Robust Construction Kit Development for Electric Traction Motors Using Model-Based Systems Engineering

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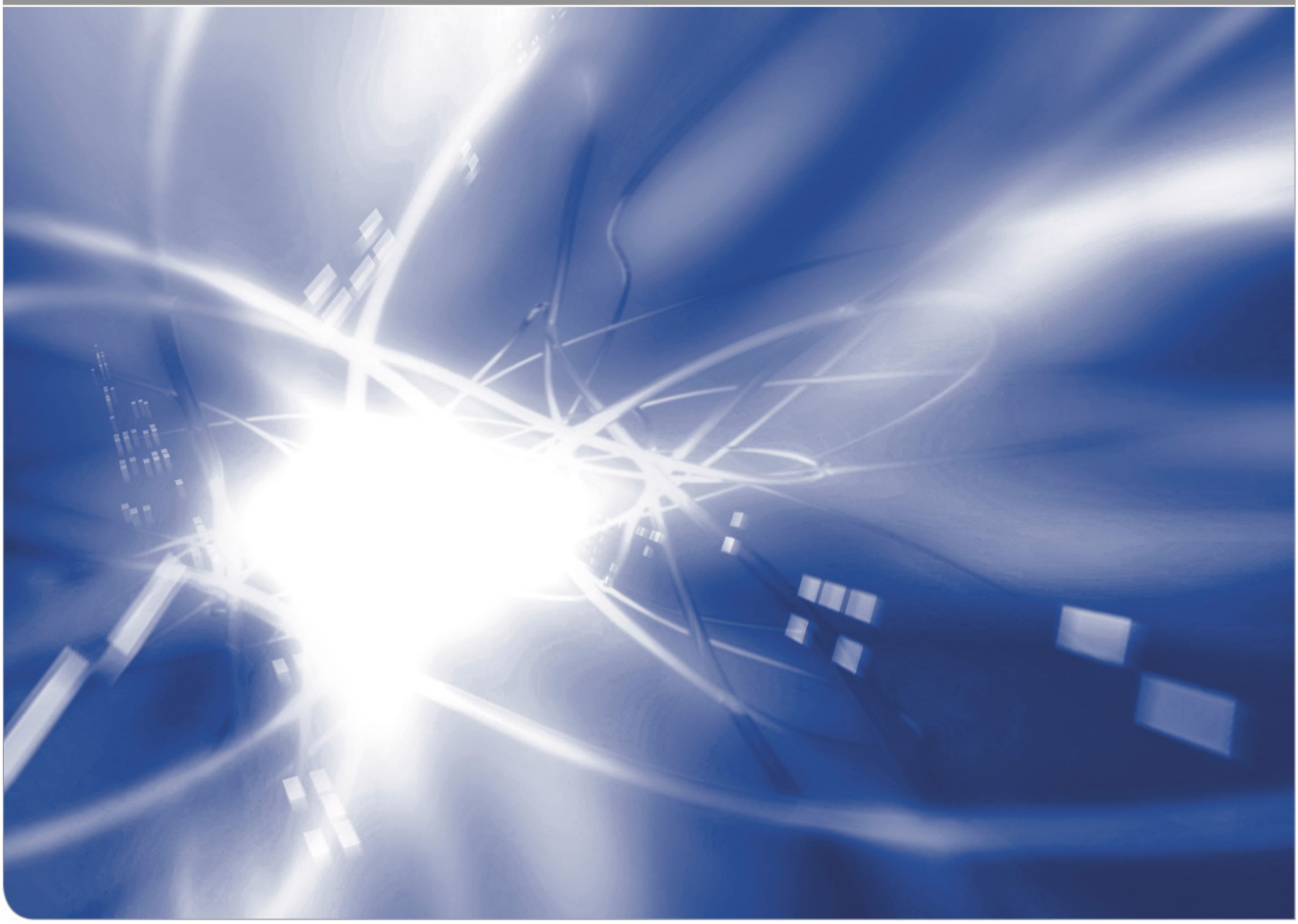

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Abstract

To support the development of robust product modules that meet the requirements of the future, a process model is being developed to describe the technology-open transformation of customer requirements for electric traction motors. This method considers aspects such as performance, installation space and costs. The aim is to derive and describe an optimized, resource-efficient motor design using product modules to meet the requirements of agile production systems.

The process model is made up of four main activities, which were applied and analyzed as part of the project AgiloDrive2 "Agile production systems and modular product construction kits for electric traction motors" founded by the German Federal Ministry of Economic Affairs and Climate Action and the European Union. Starting with the derivation of future-proof requirements for traction motors by analyzing the future market. This involves creating customer, environment and product scenarios and selecting suitable motor topologies. Aspects of the modeling of future-robust product structures and their validation for future-robust production possibilities are also considered by analyzing interactions in the product-production co-design for the agile production system. Furthermore, the modelling and operationalization of the modular system using Model-Based Systems Engineering (MBSE) in the Enterprise Architect software is described. Among other things, the product structure of permanent magnet and separately excited synchronous motors as well as their possible variants, function-design relationships, and interactions regarding the production system were integrated. The application of the described approach promotes future-proof design and the digitalization of the product creation process in the early phase of product development. This approach also provides support in the selection of customer-oriented product configurations and in analyzing the feasibility of technical changes. These changes may be necessary, for example, due to new and changing customer requirements. In addition, the approach makes it possible to evaluate the associated effects on the production system.

1 Introduction

As the modern world advances towards more sophisticated mobility systems, the role of vehicles and their propulsion systems becomes increasingly pivotal in shaping the efficiency and sustainability of transportation. This mobility framework can be seen as a complex network of interconnected systems, encompassing vehicles, propulsion mechanisms, communication networks, and infrastructure, all working together to deliver seamless mobility services to users. Among these, propulsion systems stand out as critical components, profoundly influencing the efficiency, sustainability, comfort, and accessibility of the entire mobility ecosystem. Electric propulsion systems comprise various components like electric motors, energy storage units, drivetrains, and control systems, intricately linked across different domains. This heightened complexity underscores the need for closer collaboration and integration among developers hailing from diverse backgrounds such as mechanical engineering, electrical engineering, and software development.

The electric traction motor, a cornerstone of electric drive systems, can be conceptualized as a cyber-physical system (CPS), where physical elements such as stators, rotors, and sensors interact with computational elements like controllers. Leveraging Model-Based-Systems-Engineering (MBSE) methodologies facilitates a deeper understanding of CPS, aiding developers in pinpointing potential issues or risks and optimizing system performance. Moreover, employing Product-Production-CoDesign to outline the integrated and collaborative development of electric traction motors and their manufacturing processes holds promise for reducing development timelines and production expenses [1, 2]. Ott et al. [3] present a corresponding proposal to address these considerations. Based on this proposal this paper presents a process model describing individual steps observed and investigated during the development of future robust construction kits for electric traction motors. It also focuses on the implementation of construction kits using MBSE. This intends to support future construction kit development processes.

2 Theoretical Background

2.1 Electric Traction Motor Development

Due to the versatility of electric traction motors in different areas of application, a wide range of requirements are placed on the electric motor to be developed. Key design features include the motor topology, the size in terms of diameter and length as well as the winding and magnet design [4]. Requirements exist regarding the maximum power, torque, and speed, but also with regard to the efficiency or cost of the traction motor. Possible options in terms of topology along others include permanent magnet synchronous motors (PSM), externally excited synchronous motors (ESM) or asynchronous motors (ASM), which are the most used topologies for electric vehicles. It is also possible to define the diameter and length of the motor required for the performance requirements. Depending on the selected motor topology, the magnet arrangement and selection or the winding type and topology also represent a design factor. [5]

In a development process, various design parameters are often first determined by the rough design of a motor and then detailed models for further design and optimization are created using these [6]. For example, once the magnet arrangement and winding topology have been defined, FE simulations can be used to determine temperature distributions, losses at various operating points or mechanical stresses [7]. This is often followed by physical tests to validate the designed traction motor, e.g. regarding its NVH behavior. With many applications to be served and the resulting demands on the traction motors, a new development represents a time-consuming and cost-intensive factor [8]. The development of a modular system for traction motors with clearly defined components therefore offers a promising solution for reducing internal diversity and therefore development costs.

2.2 Modular Product Design

Meeting individual customer needs while simultaneously exploring niche markets is a crucial success factor for global companies [9]. Consequently, the expansion of extensive product portfolios leads to increased production costs, driven by the reduction in the number of parts for individual components due to a high number of variants. As a response, companies incorporate modular product architectures to structure their product range [10]. Modularity allows increased unit numbers through the reuse of individual modules and components [11] while extending their lifecycles through cross-generational use [12]. As modular approaches provide crucial advantages, a multitude of different design methods in context of modularity have been developed [13]. Based on a comprehensive literature review and the analysis of development processes in different companies, Otto et al. [13] developed a model based on a generic sequence of steps to create modular product families (see Figure 1). The presented model reconciles 13 steps which can be clustered into preparation, dedicated modularization and postprocessing of the development process. It is important to highlight, that identifying and structuring the right influence factors to shape the targeted product portfolio in the beginning is crucial [13].

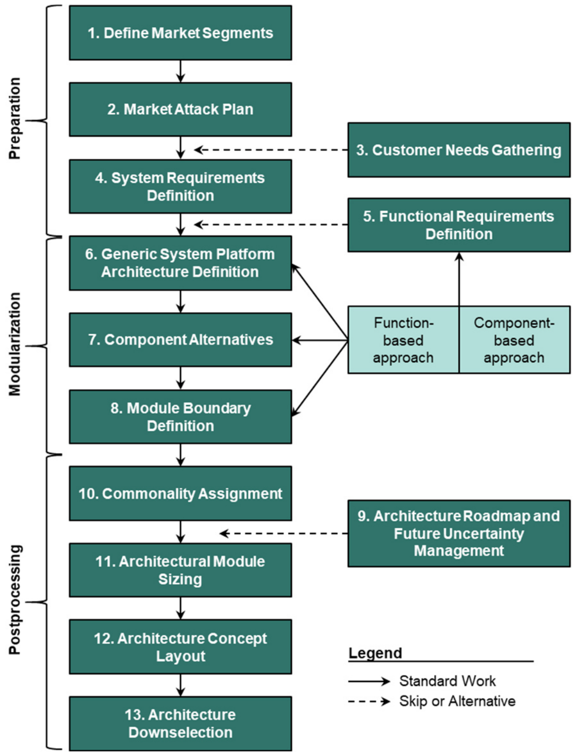

Figure 1: Model based on a generic sequence of steps to create modular product families [13]

2.3 Implementation of cross-generational modularization

To describe, structure and model the engineering process of such complicated and cross-generational modular products the model of SGE – System Generation Engineering can be considered [14]. With its approach, SGE can model products on system, subsystem, and component level. SGE is based on two hypotheses: (I) Elements from existing or already planned systems, as well as from other sources such as competitors, research institutions, or patents, serve as references for the development of new system generations (Gi) and are assembled considering their interactions within the reference system (Ri). (II) New products and systems are developed based on the reference system (Ri) through the activities of Carryover Variation (CVi) - where the subsystem to be developed is adopted from the reference system with only interface adjustments; Attribute Variation (AVi) - in which the links in the subsystem to be developed are essentially retained, but the attributes are changed; and Principle Variation (PVi) - here, connections and elements are added or removed in the subsystem to be developed compared to the reference, thereby changing the principle. [15] In context of modularization, the integration of different subsystems into a system can be described according to the three variation types (see (II)). Additionally, there is a need for time-independent production systems, as different modules need to be produced for different product generation. A strong parallelization and interconnection of product engineering, extending to the parallelized development of production systems and the operation of production, gets essential. The Model of SGE model allows such a model description in context of Product-Production-CoDesign, capturing the interactions between product and production [2].

2.4 Methods and Tools for Identifying and Modelling Requirements for Modular Product Kits

As stated, identifying the right influencing factors and therefore future requirements early on is crucial for modular design. They must be identified for multiple product generations ahead, thus extending over a long-time horizon. As stated by Fink & Siebe [16], the future, and its requirements, gets increasingly uncertain and less plannable with an increasing time horizon. Therefore, foresight instruments can be used to anticipate future customer needs and requirements [17]. Scenarios, as one foresight instrument for long time horizons, are consistent combinations of possible alternatives and definable development options for uncertain key factors [17]. Therefore, scenarios present a particular challenge due to their complexity [18] while giving the chance of future planning. In the context of product development, the incorporation of scenarios can particularly be used to anticipate future product requirements. However, by analyzing several development processes, Hirschter et al. [19] state that the integration of scenarios into the product development process is expandable. Based on this, [18] describe a future-oriented approach of SGE providing a procedure model for the systematic transfer of future scenarios into product profiles for several generations. Yet, the gained knowledge needs to be transferred on system level.

To model the gained knowledge in a systematic approach based on SGE, Albers et al. [12] propose a Product Modelling Framework to streamline the creation of product models and leverage knowledge from past projects [12, 20]. The framework facilitates referencing past system generations in system modelling within SGE, aiming to establish a shared understanding among developers regarding the abstraction levels of the used system models [12]. The framework is delineated by two axes: the horizontal axis distinguishes between Meta-System Models, Reference System Models, and System Models, while the vertical axis encompasses generic, domain-specific, and system levels [12]. Four essential system models for modular design are introduced: Product Models (7), Reference Product Models (6), Modular-Kit Reference Model (2), and the Modular-Kit Model (3).

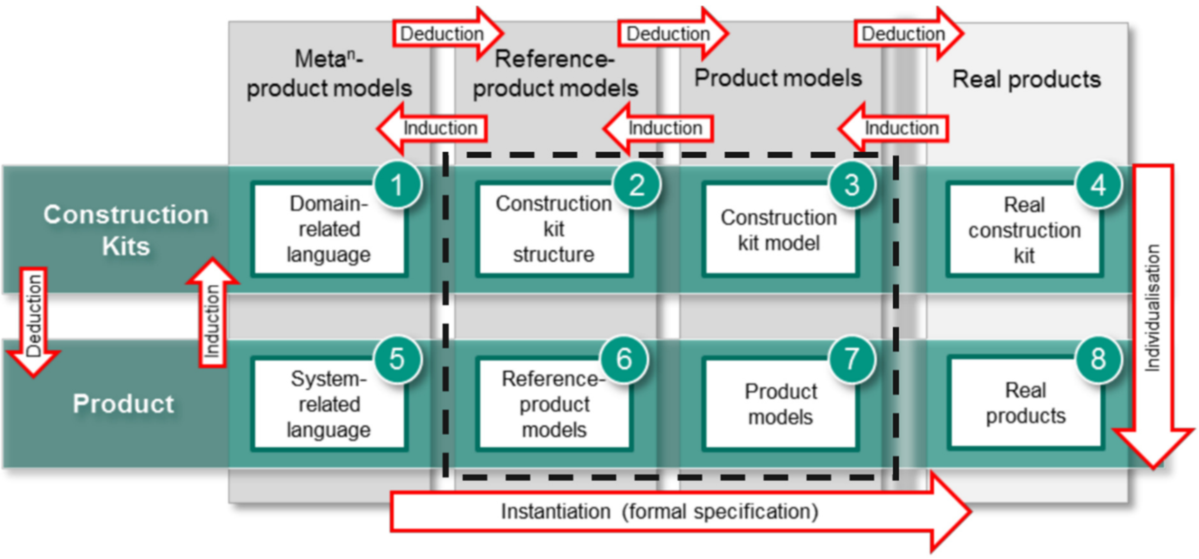

Figure 2: Elements of modular development in the product modelling framework (own illustration based on Bursac [21])

Modelling for modular product design begins with the last real system generations, portrayed as Product Models (7). Through the abstraction of multiple product models, these can be overlaid to form Reference Product Models (6), incorporating information about generic product structure, common parts, costs, and spatial requirements. The Modular-Kit Reference Model (2) is constructed from commonalities among Reference Product Models, describing the framework of the kit, including the type of elements and the architecture of the products. Based on the Modular-Kit Reference Model (2), individual components of the products can be assigned to the Modular-Kit Model (3), providing an overview of existing components, their reusability, and variant diversity. Using (3), components from the modular kit can be assigned to the Reference Product Model. To form the final product, product-specific differentiating features are then added.

3 Derivation of the process model for future-robust and model-based modular product development

The authors present a process model to support the development of a future-proof modular system for electric traction motors. The process model consists of four central activities that were carried out and analyzed as part of the project AgiloDrive2 “Agile production systems and modular product construction kits for electric traction motors”. The first step involves the derivation of future-proof requirements for traction motors through a comprehensive investigation of the future market. This involves creating customer, environment and product scenarios and selecting suitable motor topologies. In addition, aspects of modeling future-robust product structures are considered, including their assurance for future-robust production possibilities. This is done by analyzing interactions in the product-production co-design for the agile production system. Another focus is on modelling and operationalizing the modular system using Model-Based Systems Engineering (MBSE), which is described in detail in the Enterprise Architect software.

3.1 Derivation of Future-robust Procut Requirements

The approach according to [22] begins with identifying product requirements and the selection of suitable system topologies. Therefore, the corresponding future analysis compares today’s product properties with described uncertain future environments, customers, and products based on scenarios (see Figure 3).

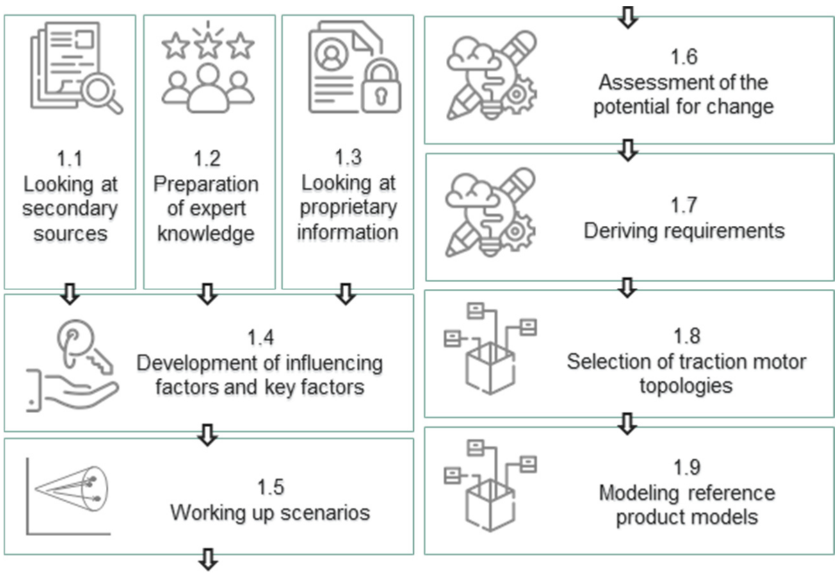

Figure 3: Process model steps for derivation of future robust product requirements

The first phase includes analysing reference products and today's product features to form a system model and gain knowledge on the providers core competencies. This is needed to allow a later strategic decision on system topologies based on abilities. Additionally, the analysis of today's products prepares a property catalogue of the system under development for subsequent creation of product scenarios on a property level.

To derive the targeted future state, future images are systematically developed through environment and customer scenarios in the second phase. This is required to be able to derive future market potential for the individual types of electric motor in their future application environment. The scenario-management method as stated above is used in this context. Furthermore, for creative or systematic derivation of future product properties Albers et al. [18] is taken into account. The previously depicted property catalogue of today's products is combined with the derived future properties and gets narrowed down to 10 to 15 relevant properties.

In the third phase, changing product characteristics are identified based on the previous steps. Through analyzing the performance of future product scenarios in future surroundings, the product characteristics can be classified as static time-dependent (one future-relevant property) or dynamic time-dependent (several future-relevant properties). Furthermore, based on the SGE risk portfolio the risk induced by characteristic variation can be depicted for the considered provider. As a result, a decision base for strategic selection of electric traction motors is possible according to future risk:

- Dynamic properties with high risk entail high change effort and should be prioritized.
- Dynamic product properties with low risk can be adapted quickly.
- Static product properties, dominated by one property, indicate unlikely changes in the future.

3.2 Modelling of Product Structure and Embodiment-Function-Relations

After the assurance of a future robust definition of requirements and selection of motor topologies the actual product structures and interrelations within the construction kit can be defined. For this purpose, the steps shown in Figure 4 are derived.

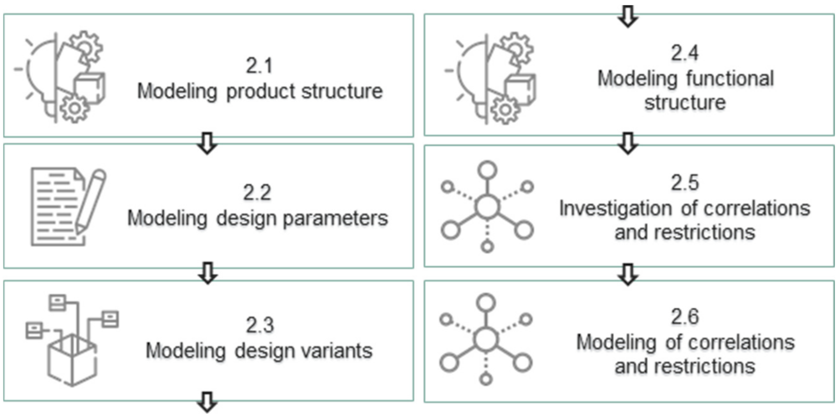

Figure 4: Process model steps for modelling of product structure and embodiment-function-relations

The product structure can be modeled based on the motor topologies and reference product models defined for the modular system. For this purpose, the subsystems required for the respective topology must be mapped, as well as the overall system structure. In addition to mapping the product structure, it is also necessary to identify parameters that can be used to describe the product properties. These can also be assigned to the individual subsystems and describe both principle solutions and physical variables. In the next step, individual building blocks in the form of variants of the product parameters must be defined to define the modular system. These can, for example, represent different magnet classes or voltage levels as well as geometric dimensions and should be derived based on the previously determined future robust requirements and static and dynamic product properties. According to Albers, a distinction can be made between parameters with and without different variants, which ultimately together represent the hat and platform. In a final step, an evaluation of interactions in the product is required. This is done in matrix form by evaluating the influences of individual parameters on each other in pairs. Combination restrictions of the individual parameter variants can also be evaluated in the form of a matrix.

3.3 Product-Production-CoDesign

In addition to the development of a modular product system, the simultaneous development of a production system is required. This must do justice to the diversity of the product construction kit in terms of Product-Production-CoDesign. Restrictions resulting from production must also be considered in the product construction kit. For this reason, the process model also provides for an analysis of the interactions between the product and the production system, analogous to the analysis of interactions in the product. The steps required for this are shown in Figure 5.

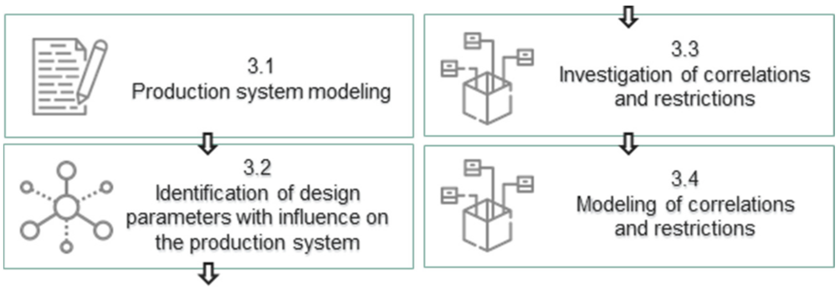

Figure 5: Process model steps regarding Product-Production-CoDesign

In the first step, the process model provides for the modelling of the process steps required to produce the motor topologies and variants contained in the construction kit. In the case of PSM, ESM and ASM, which are chosen as most relevant for a future robust construction kit, these can be partly identical and partly different. In the following, it is necessary to identify the product parameters contained in the construction kit with an influence on the individual process steps. The interactions between the product parameters and production processes can then be examined in more detail. It makes sense to differentiate between the strength of the influence. The matrix-based evaluation of all influences of the product parameters on the production processes is a good option here.

3.4 Continuous Modelling of Construction Kit

To simplify the design and use of the developed modular system for traction motors, it is advisable to use model-based systems engineering (MBSE) methods. The aim is to utilize the defined modular structure in the development process. The aim is therefore to map the product structure and different variants, as well as a criteria-based preselection of parameters and the transfer of data to further design steps and tools. The steps envisaged for this in the process model are shown in Figure 6.

Figure 6: Process model steps for continuous modelling of product construction kit

The construction kit is modeled on the basis of Albers et al. [23] and Weilkiens [24]. In addition to mapping the product structure, this also provides for the mapping of individual variants. On the one hand, this provides for the modeling of the already described contents of the product structure, the embodiment-function relations and the Product-Production-CoDesign. On the other hand, functionalities for preselecting variants and for analyzing the derived dependencies in the product and the production system are integrated into the MBSE model.

Ultimately, the construction kit modeled in MBSE is intended to serve as a starting point for the preselection of suitable traction motors and the subsequent transfer and mapping of information required or generated by development engineers in further development steps. To ensure the applicability of the modular system, the process model also provides for validation of the model through application in the development process. Based on the results, the functionalities of the modular system are adapted and optimized again to ensure an improved traction motor development process.

4 Results

4.1 Derivation of Future-robust Procut Requirements

Considering the results of the reference analysis and the scenario process, the identified product potentials were employed to validate the configuration of the construction kit in the third process step. Seven static and seven dynamic product properties were defined. For instance, synchronicity was identified as a static operating principle, while the level of system integration and the generation of the magnetic field were recognized as dynamic product properties. Figure 7 illustrates an excerpt of the results in the shell model for classifying statics and dynamics. The inner part of the shell model displays static properties, while the next shell exhibits dynamic properties with several anticipated characteristics. On the outermost shell, dynamic properties with various equally anticipated characteristics are presented. This visual tool facilitates the identification of critical characteristics in the construction kit and therefore can be used in choosing different topologies of electric traction motors.

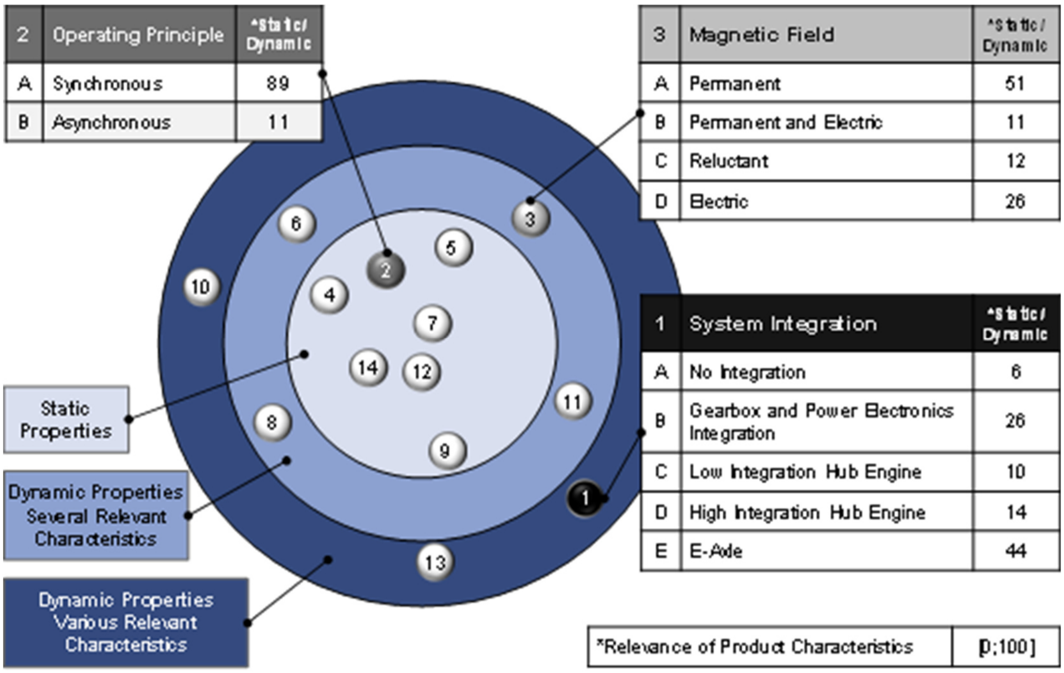

Figure 7: Excerpt of the results in the shell model for classifying statics and dynamics [22]

4.2 Modelling of Product Structure and Embodiment-Function-Relations

The modelling of the product structure and embodiment-function relations provided for in the process model was carried out using the Enterprise Architect program, which can be used for MBSE modelling. Figure 8 shows an excerpt of the modelled product structure.

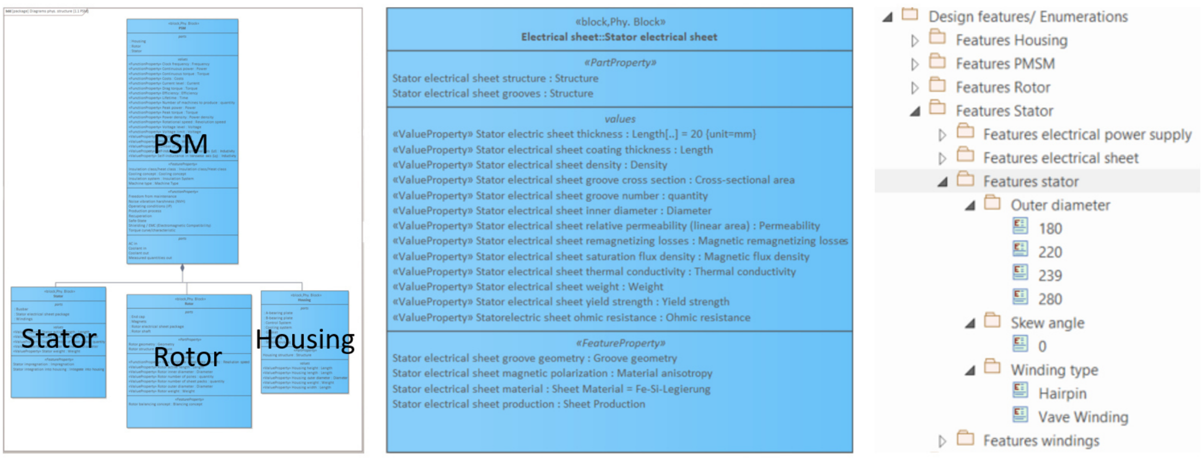

Figure 8: Excerpt of modelled product structure

To model the product structure, the individual system levels for the motor topologies contained in the modular system were examined and the subsystems to be modelled were identified. These represent, for example, the windings, magnets, electrical sheets or the housing. These were modelled in the form of blocks in block definition diagrams. For the individual subsystems, additional design parameters essential for the fulfilment of the function were identified. For example, the stator's electrical sheet can be described using its outer diameter, inner diameter, sheet thickness and other parameters such as the number of slots. To separate the design parameters into the individual subsystems, these were modelled as properties. A library with enumerations describing the individual properties was created to map the variants provided in the modular system, such as different outer diameters. The system model also includes a functionality for preselecting certain variants based on simple criteria. This links simple requirements that are to be fulfilled with the subsystems that are involved in fulfilling the respective function.

4.3 Product-Production-CoDesign

The influences of various product parameters on the production system were examined for PSM, ESM and ASM. Of particular interest were the production processes that significantly change the shape and properties of electric traction motor components. To evaluate the influences, a pairwise evaluation of the influence of a product parameter change on a production process was carried out. A distinction was made between: "no influence", "requires software-specific adjustments or mechanical settings", "requires adjustments to tools and/or process development", "requires adjustments to the machine structure/technology". Both stator parameters with their respective production processes and rotor parameters with their respective production processes for PSM, ESM and ASM were considered. Figure 9 shows an excerpt of the matrix-based evaluation of dependencies.

Name	Electrical sheet handling	Magnet assembly	Winding	Transfermolding	■ ■ ■
Air gap	0	0	0	0	
Active length	3	3	3	5	
Magnet position	0	5	x	5	
Inner diameter electrical sheet	3	3	0	3	
⋮					

Figure 9: Excerpt of matrix-based evaluation of dependencies between product parameters and production processes

Parameters such as the winding scheme, the conductor cross section and the number of conductors per slot, as well as the number of poles and phases, are parameters that have a major influence on the overall production process. In contrast, parameters such as the magnet or wire coating only have a minor influence on the overall production process. It was also found that production processes such as slot base insulation, insertion of the hairpin basket and twisting of the hairpins are influenced by many product parameters. In a final step, the identified interactions between product features and production processes were incorporated into the system model that was created. To this end, all relevant production process steps for the rotor and stator of a PSM and FSM were first modelled. The interactions were then stored in a relationship matrix. To map the varying degrees of influence, an overlay was created in Enterprise Architect specifically for the interactions with the production system, which corresponds to the classifications described above and thus enables a differentiated description of the dependencies.

4.4 Continuous Modelling of Construction Kit

As part of the AgiloDrive project, the Enterprise Architect software was used to model the developed construction kit. The contents modeled for this are shown in excerpts in Figure 10.

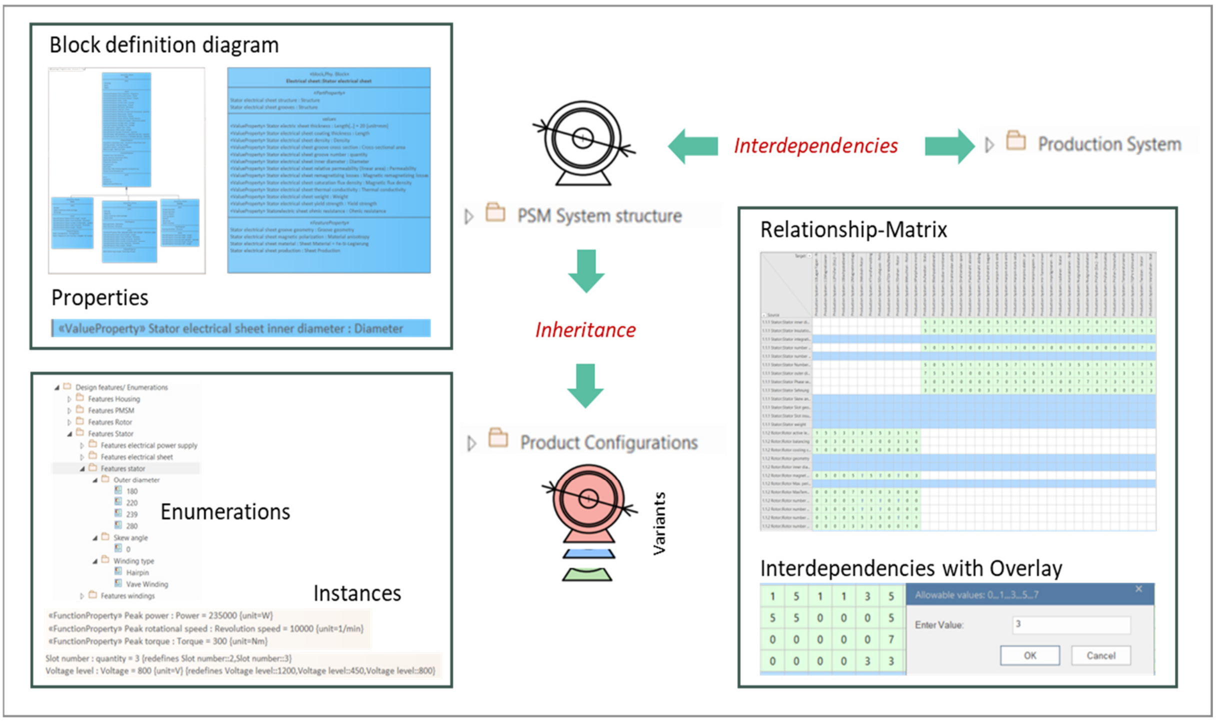

Figure 10: Excerpt of modelled contents and interactions

During this, the product structure for PSM and ESM was modeled using block definition diagrams. The individual blocks, which represent the subsystems of the traction motors, were also assigned the defined parameters and variants of the modular system in the form of properties. These are directly linked to their physical units via a unit library. The individual variants to be provided in the construction kit can be modeled using enumerations and assigned to the properties. Inheritance can then be used to generate instances of the created product structure in the created model, to which specific parameters can be assigned from the defined parameter variants. The embodiment-function relationships and interactions with the production system identified in the previous steps were stored in Enterprise Architect in the form of relationship matrices and are linked to the product structure via the product parameters assigned to the subsystems. With the help of overlays, the modeled dependencies could also be assigned a weighting. The possibility of exporting the relationship matrices in the form of csv files also allows further analysis of the dependencies stored in the system model, which enables, for example, an impact and risk analysis of parameter changes. Ultimately, the model can also be used to derive parameter sets of individual traction motor variants for further design steps. For this purpose, decision criteria are implemented within decision tables which can be used to select individual parameters based on input data sets including requirements for the traction motor. Furthermore, additional data such as simulation or test results can also be linked in the system model. The model has yet to be implemented and validated by development engineers. During this, the interfaces to other design tools and data transfers, as well as the criteria for parameter preselection, will be further refined.

5 Conclusion and Outlook

Due to various economic, legal, and technological factors, the future demand for electric traction motors in the market remains uncertain. Despite the growing popularity of hybrid and battery-electric vehicles, key aspects such as required quantities, types of motors, necessary power ratings, and other relevant parameters are not yet clearly defined. Therefore, the development of a future robust construction kit of electrical traction motors offers a solution to fulfil these uncertainties. This development requires the consideration of multiple aspects such as the derivation of requirements in the future, the selection and modelling of suitable product topologies and structures, the simultaneous development of a production system as well as the consideration of interdependencies. Finally, a continuous modelling and adaptation of the construction kit for changing requirements is necessary. In this paper the authors derived and presented a process model that can be used for future construction kit developments. Also, an exemplary application of the process model for a traction motor construction kit which was modelled in Enterprise Architect was shown. In future work the usage of the construction kit during a development process is evaluated and adapted to further improve the usability as well as the data transfer to other development tools.

6 Acknowledgments

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