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Product-Production-Co-Design for Agile Production of Electric Traction Motors

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Summary

The state of the art for manufacturing of electric traction motors are rigid production systems with low flexibility and scalability but high productivity. However, the demand for different types of electric traction motors is volatile due to economic and market trends as well as technological developments. Hence, employing rigid production systems imposes an entrepreneurial risk since they require high production numbers to be profitable. Agile production systems, capable of reacting to changing demands and producing different types of electric motors, are a future-proof alternative. Thus, an approach towards the integrated development of product and production system for the agile manufacturing of electric traction motors is presented in this publication.

Keywords: electric drive, motor design, industrialization, digitalization, efficiency, research

1 Motivation and State of the Art

Regardless of the level of electrification, electric traction motors play a central role in current development trends of passenger cars and commercial vehicles. Both in theory and in practice, there has been at least a hundred years of experience in the design, testing and manufacturing of electrical machines – primarily based on industrial applications. In particular, three-phase machines are used according to the state of the art as electric traction motors. A further distinction can be made between permanent-magnet synchronous machines (PSM), separately excited synchronous machines (SSM) and induction machines (IM). The synchronous reluctance machine (RM) as well as special types as the transverse flux machine (TFM) are subject of research and recently not state of the art in applications for traction drives. [1]

Depending on the machine type, various known manufacturing processes can be used. In principle, the relevant types of three-phase machines (PSM, SSM and IM) are constructed in the same way and consist of the three subsystems stator, rotor and housing from a mechanical point of view. The stators are designed following the same basic principles, but at the highest level of the subsystem, there is a distinction in between distributed and concentrated windings regarding the copper conductors, which are forming the functional coils. In addition, conductors with a round or a rectangular cross-section can be used for both winding types. The structure of the rotor varies strongly depending on the machine type: Whereas bearings, lamination stack and shaft are similar, PSM rotors basically consist of permanent magnets, SSM rotors contain a winding, which is separately excited, and IM rotors are based on massive conductor bars, which are excited by the rotating stator field. The housing is casted from aluminum alloys in most cases and has no further requirements that are unfamiliar in industry applications. [1, 2]

But because of uncertain forecasts regarding the types of electric vehicles demanded by customers as well as the quantities and product life cycles coming along with this, the risk of investments in available state-of-the-art production systems needs to be classified as high. For this reason, the AgiloDrive research project, funded by the Ministry of Economic Affairs, Labour and Tourism Baden-Württemberg as well as the Federal Ministry for Economic Affairs and Climate Action, is focusing the integrated development of modular product and production modules with the aim of creating an agile and demand-oriented production system, shown in Figure 1 and outlined in [3]. In this context, the interrelationships of the product construction kit, the product design methods and the production construction kit play a decisive role.

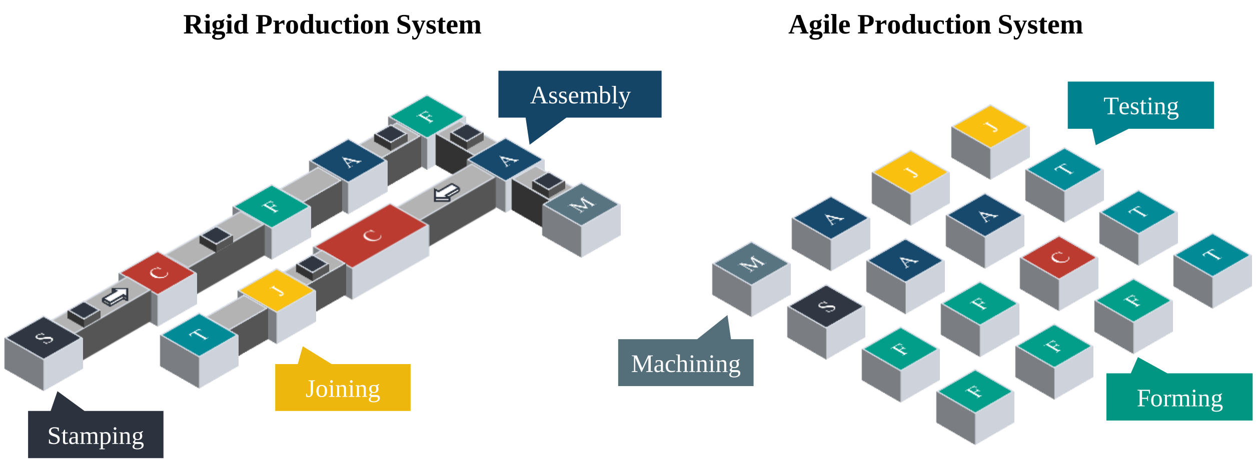

Figure 1: Rigid production system (left) and agile production system with configurable modules (right) [3].

The authors have already demonstrated the existing interrelationships between product and production [4, 5] and pointed out the need for a parallel technology and product development process in the automotive environment [6] in initial investigations.

The product construction kit determines the framework of all available design parameters as the number of stator slots or the operating voltage for the machine designers and the production engineers derive the production construction kit based on the range of the resulting machine parameters as the outer diameter of the stator lamination stack. This development process needs to be parallel in the project AgiloDrive – a process which is comparable to sequence of iterative negotiations of product designers and production engineers.

2 Product Construction Kit

Several approaches describing the development of products, production systems and their interrelationship have been published. The need for an integrated approach towards the development of product and production system is mentioned in both standards and scientific publications on this subject. Integrated product development approaches take a consistent view of the entire product life cycle, always considering the interrelationship between products and production processes [7]. The standard VDI 2206 [8] describes how to simultaneously develop product and production system considering restrictions of the production system. The aim of these and other approaches towards an integrated development are the best possible product combined with a highly efficient production, a satisfying use and an appropriate disposal of the product [9]. The required interdisciplinary collaboration and simultaneous development in the product, production and also sales departments are especially considered in collaborative design approaches [10]. The approach “Product-Production-Co-Design” (PPCD) presented in [11] describes the collaboration and parallelization of the following activities: planning, development and realization of products and the associated production system, efficient and effective operation of production, development of associated business models and the systematic decommissioning of products and production systems. It is necessary to consider several product generations and the corresponding production system evolutions in the context of PPCD to effectively support product and production system engineers by enabling them to utilize existing knowledge and consider potential future developments.

Another challenge in current product engineering processes is the increasing system complexity which requires the utilization of new methods and tools for continuous and integrative user support. Shifting from classic document-based approaches towards the framework of “Model-Based Systems Engineering” (MBSE) is a possible solution to manage interrelationships between product and production design by linking requirements, functions and product features. Furthermore, manufacturing and assembly processes can be linked to product components and their design while also linking manufacturing and assembly processes to tools, process parameters, process and machine modules as well as functional units as presented in [12].

Based on these findings, the system of objectives of the product construction kit is defined as follows: Providing electric traction motors for different drive system architectures, the reuse of technologies instead of parts in the construction kit, a consideration of low quantities and high variances as well as product diversity are enabled while exploiting the flexibility of the agile production system. To accordingly develop a product construction kit for electric traction motors, the product modeling framework proposed in [13] is used, see Figure 2.

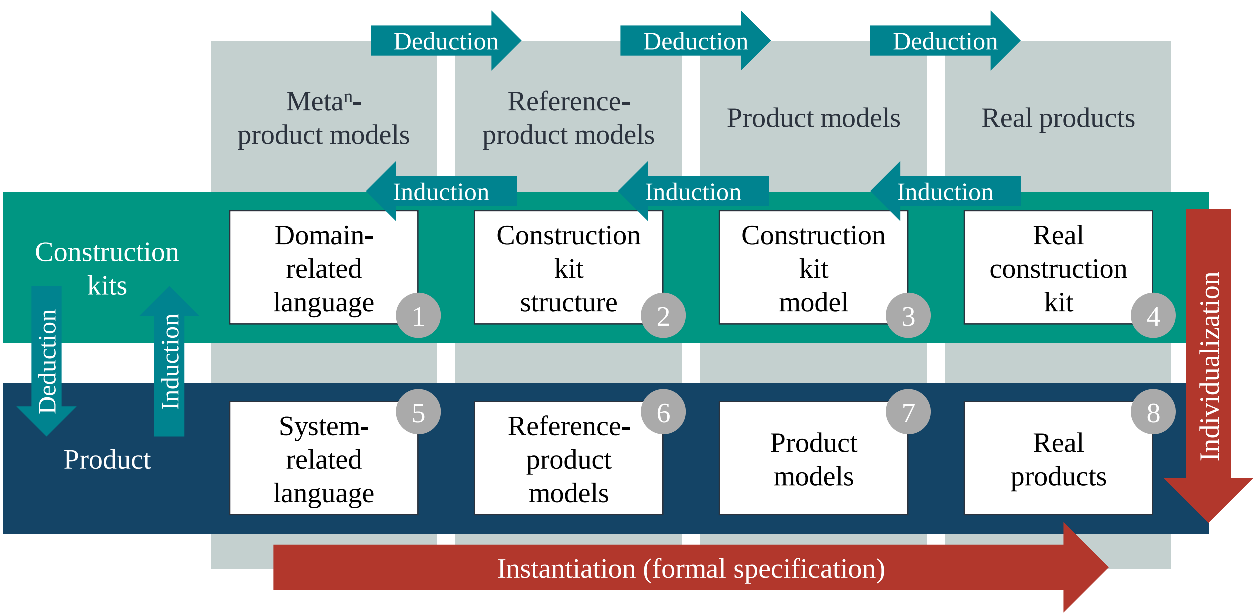

Figure 2: Product modeling framework for construction kit development [13].

To ensure a future-proof product construction kit, the considered reference-product model is not only based on electric traction motors which are currently available but also on product scenarios of potential future drive systems. To develop these product scenarios, methods of future management are utilized [14]. Initially, a requirements analysis is conducted to identify current and future requirements for electric traction motors. While typical requirements regarding torque, power, safe-state behavior and efficiency will remain relevant, the voltage of the drive systems might change and other features might shift into focus depending on the application. Based on these sets of requirements, influencing factors on design, development and features of electric traction motors are gathered. An impact analysis is conducted to determine the influencing factors that are having a large impact on other influencing factors and features of electric traction motors. The analysis showed that for PSM the permanent magnet arrangement in the rotor, the type of stator winding, the number of pole pairs as well as geometric factors were the most influencing and thus most relevant factors to be considered when building the product scenarios. Subsequently, possible specifications of these factors, called projections, that should be used in the scenario building are determined, considering restrictions of the production system. Then, various application scenarios for electric traction motors are defined (e.g. vehicle segments, use in battery-electric or hybrid-electric drive systems etc.), which could occur in possible future mobility scenarios. The projections of the respective influencing factors are combined in a way that a consistent specification of an electric traction motor fulfilling the requirements of the respective application is obtained. Product models based on these specifications are consecutively considered in the reference-product modeling.

The product construction kit structure is elaborated based on the reference-product models. The product construction kit structure comprises various reference system elements, such as kits, their rules and regulations as well as electric traction motors. The set of rules for a construction kit specifies the architecture of the subsystems and, in particular, the interfaces to ensure compatibility of modules and subsystems of the construction kit during product synthesis. It should be noted that both technical interfaces between the modules of the product (geometric, material, energy and information flows) and organizational interfaces in the system model (information flow between the stakeholders) must be defined. The consideration of interactions in the technical design of electric traction motors is extended to include production-related restrictions in the design process as production is a major stakeholder in the engineering process.

The activities carried out up to the conceptual design of the construction kit were abstracted into a process model in order to make the accumulated knowledge accessible to future construction kit developments, see Figure 3.

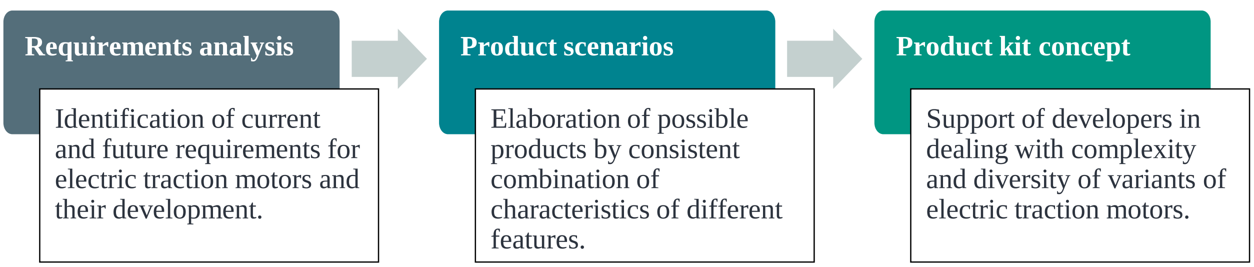

Figure 3: Abstract process model for the conceptual design of product construction kits.

3 Design Methods for Electric Machines

Fundamental to an agile and demand-driven production system as well as future-proof construction kits is an efficient machine design process. In general, the design process is a sequence of iterative optimizations in order to determine the most appropriate parameters of the electric machine. Parameters optimized during the electromagnetic, thermal and mechanical design process are the geometries of stator and rotor lamination stacks as well as the winding configuration, for example.

The conventional design process was developed for a fixed set of requirements and boundary conditions which need to be considered. In this case, i.e. the topology of the rotor and the stator winding are defined at an early stage and cannot be easily changed in the subsequent periods of machine design. This means that the first and most relevant restrictions are made at a very early stage of the design process. In addition, the state-of-the-art design process is divided into different physical domains [15] and [16], i.e. the electromagnetic, thermal and mechanical design are carried out separately. However, the different physical domains influence each other which means that they must be carried out simultaneously to achieve an optimal electric machine and the results of each single step during the design process must be incorporated into the other.

The connection in between the different physical domains and the consideration of parameter restriction in early stages of product design are some of the main drawbacks of the conventional design methods for electric machines. Adjustments resulting from these challenges lead to high costs as well as additional efforts and development time when requirements need to be changed in later stages of the design process. In contrast, a surrogate model-based optimization process helps to deal with volatile requirements and can be seen as a first step towards an agile product design process. Therefore, a multi domain surrogate model based on a “Gaussian Process Regression” (GPR) is used [17]. The advantages are that several key properties of the electric machine, such as the maximum power, the maximum torque or the efficiency, but also thermal and mechanical properties can be represented in the model. Based on this, a multi target optimization can be conducted in an efficient way. For each set of requirements an individual target function can be defined, but the surrogate model itself will remain the same – one of the main advantages of the model-based design process.

The basic workflow to create the surrogate model is shown in Figure 4. First, the parameter space must be defined for each design parameter. In the subsequent step, an initial set of training data for the surrogate model is created by a suitable design of experiments. Due to the special characteristics of numerical experiments, a “Latin Hypercube Sampling” (LHS) [18] is used to cover the parameter space with a certain number of samples. The necessary number of samples, which is essential for a good modeling quality, depends on the dimension of the parameter vector and the complexity of the relevant data. After achieving the training data based on the LHS by numerical simulations, the surrogate model is trained and the optimization is carried out according to the target function. Afterwards, the results need to be validated with a finite element simulation. Based on the validation, the training data for the surrogate model will be iteratively adjusted to obtain a more accurate result. When all requirements and constraints are met, the optimization process is completed and the best machine is identified.

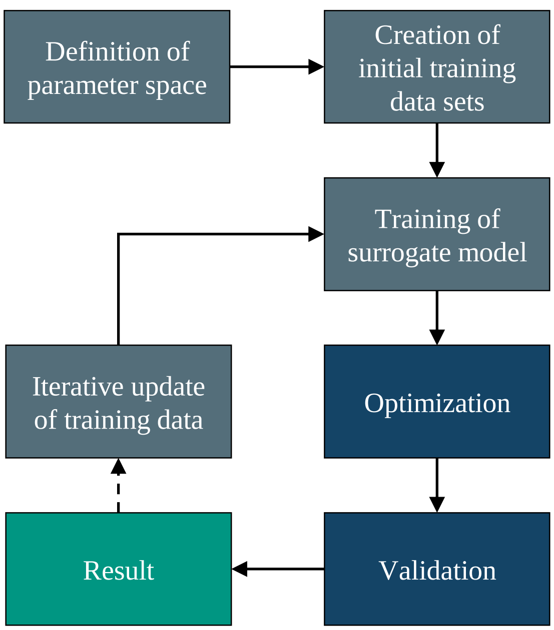

Figure 4: Workflow to perform a surrogate model-based optimization process for electrical machines.

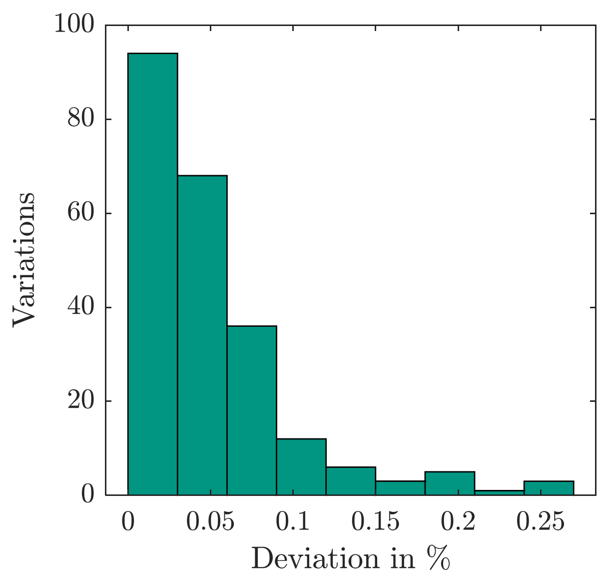

Figure 5: Deviation in percent between the predicted results and test data for the torque at base point.

To validate the approach, a surrogate model for the maximum torque at the base point was trained. In Figure 5, the deviation between the results predicted by the surrogate model and the test data is shown. It can be seen, that the model quality for the torque in the base point is sufficient, because the arithmetic median deviation between the predicted results and the test data is about 0.037 %.

The GPR modeling is already implemented and good results with small data sets could be achieved. However, for the agile development of complete product construction kit, more powerful surrogate models are needed. Building on this, more powerful modeling approaches such as "Convolutional Neural Networks" (CNN) will be investigated within the current period of the research project. A possible goal of this approach is a nonparametric optimization process for electric machines. Furthermore, operating parameters shall be included in the models in order predict a set of specific operating points in a more efficient way.

4 Production Construction Kit

The vision of the agile production system, which is capable of economic but demand-oriented manufacturing of electric traction motors, is shown in Figure 6 in comparison to a conventional rigid production system. The simplified process function structure of the agile production system shows that product variants are not realized by individual, variant-specific functional units, but by flexible functional units which are linked by flexible transportation systems. The versatility of the production system that can be achieved in this way is intended to provide all processes and resulting process chains required for application-specific electric motor production in an economic way. In contrast to flexible production systems, the forced sequence of assembly, manufacturing and testing processes leads to a virtual, but deterministic cycle time resulting in a predictable throughput time. Further details regarding the function structure of agile production systems are addressed in [3].

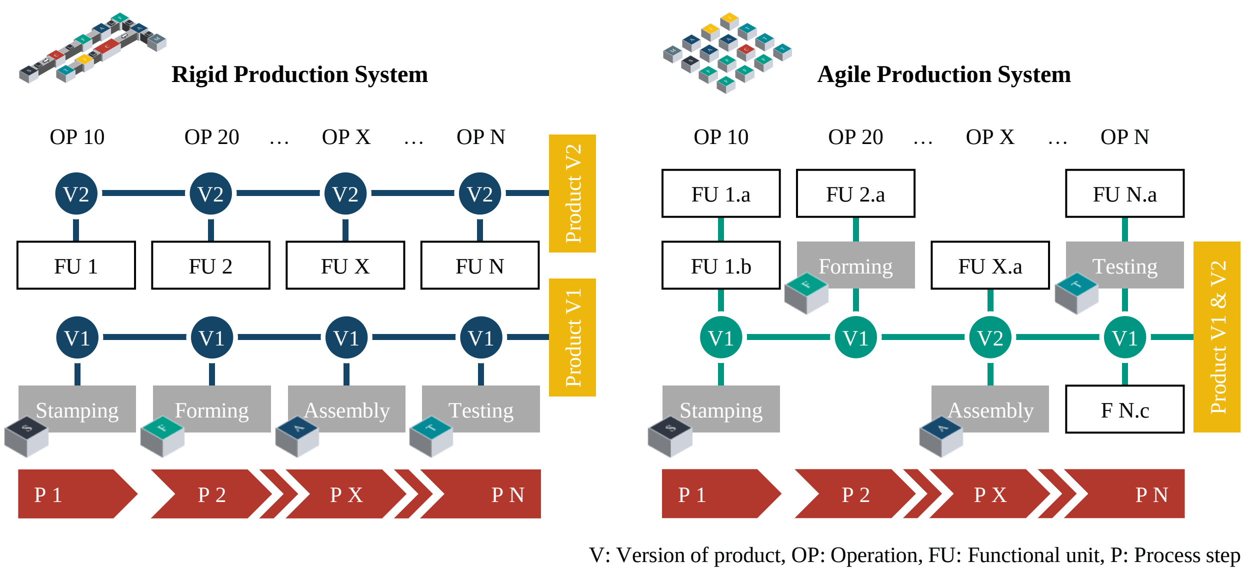

Figure 6: Function structure of rigid and agile production systems for electric traction motors. [3]

In order to discuss the interrelationships between the product characteristics and the production process it is necessary to analyze the agile production system and the construction kit referring to this at first. In general, functional units (FU) need to be considered at the highest system level (topology level). FUs are independent and fully functional subsystems which provide all services that are necessary to pass a defined process step (P). The FUs consist of machine modules (MM; machine level), process modules (PM, process level) as well as tool and handling kits (THK; process level) with an increasing level of product-based specialization in descending order. The FUs, MMs, PMs and THKs are the building blocks of the construction kit for an agile production system providing the necessary functions in a flexible and scalable way. The different characteristics of the building blocks, which are the modular basis for the production system's adaptivity discussed in the following chapter, and their interrelationships are shown in Figure 7.

A more general overview of the function structure of agile production systems for electric mobility including an introduction of the derived nomenclature is given in [19].

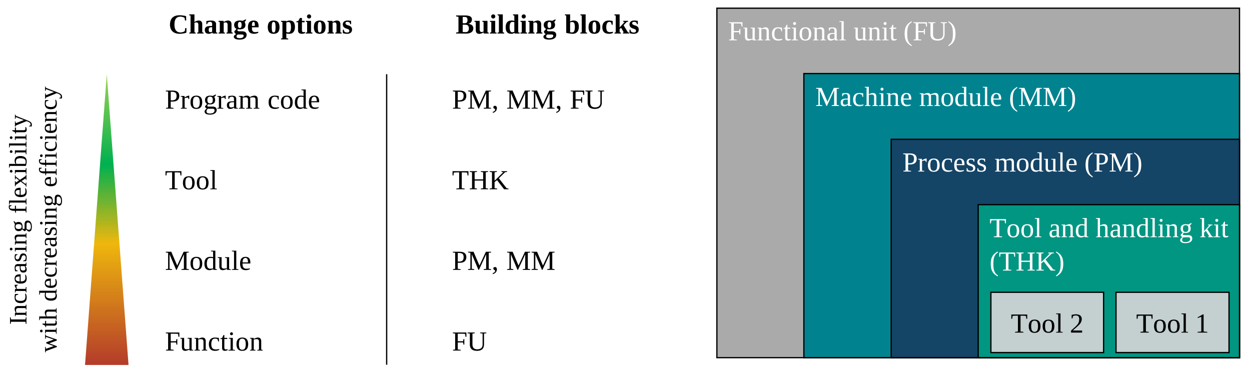

Figure 7: Four main options to change the configuration of an agile production system: program code change, tool change, module change or function change (left).
Schematic view of the modular construction kit for an agile production system (right) [19].

The change of a program code is the fastest and most efficient option to adapt the functionality of a single assembly, manufacturing or testing process. The adaption can be initiated on purpose by an interaction of the operator with the human-machine interface or autonomously by the master control in a closed-loop process. For example, the change of a program code could include the adaption of temperature profiles, machining times, tool trajectories or testing voltages. Usually, the change of a program code is conducted on the control system of the machine module or the functional unit. Furthermore, the change of tools, modules or complete functions mostly implicates the necessity of changes in program codes in production. When changing a tool in the THK, the tool is changed on the manipulator or the spindle of the machine, ideally by automated quick-change systems. Due to the mechanical intervention, this type of change is more complex than a software-based adaption but can still be considered as easy to implement based on standardized interfaces. Moreover, the change of whole modules enables more extensive adaptions of the production system but the necessary changes in software and hardware cause a higher effort for set-up. Depending on the degree of modularization, both single PMs and complete MMs can be changed on demand. Furthermore, the change of a FU enables the necessary adaptions of the process chain that come along with a change of the product or manufacturing technology. Due to the change of the function structure of the production system on its topology level this type of adaption is the most extensive but also least flexible approach. Based on the flexible linking of the agile production system adaptions on topology level can be realized without changes of the FUs if the necessary processes are already part of the function structure.

Besides the process-oriented flexibility focused above, the possibility for changing PMs, MMs and FUs also ensures an unrestricted scalability of the agile production system.

5 Examples and Discussion of Changes in the Agile Production System for Manufacturing of Stators with Hairpin Winding

The scalable and flexible function structure of the agile production system can be applied for stator and rotor manufacturing and the final assembly as well. In the following context, the manufacturing of stators is primarily focused as an example in order to point how to cope with the main challenges of agile electric motor production.

5.1 Change of the Program Code

Looking at the process chain for manufacturing of stators with hairpin winding, the hairpin bending process is a well-suited example of a program code change when kinematic or sequential tool-bound bending is used [20]. For this purpose, PMs based on flexible bending technologies need to be applied. This type of bending module provides several degrees of freedom regarding the bending kinematics using tools that are designed according to the minimum and maximum bending radii as well as the wire geometry. If a different hairpin shape is required due to a change of the product variant, the sequence of bending operations can be efficiently reconfigured by executing an adapted bending program and a new type of hairpin coil is manufactured on the existing FU.

5.2 Change of Tools

In order to stay with the example of hairpin bending, conventional tool-bound bending technologies require a change of the applied bending tools for each adaption of the type of hairpin coil which needs to be manufactured according to the product design [20]. If both the PM and MM are modularly designed and suitable bending tools are already available, the effort required to change the type of hairpin coil can be estimated as low. Besides, changes of the wire geometry also cause a necessity for changing handling tools, e.g. the guidance, if PMs based on kinematic or sequential tool-bound bending technologies are applied for the manufacturing of hairpin coils.

Another example for tool-based adaptions of the process chain is the hairpin twisting process. If the inner and outer diameter of the stator, the number of slots, the winding scheme (i.a. coil width, number of holes etc.) or the wire geometry are modified amongst other physical characteristics, the set of twisting tools installed in the FU needs to be changed. Therefore, these modifications are linked to high investments and long manufacturing times if the tools are not part of existing THKs [21]. In contrast, some modifications of the product design as the number of wires per slot require changes of modules at the machine and process level if the available degrees of freedom of the production equipment are exceeded.

5.3 Change of a Module

If modifications of physical product characteristics implicate changes on machine and process level of the function structure, a distinction must be made between changing modules of PMs and MMs. For example, a change of the wire's insulation system could lead to a necessity for changing the manufacturing technology to the application of mechanical tools instead of laser ablation. Due to the technological change of the process, the PM must be changed considering the function structure on machine level as well as the predefined interfaces. If the installation space and number of interfaces is sufficient, both types of PM can be installed in the MM at the same time to speed-up future process adaptions.

In contrast to process-oriented PMs which cannot be run as a stand-alone system, MMs contain both a control architecture – consisting of a process control, a safety control as well as an interface to the master control – and parts of the mechanical structure of the FU. Hence, changes of MMs are a more extensive intervention to the function structure in comparison to a PM which is usually linked to high investments and a possible downtime of production. For example, the change of a MM may be necessary if dip impregnation is to be substituted with trickle impregnation regarding the impregnating process. As a result of the technological change, the mechanical structure needs to be changed to realize the differing handling and impregnating processes. However, the upstream and downstream subprocesses of heating and cooling can be reused due to the modular function structure on machine level, whereby the corresponding FU can remain.

5.4 Change of a Function

In principle, the need to change a complete function of the process chain is usually initiated by a change of the applied manufacturing technology. Some examples which would cause the necessity for adaptions on topology level are modifications of the stator winding technology from hairpin technology to continuous hairpin technology or from hairpin technology to coil winding technologies [5]. To cope with this demand, additional

FUs need to be integrated in the function structure of the agile production system considering the standardized requirements regarding mechanical, material, energy and information interfaces.

6 Summary and Outlook

The future market demand for electric traction motors is subject to uncertainties which result from economic and legal boundary conditions as well as technological developments. Hence, in spite of increasing sales of hybrid- and battery-electric vehicles, there is still an extensive uncertainty regarding the required quantities, the deployed motor types, the necessary motor power and other parameters. However, the economic operation of conventional rigid production systems as transfer lines which used in automotive industry according to the state of the art is limited to a very small number of product variants and the production capacity specified during the period of production design. As a consequence of the highly restricted flexibility and scalability according the actual market demand the entrepreneurial risk of investments is significant. To reduce this risk, agile production system providing high versatility and productivity can be employed as a future-proof alternative. But there are still challenges regarding technology and costs which must be solved, i.e. the economic definition of boundary conditions for product and production construction kits which are strongly linked by numerous interrelationships. Against this background, methods for the integrated development of product and production kits for agile manufacturing of electric traction motors are researched in the AgiloDrive project in order to establish novel industrial standards to industrialize the future-proof concept of agile production.

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References

[1] M. Doppelbauer, *Grundlagen der Elektromobilität: Technik, Praxis, Energie und Umwelt,* 1st ed. Wiesbaden: Springer Fachmedien Wiesbaden; Imprint Springer Vieweg, 2020. [Online]. Available: http://swbplus.bsz-bw.de/bsz1728472954cov.htm

[2] J. Fleischer and F. S.-L. Blanc, Eds., *Handbook of Coil Winding: Technologies for efficient electrical wound products and their automated production*. Berlin, Heidelberg: Springer Vieweg, 2018. [Online]. Available: http://swbplus.bsz-bw.de/bsz491749481cov.htm

[3] J. Fleischer *et al.,* “Agile Produktion elektrischer Traktionsmotoren als Antwort auf volatile Märkte und Technologien,” *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, vol. 116, no. 3, pp. 128–132, 2021, doi: 10.1515/zwf-2021-0025.

[4] M. Halwas *et al.,* “Coherences Between Production Technology and Performance of Electric Traction Drives,” in *2019 9th International Electric Drives Production Conference (E|DPC): 3 and 4 December 2019, Esslingen, Germany : proceedings*, Esslingen, Germany, 2019, pp. 1–9.

[5] M. Halwas, L. Hausmann, F. Wirth, J. Fleischer, B. Jux, and M. Doppelbauer, “Influences of Design and Manufacturing on the Performance of Electric Traction Drives,” in *Proceedings 2020 International Conference on Electrical Machines (ICEM): Online, 23-26 August, 2020*, Gothenburg, Sweden, 2020, pp. 488–494.

[6] M. Halwas *et al.,* “Entwicklung eines parallelen Technologie- und Produktentwicklungsprozesses - Am Beispiel der Wicklungsauslegung und -fertigung im Rahmen des Förderprojektes NeWwire, Development of a parallel technology and product development process using the example of winding design and manufacture as a part of the

NeWwire funded project,” *wt Werkstattstechnik online*, vol. 108, no. 5, p. 301, 2018. [Online]. Available: https://publikationen.bibliothek.kit.edu/1000128166

[7] U. Lindemann and M. Lorenz, “Uncertainty Handling in Integrated Product Development: 10th International Design Conference DESIGN 2008, Dubrovnik, Croatia,” 2008.

[8] *Entwicklungsmethodik für mechatronische Systeme,* VDI 2206, Berlin, Jun. 2004.

[9] K. Ehrlenspiel and H. Meerkamm, *Integrierte Produktentwicklung: Denkabläufe, Methodeneinsatz, Zusammenarbeit,* 6th ed. München: Carl Hanser Verlag, 2017.

[10] G. D. Putnik and Z. Putnik, “Defining Sequential Engineering (SeqE), Simultaneous Engineering (SE), Concurrent Engineering (CE) and Collaborative Engineering (ColE): On similarities and differences,” *Procedia CIRP*, vol. 84, pp. 68–75, 2019, doi: 10.1016/j.procir.2019.07.005.

[11] Albers Albert *et al.,* “Product-Production-CoDesign: An Approach on Integrated Product and Production Engineering Across Generations and Life Cycles,” *Procedia CIRP - in press*, 2022.

[12] A. Albers, T. Stürmlinger, C. Mandel, J. Wang, M. B. de Frutos, and M. Behrendt, “Identification of potentials in the context of Design for Industry 4.0 and modelling of interdependencies between product and production processes,” *Procedia CIRP*, vol. 84, pp. 100–105, 2019, doi: 10.1016/j.procir.2019.04.298.

[13] A. Albers, H. Scherer, N. Bursac, and G. Rachenkova, “Model Based Systems Engineering in Construction Kit Development - Two Case Studies,” *Shpitalni, Fischer et al. (Hg.) 2015 – CIRP 25th Design Conference*, pp. 129–134. [Online]. Available: https://doi.org/10.1016/j.procir.2015.01.044

[14] A. Fink and A. Siebe, *Szenario-Management: Von strategischem Vorausdenken zu zukunftsrobusten Entscheidungen*. Frankfurt, New York: Campus Verlag, 2016.

[15] G. Bramerdorfer, J. A. Tapia, J. J. Pyrhonen, and A. Cavagnino, “Modern Electrical Machine Design Optimization: Techniques, Trends, and Best Practices,” *IEEE Trans. Ind. Electron.*, vol. 65, no. 10, pp. 7672–7684, 2018, doi: 10.1109/TIE.2018.2801805.

[16] G. Lei, J. Zhu, Y. Guo, C. Liu, and B. Ma, “A Review of Design Optimization Methods for Electrical Machines,” *Energies*, vol. 10, no. 12, p. 1962, 2017, doi: 10.3390/en10121962.

[17] C. E. Rasmussen and C. K. I. Williams, *Gaussian processes for machine learning*. Cambridge, Mass., London: MIT, 2006.

[18] B. Tang, “Orthogonal Array-Based Latin Hypercubes,” *Journal of the American Statistical Association*, vol. 88, no. 424, p. 1392, 1993, doi: 10.2307/2291282.

[19] J. Fleischer, F. Fraider, F. Kößler, D. Mayer, and F. Wirth, “Agile Production Systems for Electric Mobility,” in *55th CIRP Conference on Manufacturing Systems - in press*, Lugano, Switzerland, 2022.

[20] F. Wirth, L. Hausmann, A. Eppler, and J. Fleischer, “Metamodeling of Numerical Simulations for Optimization of Hairpin Bending Processes,” in *2021 11th International Electric Drives Production Conference (EDPC)*, Erlangen, Germany, 2021, pp. 1–9.

[21] L. Hausmann and J. Fleischer, “Flexibles Twisten von Statoren mit Hairpin-Wicklung,” (in de), *wt Werkstattstechnik online*, vol. 111, 07-08, pp. 490–494, 2021, doi: 10.37544/1436-4980-2021-07-08-22.

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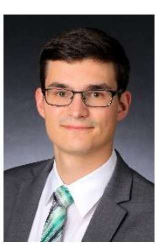

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