INTERNATIONAL DESIGN CONFERENCE – DESIGN 2024
https://doi.org/10.1017/pds.2024.84

Enhancing design automation for components of electric machines: a systematic approach

Niklas Umland [1,✉], Anton Wiberg [2], Kora Winkler [1], Jakob Jung [3] and David Inkermann [4]

[1] Fraunhofer IFAM, Germany, [2] Linköping University, Sweden, [3] Additive Drives GmbH, Germany,
[4] Technische Universität Clausthal, Germany

✉ niklas.umland@ifam.fraunhofer.de

Abstract

This paper presents a systematic approach to multidisciplinary design automation in electric motor engineering, focusing on component design. Existing work in this field is often limited to a single level and lacks portability and reusability. The approach aims to enable simultaneous component and system design, with comprehensive models capturing specifications and architecture. Feasibility is demonstrated through the automated design of additive manufactured hairpin windings.

Keywords: *design automation, multi-/cross-/trans-disciplinary approaches, electric machine, hairpin winding*

1. Introduction

Electric motor engineering is a field which displays intricate interconnections between the different engineering domains such as electro-magnetic, thermal, structural, and manufacturing. Consequently, the field of electric motor engineering has witnessed a significant rise in the application of multidisciplinary design automation approaches (MDDA) in recent years. These approaches allow for the simultaneous optimization of various properties in the design process, leading to improved performance and efficiency of electric motors. However, a recent review has revealed that despite its growing popularity, systematic approaches to set up MDDA processes for electric motor engineering are lacking. (Umland *et al.*, 2023)

Furthermore, existing MDDA applications often are limited to very specific cases, like high-speed motors or they integrate all knowledge into geometric models or hard coded procedural rules. This hinders the transfer of these approaches to other applications or motor designs (Umland *et al.*, 2023).

The same review also underscores the absence of strategies that integrate the various architectural levels of electric motor engineering, particularly the interaction between system-level and component-level design (Umland *et al.*, 2023). Moreover, it is common for design automation to be set up by engineers who, while experienced in application-specific domains, may lack formal training in software engineering, which suggests a potential gap in expertise that could benefit from additional support (Vidner *et al.*, 2022).

This work aims to bridge these gaps by proposing a systematic approach for deep diving into the design automation of a specific component of an electric motor. The proposed method enables to set up a design automation for detailed component design, with the goal to link it to the system's design procedure in future work. To highlight the applicability of the proposed approach, it is employed for the design of an additive manufactured hairpin winding.

2. Related work

In this section we provide an overview of the state of the art for setting up design automation workflows, component design in MDDA of components for electric motors and design automation (DA) for hairpin windings.

2.1. Setup of design automation workflows

Design automation represents a transformative approach in various engineering disciplines, utilizing computer-aided tools and methodologies to enhance and streamline design processes. Cederfeldt and Elgh (2005) define DA as reusable design engineering support which utilises computerized methods to automate the design process. This includes different methods and applications aimed at automation of repetitive and non-creative tasks (Verhagen *et al.*, 2012) with the common goal to increase efficiency and reduce the risk of errors (Rigger and Vosgien, 2018). DA can be utilised by using knowledge-based engineering, which is a concept connecting artificial intelligence and CAD (La Rocca, 2012). According to Colombo *et al.* (2014) creation of DA systems involves three steps: *knowledge capturing, formalization and representation*. More detailed steps to setup a DA framework is presented by Rigger *et al.* (2018), who try to identify tasks that need to be performed in order to identify relevant inputs, outputs, formalization and DA methods. Recent work focusing on hands on development of DA systems has shown how the formalized steps in knowledge collection and formalization also can be used to divide components into subunits used to build a DA framework. For instance Biedermann and Meboldt (2020) show how a knowledge capturing based on part architecture can be used to break down parts into design elements which then are used in a design synthesis step to build new variants of the design. The parts architecture is derived from an abstract system model and serves to define the different design elements and their functional and geometrical interactions. A similar approach including a more detailed description of tasks for the different steps is presented by Wiberg *et al.* (2023).

2.2. Component design in MDDA of electric motors

Component design in this work refers to MDDA processes where singular components are designed in detail, in contrast to system design, where the main parameters of all relevant components of the system are designed at once. Both can be found in the literature of MDDA for electric machines (Umland et al., 2023). Farhan *et al.* (2020) poses an example for system design in the scope of a MDDA by designing the active parts, i.e. stator, rotor and winding of the electric motor and analysing it from an electromagnetic, thermal and a mechanical view. For this, the system has to be simplified and the amount of design variables taken into account is limited. Most similar approaches focus on active parts design, passive parts and geometries are often neglected, but can have a significant influence on certain optimization objectives (Golovanov *et al.*, 2019). In (Di Nardo *et al.*, 2016) a component specific design is reported for the design of a rotor for a synchronous reluctance motor. Here only parameters of this specific component are considered, thus fixing parameters of other machine components, e.g. the stator. Consequently however, certain interdependencies between the components must be neglected. Thus, both system-centric and component-centric design approaches are constrained by their inherent limitations. Although some authors, such as Dai *et al.* (2019), adopt strategies that consider both component and system design aspects, the review by Umland *et al.* (2023) highlights that multilevel approaches are often overlooked in electric motor design, thus missing opportunities for parallel optimization processes and indicating a need for further methodological support.

2.3. Design automation for hairpin windings

A hairpin winding in electrical motors is a type of winding configuration where the individual wire turns are bent into a hairpin shape. This winding design allows for a more compact and efficient motor design, caused by improved heat dissipation and higher power density. However, the conventional production of hairpin windings requires a complex manufacturing process and is therefore only suitable for high volumes. (Du-Bar *et al.*, 2018)

Design automation of hairpin windings is subject of current research. For instance England and Ponick (2019) propose an approach for automatic design a hairpin winding scheme considering limiting factors

from an electromagnetic point of view, without considering the 3D geometry of the winding head. To deploy the benefits of additive manufacturing the 3D geometry must be designed in detail. Putz *et al.* (2023) demonstrate the automated design of a hairpin winding. The presented application is standalone and not integrated in to the motor's development process. This prevents the feedback of winding head design parameters into the system design, potentially resulting in additional design iterations or suboptimal winding designs.
In conclusion, existing approaches that partially address the setup of DAs have not been widely adopted in the field of electric machine engineering. This paper introduces a systematic approach to establish a DA specifically for a component of interest. This approach allows designers to effectively connect detailed component design with the overall motor design.

3. Approach

In (Umland *et al.*, 2023) a framework is presented that aims to include the detailed design of a component of interest in to the overall motor design process.

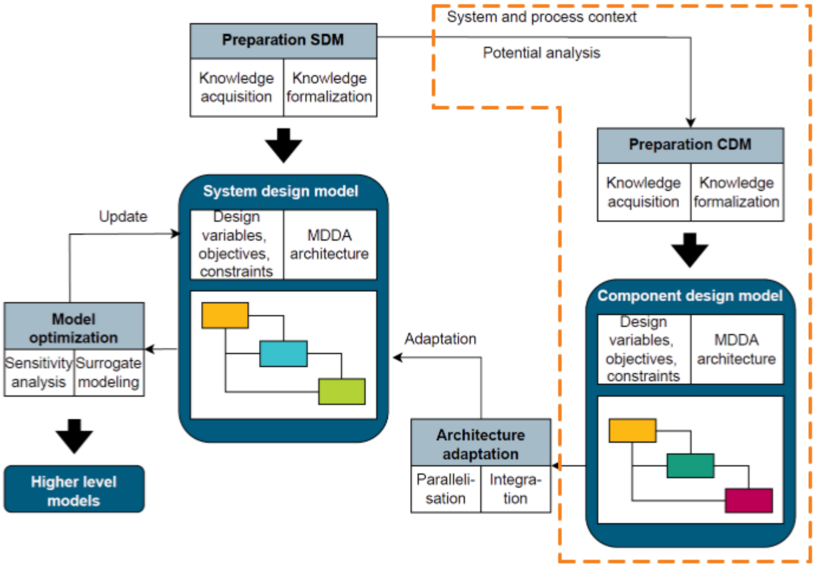

Figure 1. Framework for the MDDA of electric motors including component design aspects

The framework addresses the lack of guidance in setting up Multidisciplinary Design Automation (MDDA) processes for electric motor development. The framework consists of two main components: The System Design Model (SDM) and the Component Design Model (CDM). The SDM describes a modular framework for the design of electric motors at the system level, allowing for adaptation to specific application scenarios and design process stages. The SDM includes system level analyses from different domains, e.g. electromagnetic or thermal. For computational reasons, these models are strongly simplified, often preventing to consider component design aspects. For this reason, the CDM focuses on the design of individual components of interest within the motor. (Umland *et al.*, 2023).
The framework also provides methodological support for preparing and adapting the implementation of the CDM and SDM. This includes knowledge acquisition, formalization, analysis, optimization, and adaptation steps.
In this work the focus is put on the preparation and setup of the CDM, which is marked by the dashed line in Figure 1. Starting from inputs from the SDM regarding the component's system and process context, this involves systematically acquiring and formalizing knowledge about the manufacturing constraints, evaluations and possible variations of the component.
Overall, this paper aims to answer the following research question:

> *What are the necessary steps and considerations for engineers to set up component-specific models within a Multidisciplinary Design Automation (MDDA) framework for electric motors?*

3.1. Component design framework

The general CDM framework for establishing and executing a CDM can be divided into three primary domains: CDM Implementation, knowledge formalization, and implementation specification.
As shown in Figure 2, CDM Implementation encompasses a reasoning engine, a geometry generator, and CAE evaluations utilizing the generated geometry. To establish this implementation, an implementation specification is required, comprising a DA requirements model and a DA architecture. The DA architecture describes the structural composition of the DA blocks, their respective functions, and the interconnections between them, resembling a software architecture.

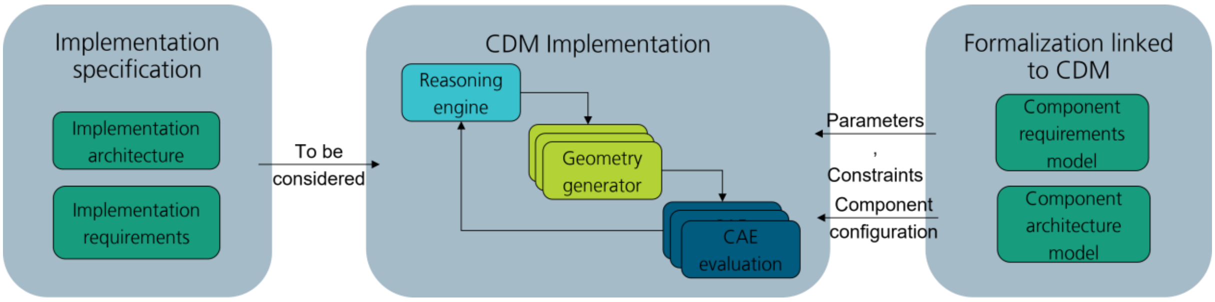

Figure 2. Component design model setup framework

The review in (Umland *et al.*, 2023) revealed, that current implementations of multidisciplinary design automations for electric motors are lacking other forms of formalization other than shape based or procedural rules, which limits the reusability of approaches. Thus, in this work additional knowledge formalization models are proposed that are directly linked to the implementation of the CDM. This includes a requirements model mainly to link constraints and manufacturing restrictions to the CDM implementation as well as a physical architecture model, where the physical architecture of the component and the electric motor can be modelled. This allows to adapt the CDM according to a changing motor configuration as well as the analysis of different configurations of the component of interest. Modelling the variability of the component and the system context can enable the engineer to reuse parts of the design automation in a different application, e.g. by reusing the component architecture model in a different motor or by reusing the system context architecture for the detailed analysis of a different component.

3.2. Set-up process for the CDM following a breakdown structure

To set up the models presented in the CDM framework, we use an approach that is oriented along the breakdown of the component of interest, adapting an approach proposed in (Biedermann and Meboldt, 2020). Overall, our approach aims to standardize and guide the knowledge acquisition, formalization, implementation, and testing of the design automation of the component of interest.
For the breakdown structure, we suggest the levels depicted in Figure 3.

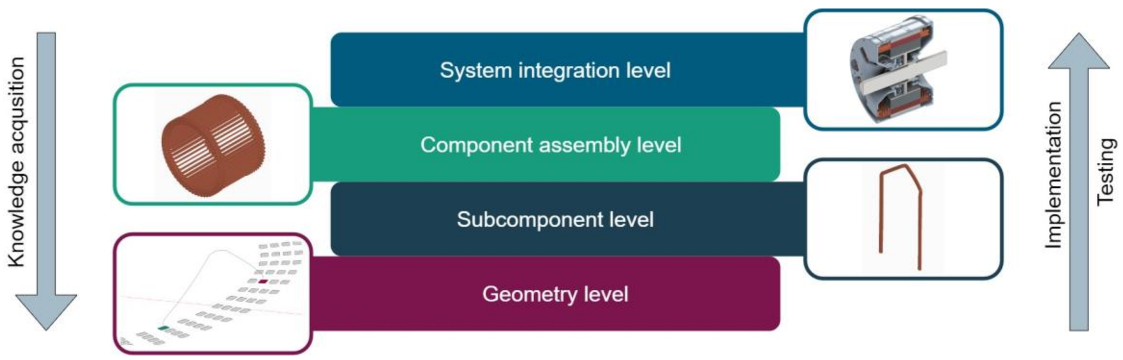

Figure 3. Breakdown structure of the approach given for the example of a hairpin winding

For the knowledge acquisition this breakdown structure is used in a top-down approach. Starting from the component's context, necessary knowledge to build the models and architectures will be collected on each level down to the geometry level. For each level a set of tasks, corresponding knowledge items as well as their proposed formalization in the framework will be presented. After the knowledge acquisition the breakdown structure will be revisited for the implementation and testing of the design automation, according to the implementation specification that was created during knowledge acquisition. This time however, in a bottom-up fashion. Starting from a geometry level to build the design automation of the subcomponent before integrating them to assemble and evaluate the component. In the following each level will be presented in more detail.

3.2.1. System integration level

The system integration level focuses on integration of the component into the system's MDDA. As shown in Figure 4, the knowledge to be collected at this level includes the component's physical context, current consideration of the component in the system-level MDO, inputs/outputs of the component design model (CDM), necessary CAE evaluations, requirements for the component's design derived from system requirements, as well as objectives and constraints derived from the system level.

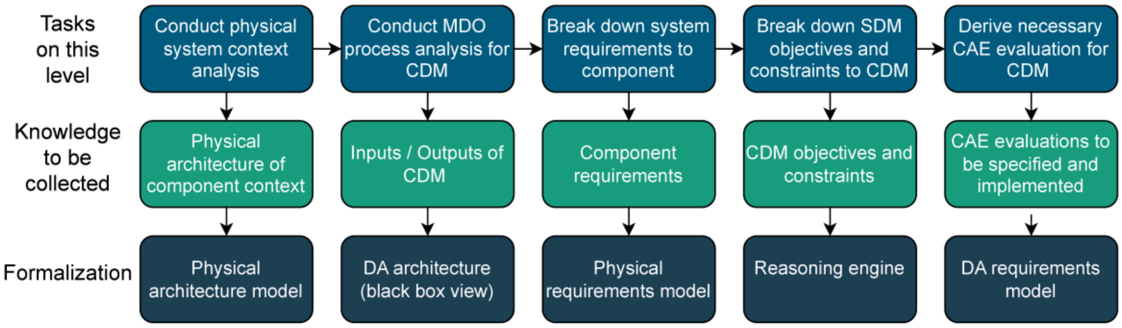

Figure 4. Tasks, knowledge items and formalizations for the system integration level

The DA architecture model on this level captures this information in a black box view of the CDM. For this framework it was chosen to adopt the SIPOC (Supplier, Input, Process, Output, Customer) analysis, as proposed by Rigger (2019).

3.2.2. Component assembly level

As it can be seen in figure 5, this level primarily emphasizes the identification of subcomponents, including their variants. This level also involves the breakdown of component requirements to the assembly level and the determination of requirements and constraints that arise from the manufacturing process at this level. The assembly level is the first level, where a white box view of the design automation becomes necessary. For this architecture diagrams are created, using the enterprise architecture modelling language ArchiMate. The modelling approach for the design automation architecture proposed by Rigger (2019) allows to model the different artifacts of the DA, as well as their interconnections with external models and applications, thus guiding the subsequent implementation. The last step aims to design tests for the design automation on the assembly level. The design automation on this level mainly aims to combine individual units of code. Consequently, we propose to use integration testing on this level as described in (Leloudas, 2023).

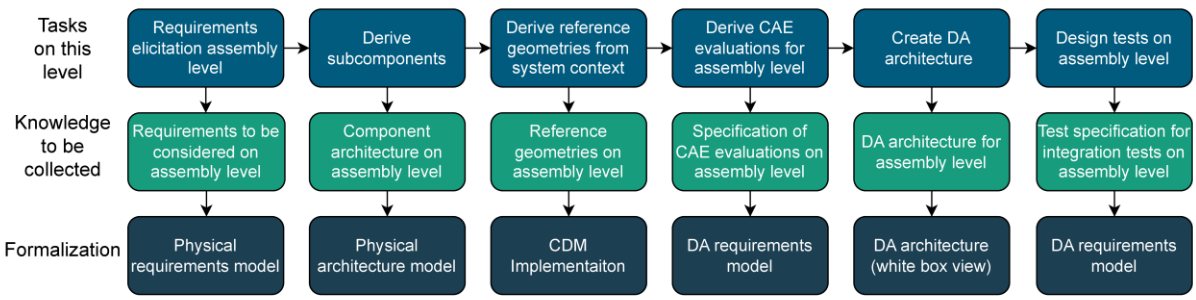

Figure 5. Tasks, knowledge items and formalizations for the component assembly level

3.2.3. Subcomponent level

On this level each of the subcomponents and their variants will be specified further, by again breaking down the requirements from the upper level to the subcomponent level and deriving manufacturing constraints that arise from the manufacturing process for this level. Dependencies between subcomponents and their variants and other parts of the system are searched for.

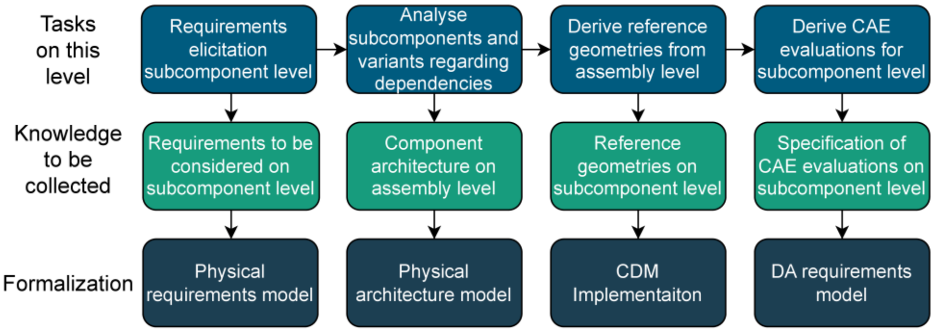

Figure 6. Tasks, knowledge items and formalizations for the subcomponent level

The subcomponent level describes the smallest part of the overall design automation, performing a very clearly defined task of generating and evaluating the geometry of the subcomponent. To make sure that each subcomponent of the design automation works as intended we propose to design unit tests on this level, following the approach in (Leloudas, 2023).

3.2.4. Geometry level

As displayed in Figure 7, for each of the subcomponents on this level a modelling strategy must be found. Furthermore, as the design automation is supposed to be part of a MDO, computational time is of highest importance, which should be considered as well.

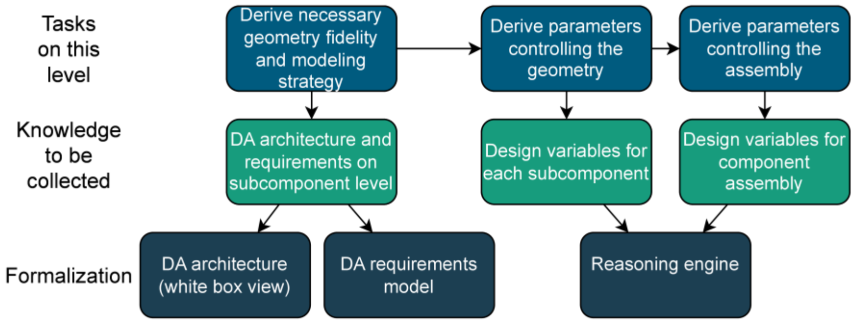

Figure 7. Tasks, knowledge items and formalizations for the geometry level

Overall, for the modelling strategy both the required geometry for CAE evaluations and the geometry fidelity to consider manufacturing constraints must be considered. Based on the modelling strategy parameters controlling the geometry will be identified, which then must be transferred upwards again, to derive the parameters controlling the assembly.

4. Application to hairpin winding

The proposed framework will be applied to design an additively manufactured (AM) hairpin winding for a permanent magnet synchronous motor, which serves as a component within the drive axle of an electric truck. Given the limited axial and radial dimensions of the motor in this specific application, the framework addresses the challenges of achieving high efficiency and flexibility, despite the relatively small production volume. By specifying and automating the design process for this component, the framework enables the evaluation and creation of multiple variants that can be integrated into the overall MDDA of the motor.

4.1. Knowledge acquisition

4.1.1. System integration level

For the physical system context of the hairpin winding head the surrounding components were identified and modelled in the architecture model. Neighbouring components of the hairpin winding are the stator lamination, the housing, the power connection, necessary sensors and the cooling system.

To gather information regarding the inputs and outputs of the CDM a SIPOC analysis as proposed in (Rigger, 2019) was conducted. From a process perspective the inputs are mainly the geometry from the surrounding components of the motor, as well as the winding scheme of the winding, which dictates the connections that have to be established in the winding head. For this, a dedicated tool, named Hairpin Winding Configurator (HairpinWiC) was developed to handle the complexity arising from the vast number of possible variants and constraints to be considered. The tool generates zone plans that depict the possible configurations of the individual phases and parallel branches. These plans serve as the basis for creating feasible winding schemes. The Hairpin Winding Configurator takes into account essential rules for the hairpin winding layout according to England and Ponick, 2019 and Zou *et al.*, 2022. The HairpinWiC produces variants of winding head connection combinations, which act as an input for the CDM. The main optimization objectives of the motor, maximizing the efficiency and minimizing the axial length, translate to minimizing the electric resistance, maximizing the thermal active surface as well as reducing the height of the hairpin winding head for the hairpin winding. In terms of CAE evaluations these objectives make a loss analysis, as well as an analysis of winding head surface area and height necessary. Furthermore, based on the application, requirements from the system level were broken down to the component and captured in the physical requirements model for the component.

4.1.2. Component assembly level

For the component assembly level four subcomponents were identified: Repeating connectors, special connectors, the star point connector as well as the connection terminal. In the next step the requirements were elicited, by breaking down higher level requirements as well as analysing the manufacturing process regarding requirements for this level. As reference geometries stator, winding in the slot and housing of the electric motor were identified. In order to represent the different views of the component model including the requirements, architecture, and constraints relevant for the DA, a SysML model is used, as depicted in Figure 8. The modelling follows the SYSMOD (Weilkiens, 2020) approach and addresses the different configurations that can be realized at the different levels.

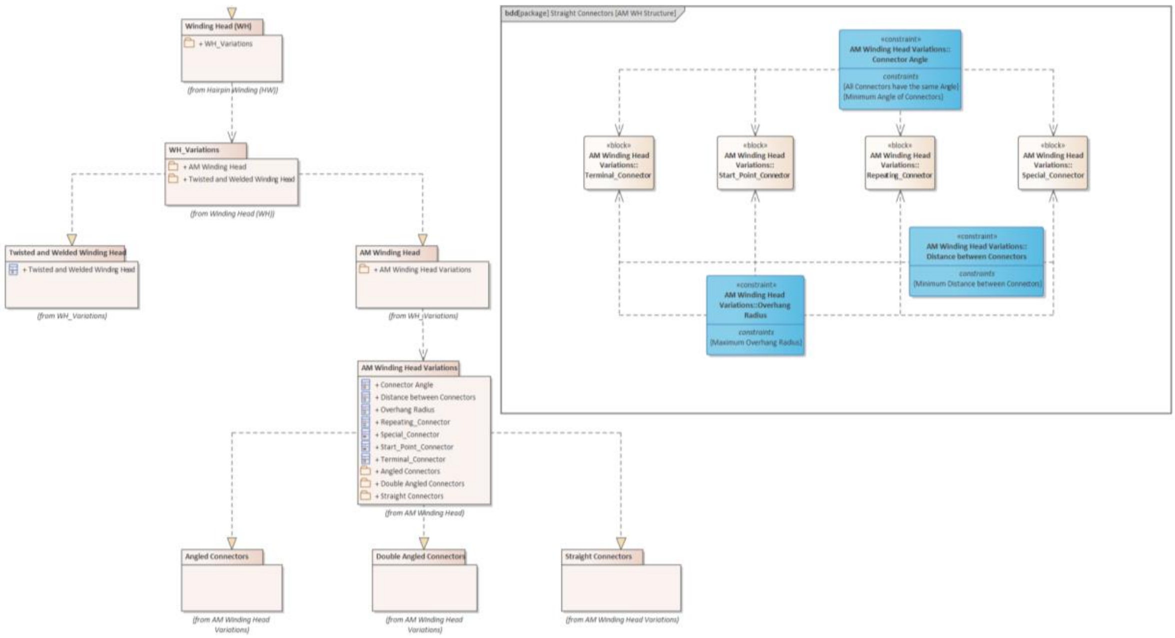

Figure 8. Excerpt of the component model realized using SysML to represent the architecture of the additive manufactured winding head including variants and essential constraints

Furthermore, the variants possible to realize the hairpin winding are represented using a class diagram using the VAMOS approach (Weilkiens, 2016) . Due to the formalization of the modelling language the different knowledge items can be transferred into XML and assigned to the elements, namely geometry and rules used within the DA. Moreover, the effect of specific manufacturing technologies, here additive manufacturing, is represented by refinement of specific constraints like the minimum distance required between conductors. Based on the gathered information a DA architecture was derived and modelled in ArchiMate following the modelling paradigm presented in (Rigger, 2019).

4.1.3. Subcomponent level

For each of the subcomponents it was analysed, how requirements from the higher level must be transferred to each subcomponent. The main reference geometries identified on the subcomponent level are the positions and the cross sections of the conductors to be connected by the different connectors.
On subcomponent level restrictions stemming from the AM process must be considered. Since support structures should be avoided, minimum allowable overhang angles as well as overhang and fillet radii were identified as requirements on the subcomponent level. The exact parameters for each repeating connector, special connector as well as the connections to form the star point and the terminal are dependent on the winding scheme and must be identified with a custom script every time a new winding head is generated. Furthermore, on the subcomponent level the AM process enables further variants of the connectors, in contrast to the conventional process which is limited by the bending process. The new variants were also modelled in the component architecture model.

4.1.4. Geometry level

A strategy for modelling the various subcomponents was developed at the geometric level. A similar modelling concept as shown in (Putz *et al.*, 2023) was used, which models the path of the connectors, transfers the cross-sections to the geometry and then sweeps to form the 3D-geometry, as depicted in Figure 9.

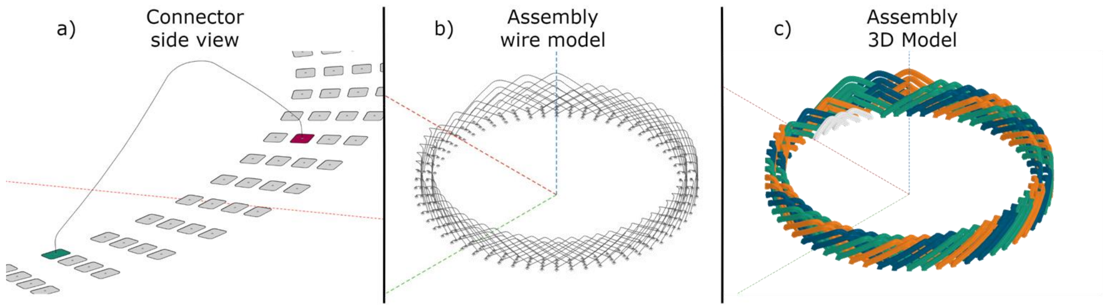

Figure 9. Hairpin-winding modelling: a) Single connector, b) assembly wire model of exemplary design, c) assembly 3D model of exemplary design, coloured to show the phase of the conductor

To keep the computational effort required by the CDM as low as possible within a MDDA, it was determined that a 3D geometry would not be used to evaluate the hairpin winding head. Instead, a skeleton model is used, which can be employed afterwards for the 3D geometry creation as depicted in Figure 9. The most important parameter for controlling the geometry is the skew angle of the conductors. The skew angle significantly affects both the height of the winding head and the distance between the conductors in the assembly. Also overhang angles and radii of the created connectors need to be considered in the requirements model and linked to the implementation.

4.2. Implementation and testing

The various levels of the component design model were implemented using Synera® software. The software utilizes a node-based editor and is capable of creating CAD models in a similar way to the Grasshopper® software used in (Biedermann and Meboldt, 2020) and (Putz *et al.*, 2023). Synera® further extends this concept by acting as a process integration and design optimization (PIDO) platform via the integration of various tools, e.g. for evaluation purposes. For the evaluation based on the skeleton model custom Python scripts were developed to calculate the resistance, height and surface area of the winding head. To prevent invalid designs resulting from design automation at the assembly level, integration tests have been executed with various input parameters. The purpose of these tests is to ensure that the connectors do not interfere with each other and maintain a certain distance for post-processing after the additive manufacturing of the winding. In addition, unit tests were conducted for each subcomponent. For the hairpin connector, we tested whether the created connection path passes through the intended starting and ending points for different connectors.

4.3. Results

Using the proposed approach, it was possible to set up a working design automation workflow for an AM hairpin winding. With the implementation of the CDM, it is possible to create and evaluate different designs for different winding schemes. Further variation points stem from changing the product architecture configuration via the product architecture model, which is linked to the implementation of the CDM. This allows to create different component designs for the same winding scheme. For this, further variants of the different subcomponents will be added in future work. Additionally, a comparison of the conventional reference motor winding and a selected automatically created design, as it is shown in figure 9c, is made. The design study was limited to winding schemes resembling the scheme of the reference motor. With the generated design it was possible to reduce the total winding head height by 15 % in comparison to the reference motor. Furthermore, the Hairpin-CDM evaluates the surface area and the resistance of the winding head, which can be fed back to the analysis models in the SDM.

5. Discussion and conclusion

The proposed approach provides a systematic way of setting up the design automation process. The DA architecture model acts as a blueprint for creating the design automation and also serves as documentation for future reference and reuse in different contexts. This makes it easier to understand the software created and enables its reuse in various developments. The breakdown structure employed in the approach allows for systematic knowledge collection, enabling the consideration of in-depth component requirements. Additionally, by separating the product architecture from the code and linking it to the CDM, it becomes possible to capture knowledge outside the code. This knowledge can then be accessed and reused in different developments. Furthermore, the design automation of specific components, such as the hairpin winding head, allows for a more detailed design that would otherwise be neglected in traditional electric machine design.

In conclusion, this article presents a comprehensive framework for the systematic establishment of a component design automation for electric motors within the framework of Multidisciplinary Design Optimization (MDO). The framework incorporates models that capture specifications for the physical component and the implementation of the design automation, allowing for efficient and effective design processes. The proposed approach, being application-independent, can be adapted for a variety of applications and components of interest.

To demonstrate the feasibility and applicability of the approach, the framework was applied the design of additive manufactured hairpin windings. Multiple variants of hairpin windings were generated and evaluated, showcasing the framework's ability to explore diverse winding schemes and product architecture configurations. The framework proved instrumental in optimizing the hairpin winding design within the MDDA framework.

Future research will focus on showing the framework's adaptability to other components of electric motors, both active and non-active. Furthermore, the utilization of additive manufacturing for hairpin windings opens up possibilities for more intricate and complex designs, which will be a subject of investigation in future studies. Overall, this framework provides a valuable contribution to the field of electric motor design and optimization.

Acknowledgements

This work is part of the research project ”KOHANA” that is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) (funding number: 01MV22007A) and supported by the project management agency German Aerospace Center (DLR-PT). The authors are responsible for the content of this publication.

References

Biedermann, M. and Meboldt, M. (2020), “Computational design synthesis of additive manufactured multi-flow nozzles”, *Additive Manufacturing*, Vol. 35, p. 101231. https://doi.org/mg2f.

Cederfeldt, M. and Elgh, F. (2005), “Design automation in smes – current state, potential, need and requirements”, *DS 35: Proceedings ICED 05, Melbourne, Australia, 15.-18.08.2005,* pp. 248-249

Colombo, G., Pugliese, D., Klein, P. and Lutzemnberger, J. (2014), “A study for neutral format to exchange and reuse engineering knowledge in KBE applications”, in Terzi, S. (Ed.), *2014 ICE: Bergamo, Italy, 23 - 25 June 2014,* pp. 1–10. https://doi.org/mg2g.

Dai, Z., Wang, L., Meng, L., Yang, S. and Mao, L. (2019), “Multi-Level Modeling Methodology for Optimal Design of Electric Machines Based on Multi-Disciplinary Design Optimization”, *Energies*, Vol. 12 No. 21, p. 4173. https://doi.org/mg2h.

Di Nardo, M., Lo Calzo, G., Galea, M. and Gerada, C. (2016), “Structural design optimization of a high speed synchronous reluctance machine”, *2016 ICEM, Lausanne, Switzerland, 04-07.09.2016,* https://doi.org/mg2j

Du-Bar, C., Mann, A., Wallmark, O. and Werke, M. (2018), “Comparison of Performance and Manufacturing Aspects of an Insert Winding and a Hairpin Winding for an Automotive Machine Application”, *2018 EDPC, Schweinfurt, Germany, 04-07.12.2018,* pp. 1–8. https://doi.org/gh93z9.

England, M. and Ponick, B. (2019), “Automatisierter Entwurf von Haarnadelwicklungen anhand von tabellarischen Belegungsplänen”, *Elektrotech. Inftech.*, Vol. 136 No. 2, pp. 159–167. https://doi.org/mg2k.

Farhan, A., Johnson, M., Hanson, K. and Severson, E.L. (2020), “Design of an Ultra-High Speed Bearingless Motor for Significant Rated Power”, *2020 ECCE Detroit, MI, USA 11-15.10.2020,* pp. 246-253 https://doi.org/mg2m.

Golovanov, D., Galassini, A., Flanagan, L., Gerada, D., Xu, Z. and Gerada, C. (2019), “Dual-Rotor Permanent Magnet Motor for Electric Superbike” *2019 IEMDC San Diego, CA, USA, 12-15.5.2019,* https://doi.org/mg2j.

La Rocca, G. (2012), “Knowledge based engineering: Between AI and CAD. Review of a language based technology to support engineering design”, *Adv. Eng. Inform.*, Vol. 26 No. 2, pp. 159–179. https://doi.org/f39n5w.

Leloudas, P. (2023), *Introduction to Software Testing: A Practical Guide to Testing, Design, Automation, and Execution*, 1st ed. 2023, Apress; Imprint Apress, Berkeley, CA. https://doi.org/10.1007/978-1-4842-9514-4.

Putz, C., Schleifenbaum, J.H., Ziegler, S., Reich, S. and Gruttke, A. (2023), “Design Automation: Digital Design Configurators of Hairpin Windings”, *E-Motive 2023, Schweinfurt, Germany, 27-28.09.2023,* pp.187-194, https://doi.org/10.18154/RWTH-2023-10426.

Rigger, E. (2019), “Task Definition for Design Automation”, ETH Zurich, 2019.

Rigger, E., Shea, K. and Stankovic, T. (2018), “Task categorisation for identification of design automation opportunities”, *J. Eng. Design*, Vol. 29 No. 3, pp. 131–159. https://doi.org/gmf64q.

Rigger, E. and Vosgien, T. (2018), “Design automation state of practice - potential and opportunities”, *DESIGN 2018, Dubrovnik, Croatia, 21-24.05.2018,* pp. 441-452, https://doi.org/10.21278/idc.2018.0537.

Umland, N., Winkler, K. and Inkermann, D. (2023), “Multidisciplinary Design Automation of Electric Motors—Systematic Literature Review and Methodological Framework”, *Energies*, Vol. 16 No. 20, p. 7070. https://doi.org/10.3390/en16207070.

Verhagen, W.J., Bermell-Garcia, P., van Dijk, R.E. and Curran, R. (2012), “A critical review of Knowledge-Based Engineering: An identification of research challenges”, *Adv. Eng. Inf.*, Vol. 26 No. 1, pp. 5–15. https://doi.org/10.1016/j.aei.2011.06.004.

Vidner, O., Wehlin, C. and Wiberg, A. (2022), “Design Automation Systems for the Product Development Process: Reflections from Five Industrial Case Studies”, *Proceedings of the Design Society*, Vol. 2, pp. 2533–2542. https://doi.org/10.1017/pds.2022.256.

Weilkiens, T. (2016), *Variant modeling with SysML, MBSE4U booklet series,* MBSE4U, Fredesdorf.

Weilkiens, T. (2020), *SYSMOD - the systems modeling toolbox: Pragmatic MBSE with SysML, MBSE4U booklet series,* 3rd edition, version 4.2, MBSE4U, Fredesdorf.

Wiberg, A., Persson, J. and Ölvander, J. (2023), “A Design Automation Framework Supporting Design for Additive Manufacturing”, *ASME CIE 2023, Boston, Massachusetts, USA, 20-23.08.2023,* https://doi.org/gthsxz.

Zou, T., Gerada, D., La Rocca, A., Moslemin, M., Cairns, A., Cui, M., Bardalai, A., Zhang, F. and Gerada, C. (2022), “A Comprehensive Design Guideline of Hairpin Windings for High Power Density Electric Vehicle Traction Motors”, *IEEE Transactions on Transportation Electrification*, Vol. 8 No. 3, pp. 3578–3593. https://doi.org/10.1109/TTE.2022.3149786.