The C&C²-Approach in a Mechanical and Electromagnetic Multi Domain Setup – Identifying Possibilities and Challenges Throughout Product Engineering of an Additively Manufactured Transverse Flux Machine Stator

Marcel Nöller[1], Joshua Huss[1], Sivasubramanian Chandramouli[2], Katharina Bause[1], Albert Albers[1]

[1]Karlsruhe Institute of Technology (KIT), IPEK – Institute of Product Engineering
Kaiserstr. 10, 76131 Karlsruhe, Germany
[2]National Institute of Technology
Tiruchirappalli - 620015, Tamil Nadu, India

ORCID IDs:

Nöller: 0000-0002-8354-4470
Chandramouli: 0000-0002-8982-1862

Corresponding Author
Marcel Nöller
marcel.noeller@kit.edu, +49 721 / 608 - 45636

Abstract

The development of electric machines brings together engineers from different fields and disciplines. In order to provide a common base model of the system in development and to serve as a communication tool between the engineers, the Contact and Channel Approach (C&C²-A) is utilized for the mechanical and electromagnetic domain simultaneously for the first time. By incorporating different views and interests into the design process concurrently, new design possibilities are investigated. This method is then applied to a transverse flux machine (TFM) with the goal to explore new design venues when switching from a conventional manufacturing process over to an additive manufacturing approach. The system TFM is analyzed and two C&C²-Models are created for two different development generations. By comparing the two models, it is shown, that optimizations from a mechanical perspective are possible without impacting the electromagnetic design negatively. Eventually, this work concludes that the C&C²-A is indeed capable and valuable as a modelling language for multi domain systems and further application and method development is encouraged.

Keywords

Embodiment Design, Modelling, Contact and Channel Approach, Transverse Flux Machine, Electric Motor, Additive Manufacturing

Declarations

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The research project itself was a joint effort by four institutes. The Institute of Electrical Energy Conversion (IEW) at the University of Stuttgart was responsible for the transverse flux machine itself and the electromagnetic and general design over the course of the project. The Institut für Strahlwerkzeuge (IFSW) of the University of Stuttgart investigated the additive manufacturing process and material properties, while the Institute of Vehicle Systems Technology (FAST) at KIT

researched potential sensor and actuator integration into the machine for NVH cancellation. The Institute of Product Engineering (IPEK) at KIT, whose research is presented here, investigated the design methods itself and the chances and potentials of additive manufacturing in the future design of electric machines. We also want to thank our project partners for their collaboration and insights during this project.

Article Highlights

- First utilization of the Embodiment Design method “Contact and Channel Approach” for the mechanical and electromagnetic domain simultaneously
- Analysis and model creation of different development generations of a Transverse Flux Machine (TFM)
- Exemplary methodical synthesis of new design possibilities when designing products for new manufacturing processes

Conflicts of interest/Competing interests

The authors declare no conflicting or competing interests.

Availability of data and material

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Authors’ contributions

Conceptualization: Marcel Nöller, Joshua Huss, Sivasubramanian Chandramouli; Methodology: Marcel Nöller, Joshua Huss, Albert Albers; Writing - original draft preparation: Sivasubramanian Chandramouli, Marcel Nöller; Writing - review and editing: Marcel Nöller, Sivasubramanian Chandramouli, Katharina Bause, Albert Albers; Supervision: Katharina Bause, Marcel Nöller, Albert Albers

1. **Introduction**

Research on theories and models of design is often motivated from observations in designing, i.e. they address a specific purpose and are intended to describe, explain or predict certain phenomena that pose an unsolved challenge both for the research community and for design practitioners [1]. Problems could arrive from a need of the market that is not yet supplied or from requirements for a product that are not yet fulfilled [2].

Thus, problem solving is a central task in engineering design. In order to solve a problem and to develop a new innovative product the design engineer has to translate the required functions into the product's embodiment [3]. Product profiles can be used to capture the benefits for the intended provider, customer and user and make them accessible for validation. It also explicitly specifies the solution space for the design of a product generation. [4]

During the product development process, methods play an important role in supporting the designer to create products of high quality in a shorter duration of time. Additionally, methods help to reduce the number of mistakes by checking, if the developed embodiment of the product really fits to the intended requirements and functions in an appropriate way [5]. New products get more and more complex. In order to handle the complexity and to be able to develop the new product efficiently, there is a need for methods which describe the connections between functions and embodiment, in order to enable new technology and to pave the way to more predictive models and new solutions, e.g. for future mobility.

In this work, the leading example to implement and test the method on is a rather special and rare variety of electric machines, the *Transverse Flux Machine (TFM)*. Utilizing a three-dimensional magnetic flux in the stator, this machine type showcases the advantages of *Additive Manufacturing (AM)* and therefore serves as an ideal example to explore new design avenues. Designing an electric machine like this one requires the combined efforts of different disciplines in engineering, from electrical and mechanical engineers to production engineering and material specialists, especially, if a new manufacturing method like AM necessitates new thought patterns and close collaboration.

The *Contact and Channel Approach (C&C²-A)* serves exactly this purpose by describing a system through structural elements with the goal of gaining insights and finding new design solutions while providing a mutual meta-model between engineering disciplines to discuss the developments. Since a thorough understanding of this method is crucial for this work, a brief outline of the method's principles is given within chapter 2.4.

2. State of Research

This chapter briefly summarizes the state of research and the necessary background for this publication.

2.1. Transverse Flux Machine

This research derives its methods using a technical system as an example. In this case, the Transverse Flux Machine (TFM) was chosen. TFMs are electrical machines offering a high torque density and can be ascribed to Herbert Weh, who patented them in the late 1980s [6–8].The high torque density results from the decoupling of the electric plane (perpendicular to the axis of rotation) and the magnetic plane (parallel to the axis of rotation) which allows for a higher number of pole pairs and hence more torque density. The three phases commonly used are aligned behind each other and slightly rotated with respect to each other in order to achieve an electric angle of 120° between the phases.

Several problems have hindered a wide dissemination of the TFM. Challenges are the nonlinear behavior, the production process and the cogging torque of the TFM [9].

Nevertheless, one of the potential future applications of the TFM can be found as a near-wheel or in-wheel design in the field of Electric Vehicles (EV) due to its high torque and slow rpm.

Compared to conventional electric motor concepts, a TFM necessitates a different mechanical structure. A complex and highly detailed three-dimensional shape doesn't allow for easy and efficient production using the two state of the art production processes, namely the *lamination of steel sheets* and the *sintering process with Soft Magnetic Composites (SMC)*.

The lamination of steel sheets poses challenges with the general shape of the TFM, as it is no two-dimensional shape known from conventional motor designs. It also hinders the three-dimensional magnetic flux in some TFM topologies unnecessarily while not inhibiting eddy currents along the circumference. SMC on the other hand can form three-dimensional shapes but have difficulties incorporating finer structural and inner details because of process limitations. Additionally, SMCs typically have worse magnetic properties resulting in higher hysteresis losses but on the positive side offer lower eddy current losses compared to laminated machines.

A brief history of the design of the TFM in general is presented below to give context and a thorough understanding to the later application of this research.

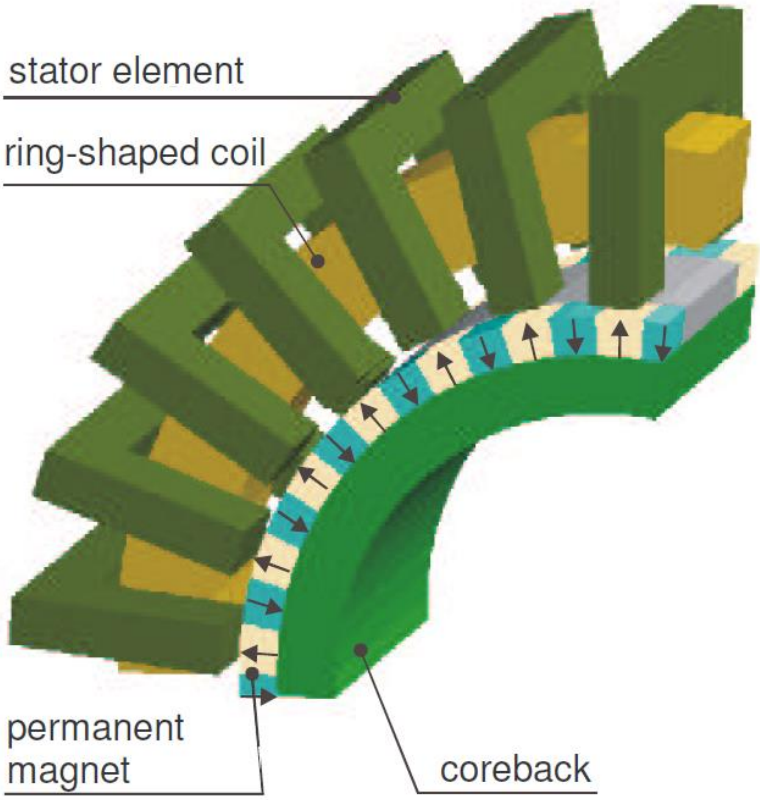


Fig. 1 Transverse Flux Machine with U-shaped stator elements [1]

A basic TFM can be seen in Fig. 1. This machine has an annular winding which is enclosed on the top by U-shaped irons. This part forms the stator. The rotor is located inside and consists of permanent magnets in alternating polarity and an iron segment under the magnets that connects the magnets axially. The magnets to the left and right of the ring-shaped winding have opposite polarity.

This arrangement creates a magnetic flux that flows in the U-shaped iron around the conductor and across the air gap through the magnets. The flux path is closed by the iron segment under the magnets. This process takes place every two poles apart.

If the rotor is moved by one pole pitch, the direction of the current is reversed and with it the magnetic flux.

With the arrangement shown, however, only half of the magnets are involved in generating the driving force at the same time. The magnetic flux in the row of magnets in which there is no U-iron is not closed. As a result, these magnets generate a leakage flux that affects the effect of the remaining flux.

A first step to alleviate this issue was to introduce an I-shaped iron between the magnets not facing the U-iron. These I-irons close the magnetic path between the magnets. Additionally, Henneberger [10] discussed, that some of the rotor material is superfluous. Because, as can be seen in c) of Fig. 2, the magnetic fluxes that meet at the top cancel each other out. In this area, material can be removed and weight can be saved. With this design, the magnetic flux

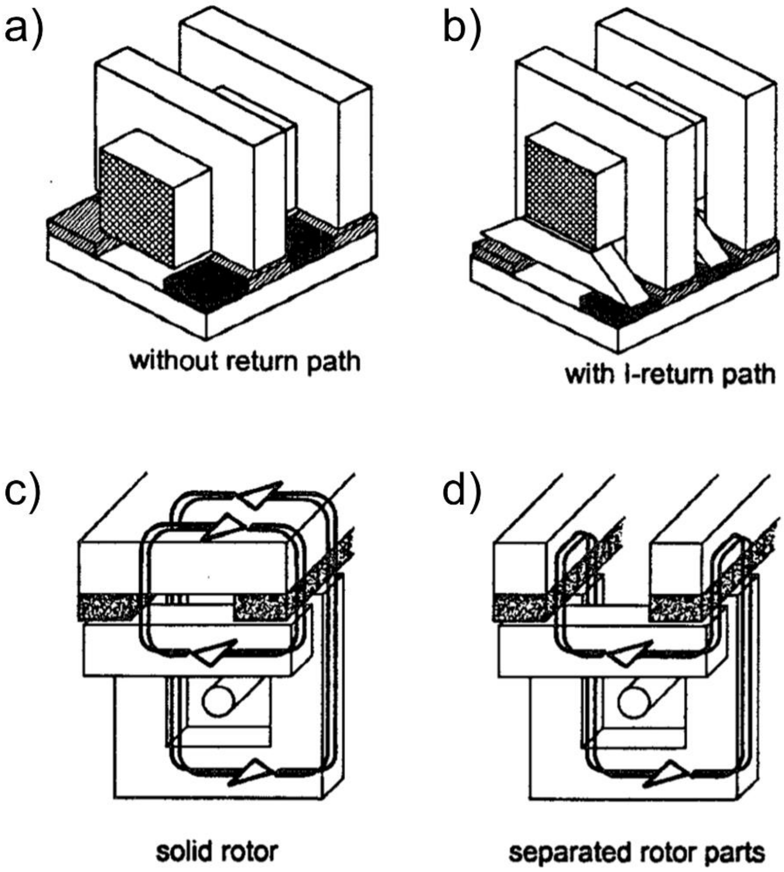


Fig. 2 Different transverse flux motor topologies, a) Simple U-Irons without return path, b) including a I-return path, c) solid rotor with mostly planar magnetic flux, d) separated rotor with three-dimensional flux [11]

also flows in the longitudinal direction and thus now describes a three-dimensional flux. Fig. 2 outlines the advancement in TFM design described in this paragraph.

The other basic design of a TFM is the double-sided design. This design has stator cores and a winding on both sides of the rotor. This makes better use of the magnets, which is why greater torque densities can be achieved with this design. Henneberger et al. [11] argues that the double-sided TFM offers performance advantages, but the construction is more complicated and also requires more installation space than the single-sided version. Fig. 3 shows two double-sided design with and without I-Iron and different rotor configurations, which are discussed below in more detail.

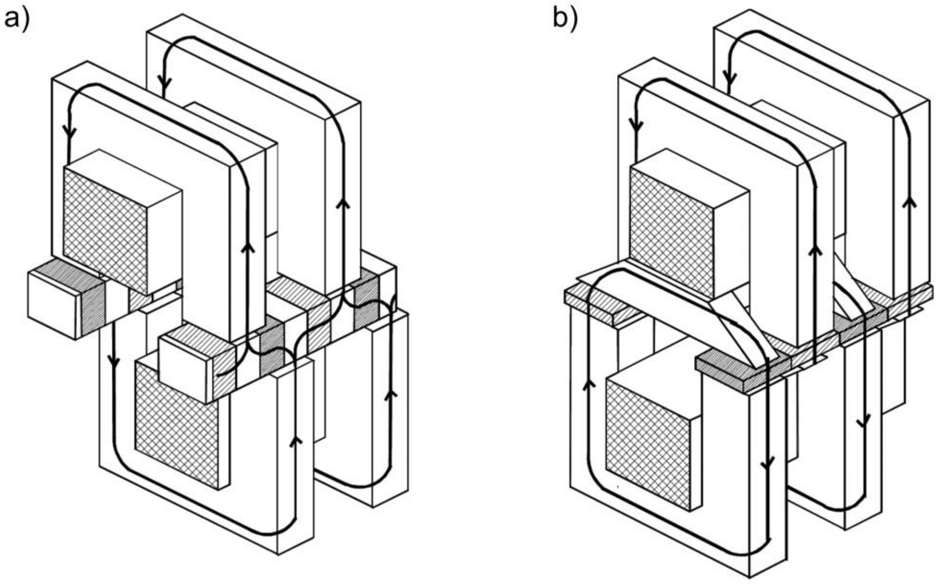


Fig. 3 Double-sided TFM design, a) without return path, b) with I-return path [11]

Furthermore, from Husain et al. [12] the division is made into machines with magnets attached to the surface of the rotor and machines with magnets embedded in the rotor. In the English literature the second arrangement is called *flux concentrating*, in the German literature and in this work this arrangement of the magnets is called the *collector arrangement*. The advantage of this design is that higher flux densities are possible in the air gap. The magnets are not attached to the rotor surface perpendicular to the air gap, but rather radially inside the rotor, collecting (or concentrating) the flux to a smaller rotor surface area between the magnets, eventually increasing the flux density.

Most of the designs shown so far are TFM with the magnets on the surface of the rotor. Examples of single-sided and double-sided designs with the magnets in the collector arrangement can be seen in Fig. 3 and Fig. 4.

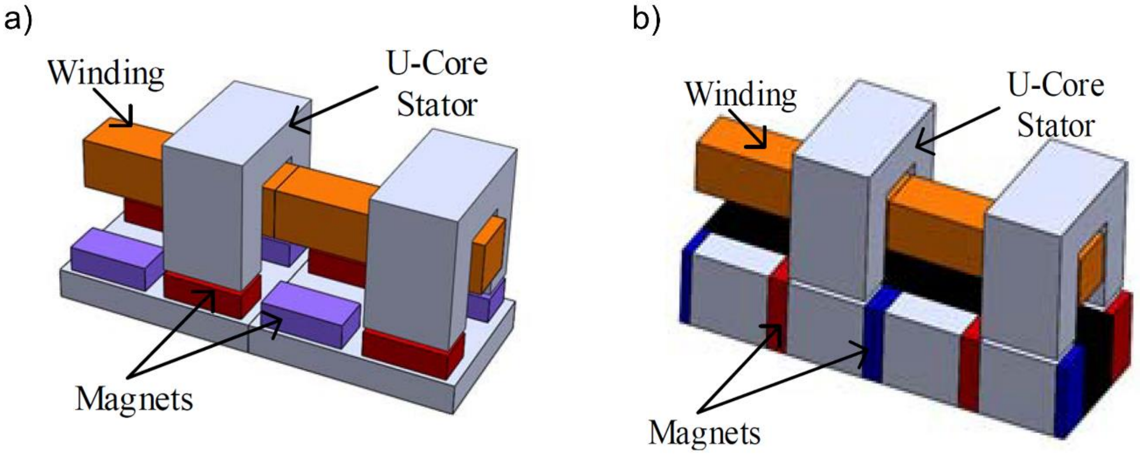


Fig. 4 Single-sided TFM without return path, a) with surface magnet, b) with a collector arrangement [12]

In a TFM, continuous torque cannot be generated with just one phase, which is why, according to Washington et al. [13] in practice the three conventional phases are usually arranged axially behind each other in order to be able to operate the machine smoothly.

In addition to the conventional three-phase design, these machines can also have a two-phase design, such as a demonstration engine for a ship drive [14]. But concepts with even more phases are also proposed, such as a 16-phase TFM [15].

This research focusses in the beginning on a single-sided permanent magnet external rotor TFM with an initially U-shaped stator and a collector arrangement rotor. Later the design moves to claw-shaped poles for the stator and surface magnets for the rotor for the last development generation of this research.

Conventionally, electric machines are developed and designed using the expertise of different disciplines in engineering. Many different views and experts can be involved, using analytical or numerical modelling for the electromagnetic, the thermal and the mechanical behavior, as well as NVH or EMC phenomena to name a few. [16, 17] Where one engineer might be concerned with the insulation, another one is doing calculations and CFD simulations on the cooling system. Proper requirement engineering, exchange of data, keeping the models concurrent with one another and eventually the optimization of this design incorporating multiple disciplines and arriving at the best trade-off for the derived product profile are core challenges. All of this becomes elevated, if the different disciplines are competing for the same volume within the product. While a conventional cooling jacket might not have big and direct influences on the magnetic flux path, integrating inner cooling channels within the stator core might alter the flux paths drastically and takes away valuable soft magnetic material at the same time. AM enables very integrated product design and offers a high resolution of details and geometric features as well as largely unrestricted freedom during design. All of this emphasizes the need for early and proper communication during the early stages of product development and points towards the need of a common reference, a model to develop and discuss functionality together and to describe the system, before in-depth specialized view-specific models are created.

2.2. Additive Manufacturing of Electric Machines

With growing interest in electrification from clean energy technologies, such as wind power and use of pure electric powertrains in various applications, the demand for next-generation, high-performance magnetic materials has risen significantly [18]. Electrical machine design for these applications is facing challenges in terms of meeting very demanding metrics for power densities and conversion efficiencies, thereby motivating the exploration of advanced materials and manufacturing for the next generation of lightweight ultra-efficient electric machines [18]. AM, colloquially known as 3D-printing, opens up new venues of improvements for industrial manufacturing of electrical machines via the printing of complex geometries, reduction of part count and lead time as well as the integration of functions. The limited usage of expensive critical materials such as rare-earth magnets as well as nanocrystalline and amorphous soft magnetic composites allows their use only in critical regions required by desired properties of the printed parts. The magnetic, electrical, thermal, and mechanical properties of the magnetic materials are greatly influenced by the selection of the AM method and the process parameters. Among the seven major American Standard

Testing and Materials-defined standard modes of 3D printing, laser powder bed fusion is the dominant process for the AM of metals [19].

Current research on AM of electric machines is conducted on multi-material printing [20] and the design implications of printing parts of an electric machine, such as the coils or direct winding heat exchangers [19, 21–23], but not on the overall machine design itself.

Therefore, in this research the effects of AM on the overall design of the stator of a TFM are explored.

2.3. Contact and Channel Approach (C&C²-A)

The C&C²-A was created by Matthiesen and Albers [2, 3, 24] to help engineers to recognize function related parameters of the embodiment and support thinking in a system context. It can be understood as a meta-model and consists of elements and rules to build up explicit models. The C&C²-A can be compared to a language, that contains words and grammar to express knowledge [25].

It consists of three key elements and three basic hypotheses, that define the usage of said key elements. Its key elements are the *Working Surface Pair (WSP)*, the *Channel and Support Structure (CSS)* and the *Connector (C)* [24]. A brief summary is given below.

A WSP describes the interface, where parts of the system continuously or temporarily connect while it fulfils its function. The CSS runs through system parts and connects the WSP. A CSS can for example include parts of components, whole subsystems or the volume interspersed by a field according to the modelling purpose. The C represents the model of the system’s environment, sets the boundary and transfers effects from or into the system.

These elements contain parameters of the embodiment, that are relevant for the function fulfilment. For example, a friction coefficient is a parameter of a WSP, the stiffness of a component or subsystem is a parameter of a CSS. These parameters cause the functions of a system and are therefore relevant for simulation models [25]. The C&C²-A supports the documentation of these parameters and their relation to functions in the system.

The second important part of the C&C²-A are the three *basic hypotheses*. They describe relationships between the elements and the function and provide possibilities and boundaries for modelling with C&C²-A:

- The first basic hypothesis states that the function always needs interrelations of components through WSP.
- The second basic hypothesis states that a function is fulfilled through a minimum of two WSPs, that are connected by a CSS and integrated in the environment by Connectors.
- The third basic hypothesis describes the fractal character of modelling and shows, how the created C&C²-Model of a system differs according to the point of interest and the purpose of modelling.

The models created are called *Contact and Channel Models (C&C²-M)* and connect the investigated function to the design elements that cause it. With the built-up C&C²-M, function relevant embodiment parameters are explicitly documented and can be used as a starting point for creating simulations. Fig. 5 shows an example C&C²-M for the purpose of explaining the transmission of torque in a single gear stage.

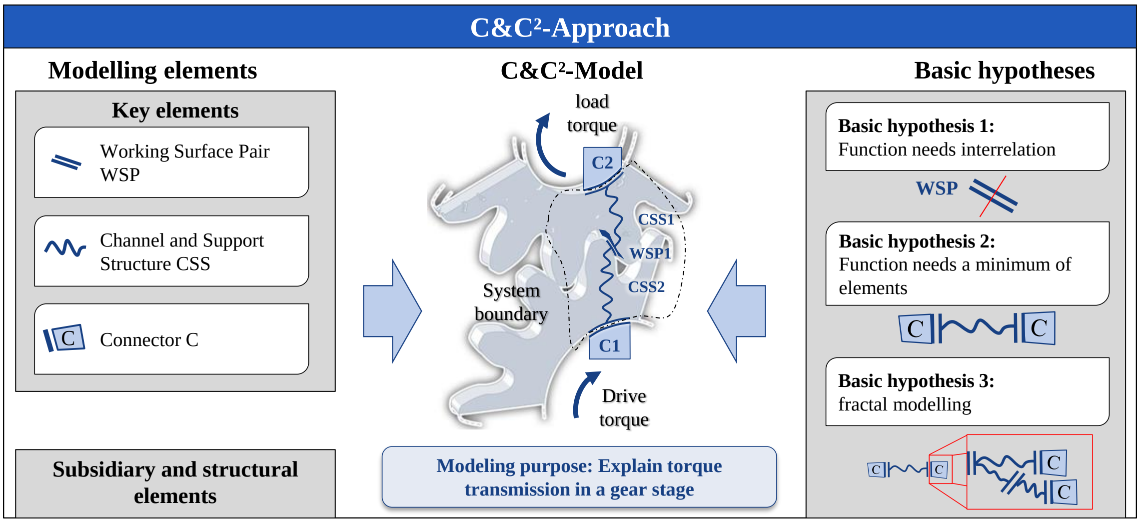


Fig. 5 Example C&C²-Model and summary [25]

The only way to change the system is to add, remove, or alter a CSS or WSP [25].

The C&C²-A has been utilized for many years and is still in active development. An extensive summary of the usage in the past 20 years and the current limitations is given by Grauberger et al. [2]. This summary clearly highlights, that while the C&C²-A is *theorized* to be applicable to liquid and gaseous elements as well as magnetic and electric fields, *no direct attempt* to facilitate C&C²-A for these elements and / or fields is known to the authors.

3. C&C²-A for an Electric Motor

In chapter three the modelling of the electric motor elements is introduced, focusing on the aspect on field interaction between solids.

3.1. Model Visualization

When creating a C&C²-M for a complex system such as an electric motor, it is to be expected, that a very large number of CSS and WSP will occur. An advantage of the C&C²-A is, that its rules enable arbitrary simplifications (fractal character) deemed suitable by the model builders. This is often done in analysis of complex mechatronic systems, e.g. a sunroof system [26]. However, in this case, due to the many interrelated components but also in particular, the repetitive nature of certain parts such as the metal sheets of the soft magnetic stator and rotor alternating with electrically insulating varnish coats, simplifying the visualization remains a challenge. Fully detailed, the WSP or CSS count could easily exceed a thousand and because AM of the stator would directly affect these WSP and CSS, the system has to be analyzed at least on this level of detail. For this reason, simplifications in how elements are displayed were made in the TFM C&C²-M, in order to analyze the entire system with sufficient resolution and clarity. These deliberate visual simplifications are presented in the following paragraphs.

As mentioned before, one challenge is the representation of WSP and CSS that are repeated multiple, potentially hundreds, of times before a new situation arises. The inner repetitions are collected and shown once in the model in order to understand the underlying functions and to assign properties. The further repetition is not shown for reasons of clarity and simplicity. The WSP and CSS within the repetition share the same number, properties and designation in this model. The engineer who looks at this representation for analysis or synthesis only needs to know that this process is repeated in order to understand the overall system. In the case of synthesis, CSS and WFP can be added, removed or altered as described in chapter 2.1. Changes to the WSP and CSS are then repeated throughout the iteration chain, but changing the repetition count would also be possible in conjunction to changing the properties accordingly.

The second simplification is the handling of volumes in the system combining many WSP and CSS. The definition described in chapter 2.1 emphasizes, that a CSS always connects two WSP. In the case of the stator, the amount of CSS necessary to satisfy this second hypothesis would make the representation unwieldy and difficult to interpret. As a result, several CSS in a volume are combined into one CSS. This simplification of the representation is illustrated by Fig. 6.

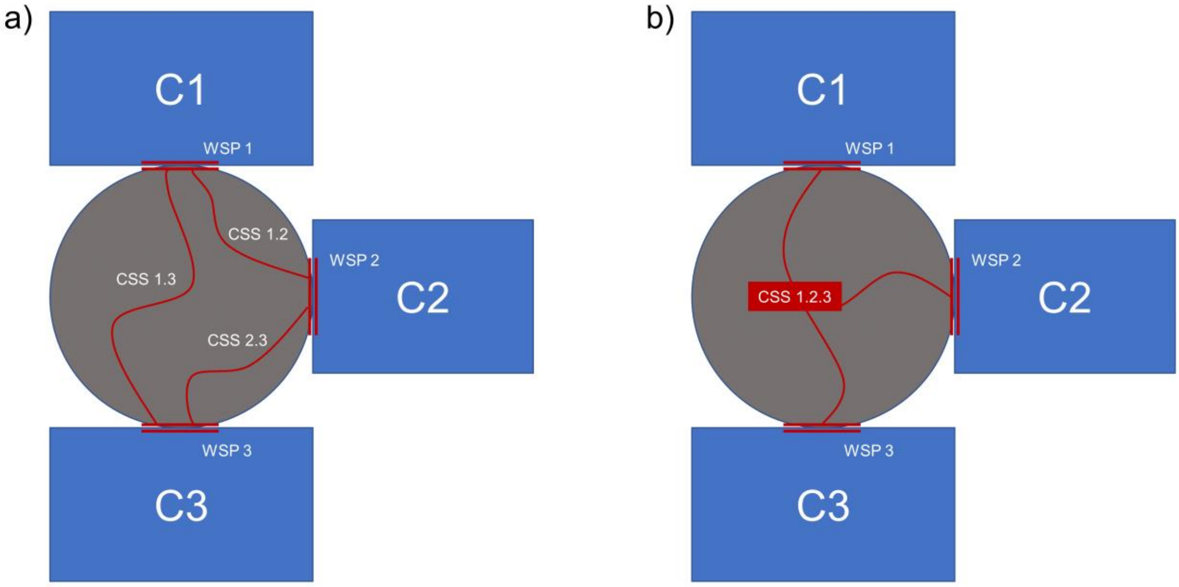


Fig. 6 Simplification of the C&C²-M visualization; a) shows the original separate CSS, b) shows the combined CSS

It is important to stress that there are still multiple CSS connecting the different pairs of WSP fulfilling functions, but they are represented in a combined manner for ease of representation. CSS 1.2.3 for example denotes CSS 1.2, CSS 1.3 and CSS 2.3 in this example.

3.2. Multi Domain C&C²-A – Incorporating the Electromagnetic Domain

One core aim of the C&C²-A is to find the relationships between embodiment and function. As an electric motor not only deals with mechanical challenges, like mechanical stress or thermal management, the embodiment is also of critical importance to the electric functionality. After all, the core parts of a motor are made out of ferromagnetic materials to guide and concentrate the magnetic flux and aid the main function of converting electric into kinetic rotational (meaning mechanical) power and vice versa. It achieves this by using interacting magnetic fields between the stator and the rotor leading to attracting (and/or repelling) forces between the two. Therefore, it is essential to also consider electromagnetic fields and their implications and effects. The application to fields is theorized and within the original scope of C&C^2-A already, but has never been carried out before [2], this research proposes a first representation method of this for further refinement, discussion and improvements. The following shows, how the application of the C&C^2-A to electromagnetic domain was carried out with the aim of providing a more thorough understanding of the relationship between embodiment and function by analyzing two flows – the mechanical power flow (also called force flow) and the magnetic flux – simultaneously.

The consideration of the power flow has the same purpose in this model as in other C&C^2-M. It should show where CSS and WSP direct and transmit mechanical power through the system. The aim is to understand where mechanical loads occur as well as how they work and proceed through the embodiment. The shapes of the WSP and CSS play a central role in this. With this model, an understanding of the mechanical processes in the machine can be generated.

The magnetic flux should be represented analogously to the force flow, but in a different color to tell them apart. This implementation however leads to three core observations:

1. Magnetic fields (or fields in general) are not necessarily bound by or to physical bodies, but can penetrate them and can also exist in fluids and in a vacuum, this differentiates this domain clearly from the mechanical domain.
2. The forces acting on the stator and rotor are not describing a closed force loop within the EM anymore, because the energy is converted and transmitted in another domain.
3. The force does not originate or is transmitted from a surface to a surface but rather to a volume.

When considering the magnetic field in this model, CSS are all continuous volumes that are penetrated by the magnetic field and guide the magnetic field between two surfaces. For this reason, volumes outside of the solid bodies are also considered when creating the model.

Effective volumes are difficult to define in connection with magnetic fields and depend on the selected level of detail. This is also due to the fractal character of the C&C²-A when considering electromagnetism. In this consideration, the transition from one material to another or from one component to the next is assumed to be a WSP. This is in line with the conceptualization of Matthiesen, that working surfaces develop on the surfaces of field-generating bodies and on bodies in the field-penetrated space [24]. The properties of the magnetic field change on these surfaces and the shape of the WSP can influence the function of the system.

An extension to this is the division of fluid (in this case air) volume or vacuum volume. These volumes can be contiguous, but fulfill different functions at different points. In these cases, it is advisable to subdivide the volumes into smaller control volumes in which effective areas are assumed. This creates WSP at the boundaries between the control volumes, although the control volumes are not solid bodies. This procedure was incepted and successfully applied by Brezger [27] for the consideration of fluids.

The second observation stems from the direct interrelation between the two domains, not only in their effects on the embodiment, but also in fulfilling the main function of the electric motor itself.

A first attempt to represent the interface of the components force and magnetic flux was made in the model of the TFM in this work. Fig. 7 shows an example with two solids (CSS 1.X and CSS 2.X) and a volume in between (CSS 1.2). This CSS is assumed to be a vacuum for this consideration. A force interaction takes place between the two solids, although the CSS 1.2 cannot transmit any mechanical forces directly. However, the energy of the system is transported across the vacuum. In the C&C²-M, the electromagnetic fields from the two solids interact and originate the force in the respective neighboring body volume fractions. This means, that no concrete outer surface area of application of the force can be defined, but rather a volume, where the transformation of energy takes place.

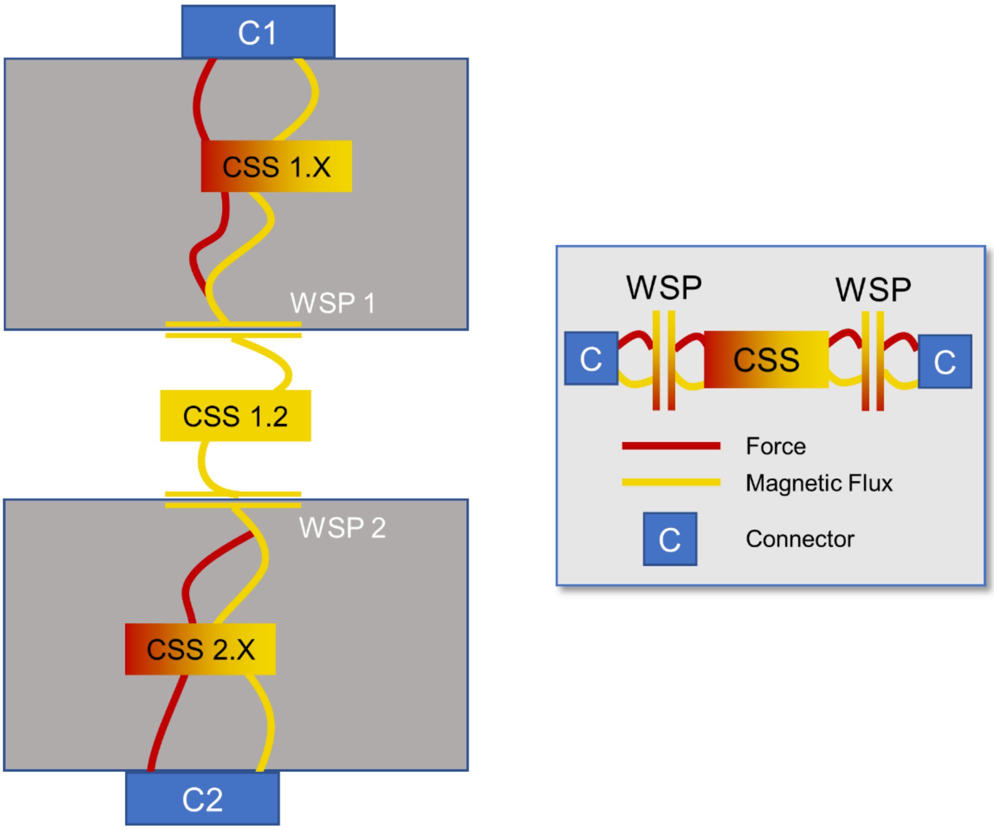


Fig. 7 C&C^2-M depiction of the interaction between force and magnetic flux

As the aggregated sum of these continuous forces resides indeed very close to the outer surface of the body, they are originating very close to the WSP on the outer surface and for the purpose of this research are displayed as originating at the surfaces. This doesn’t always have to be the case and careful consideration of representation of field-penetrated-space and the resulting energy transformations and points of attack is advised.

4. Application

After deriving the general model elements, this chapter explores its usage by applying the elements and their depiction for different product generations of TFM.

4.1. Development Generations of the investigated TFM

Over the course of this research the TFM saw substantial changes to the used material, the production and assembly process as well as the electromagnetic design, researched by the partners of the underlying research project respectively. There are three distinct development generations, which are briefly introduced in the following paragraphs, while the first and the last generation were chosen for detailed analysis with the C&C²-A. Fig. 8 outlines the different parts of the first TFM generation and introduces the general nomenclature used in the following chapters.

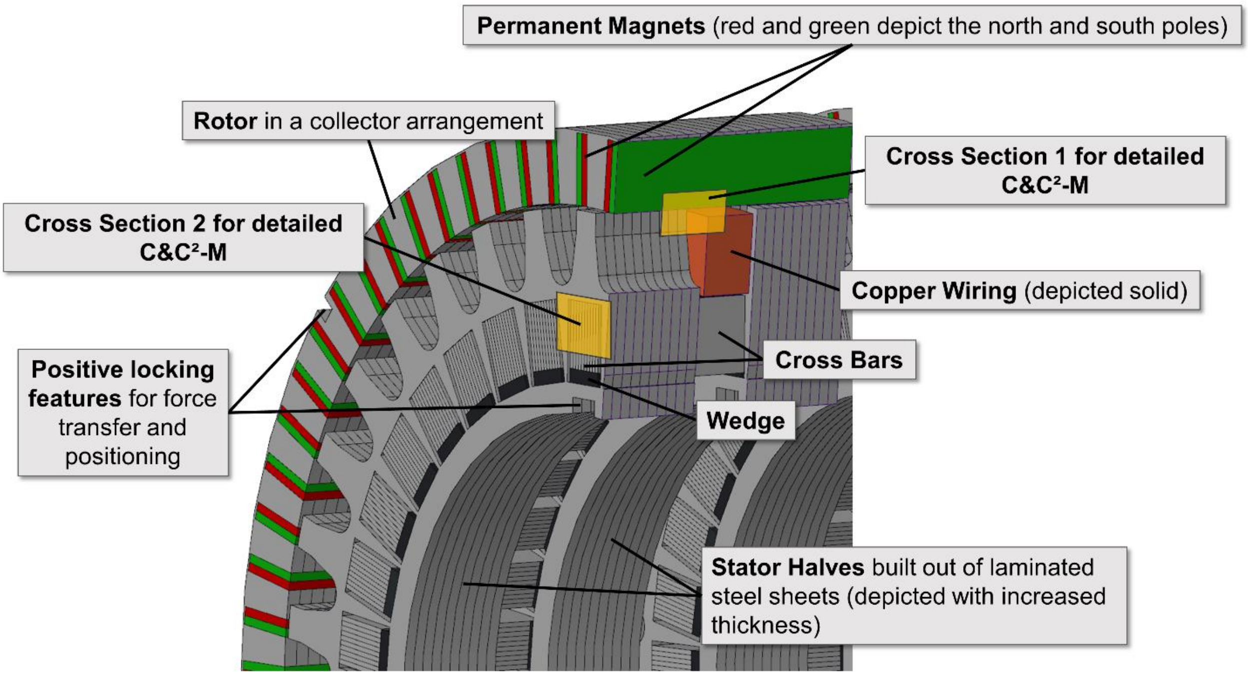


Fig. 8 Overview of the TFM assembly and nomenclature of the parts using the first development generation

The first generation of the TFM ("Laminated") was designed with a U-shaped stator as an assembly of steel laminations and can be seen in Fig. 8. As mentioned earlier, the U-shaped design discourages the use of surface mounted permanent magnets (PM), therefore the rotor had its magnets buried inside in a collector arrangement. As the 2D cross section changes beneath the copper wires, the orientation of the laminations also changes to cross bars. Wedges are used to hold the two stator halves and the cross bars together. This change to orientation also serves as an improved magnetic flux path not passing through the non-ferromagnetic varnish layers while simultaneously slightly hindering the annular eddy currents along the inner circumference of the stator. The laminations are standard M250-35A silicon-electrical steel sheets coated with an electrically insulating varnish. [9, 28]

For the second generation ("SMC"), the principal design was changed drastically and marks a shift from the lamination approach towards a closer representation of an additively manufactured stator. The stator halves are now parts by themselves instead of being assemblies and reach over the copper wiring, aiming to provide more surface area facing the rotor for the magnetic interaction, which can be seen in Fig. 9. As the full depth of the PM can now be utilized, the design was switched to surface PM. The two “claw pole” halves close the magnetic flux path beneath the copper winding. The claws themselves render a conventional lamination infeasible, therefore the halves are now sintered SMC parts. [29]

Fig. 9 Second generation “SMC” stator [29]

While the wiring could also be additively manufactured with a multi-material approach and even the insulation and encapsulation could the integrated into one another by facilitating a ceramic printing material, this research does not focus on changes to the wiring. Therefore, the standard wire with a direct coating, encapsulated after initial assembly, is kept. The rotor remains laminated, as the magnetic flux is mainly two-dimensional in the sheet plane and also the cross section doesn’t change along the axis of rotation. Therefore, the direct advantages of switching away from laminations do not seem as apparent as for the stator side.

The third and final generation (“AM”) of this research goes one step further and draws on the capabilities of AM to improve the TFM and to tackle the weaknesses from the laminated and the SMC generations. The principal claw pole shape is kept and the stator remains as two halves for ease of assembly. This could change in the future with the advancement of multi material printing however. The main difference is the incorporation of finer details, which could not have been done with a SMC part. As such, new and radially formed slots bring back the hinderance of annular electric eddy currents while impairing the magnetic flux and therefore the torque of the motor only slightly. This tradeoff was made deliberately, as the high losses due to eddy currents were a main concern for an efficient motor use. The wiring and rotor are kept from the second generation.

4.2. Modelling the TFM Development Generation “Laminated”

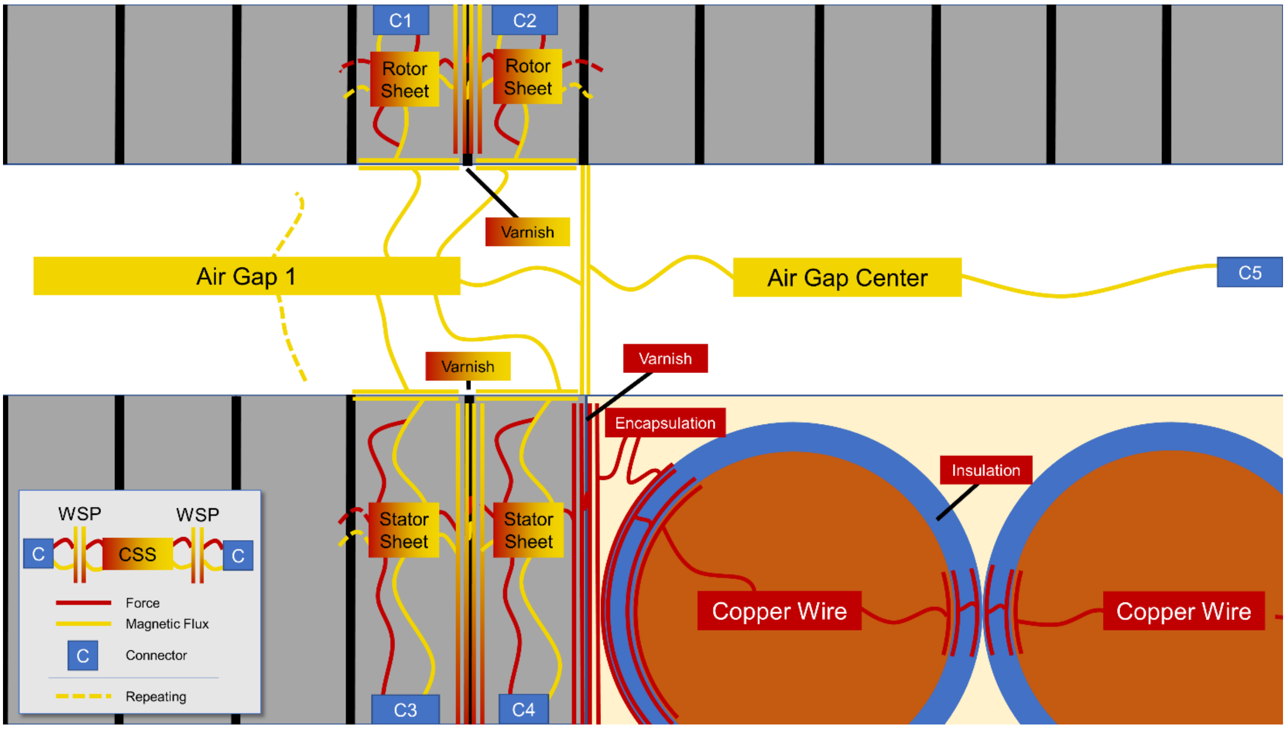


Fig. 10 C&C-M TFM “Laminated” cross section 1; Detail with a cross section perpendicular to the laminate sheets showing the force flow and magnetic flux between the copper wire, the stator and the rotor via the air gap

As shown in Fig. 10 a small cross section of the TFM stator, air gap and rotor are displayed and the C&C²-M is developed. The location of this detailed view in relation to the whole motor can be seen in Fig. 8. While yellow shows the magnetic flux, red denotes the mechanical power flow through this motor section. On the bottom right, one can see the copper wires, electrically insulated with a coating (blue). We then see the encapsulation of the wiring to link them mechanically and thermally to the stator core. From the stator core, five sheets of one stator half are shown, in this case these are the legs of the U-shape. As discussed in chapter 3.2, the force in the stator core starts in the volume close to the outer surface of the stator and is originating from the magnetic interaction between the magnetic fields of rotor and stator. Between every steel sheet there is a layer of varnish for electric insulation, creating two WSP, one for each varnish – sheet contact. The air volume in the air gap is sectioned into control volumes forming a section above the stator sheets and one above the winding. The magnetic flux passing through the WSP "Air Gap Center" shows the flux leakage. The copper wire is assumed to conduct current, inducing a magnetic flux in the surrounding ferromagnetic material. The magnets are not shown in this cross section as they are behind and in front of the cross-section plane in order to position the flux collecting rotor core sheets centrally above the stator core sheets. The repeating pattern of the passing through the sheets is only shown once for the sake of clarity.

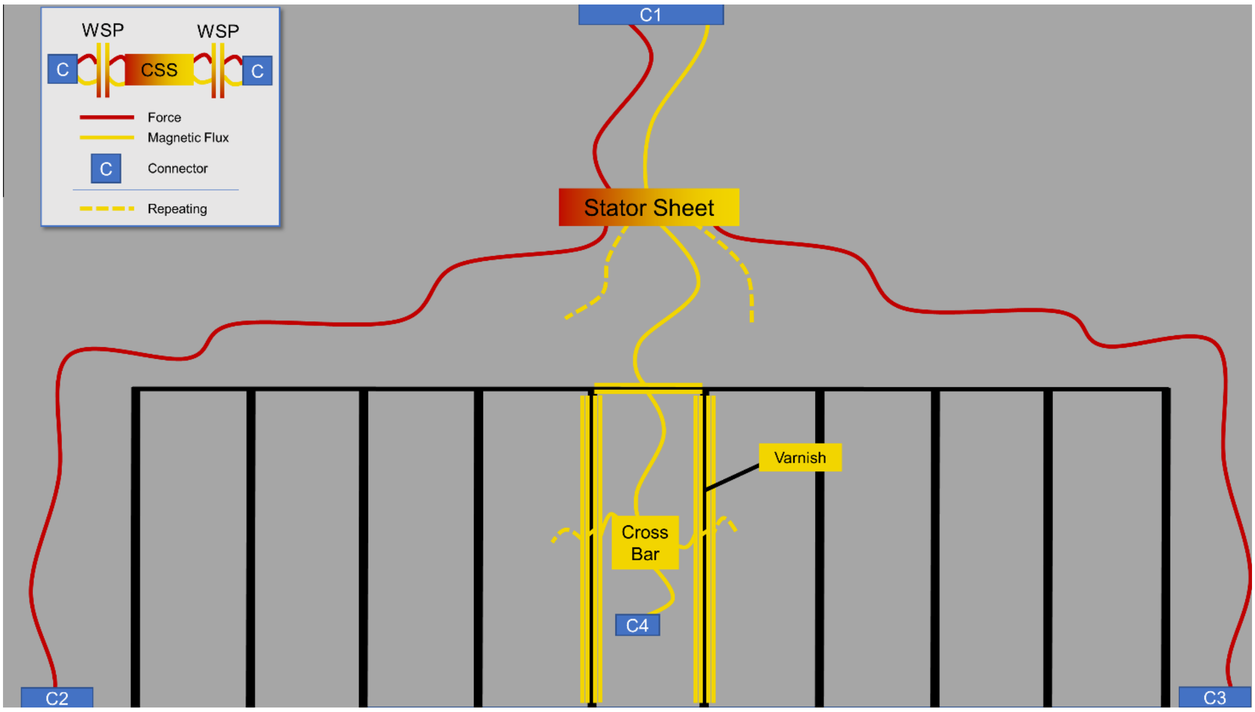


Fig. 11 C&C-M TFM "Laminated" cross section 2; Detail with a cross section perpendicular to the cross bars showing the force flow and magnetic flux

Fig. 11 shows a different section of the laminated TFM, rotating the viewing angle by 90° and focusing on the lower stator section, where the cross bars can be seen. For reference, check Fig. 8 to see, where this cross section is located within the TFM. The mechanical power flows around the cross bar stack, as the wedges are not enforcing a rigid and load bearing mechanical connection between the stator core sheets and the cross bar sheets, but rather position them for their core function of connecting the two stator halves with a ferromagnetic and thus highly magnetically permeable material to close the flux path.

4.3. Modelling the TFM Development Generation “AM”

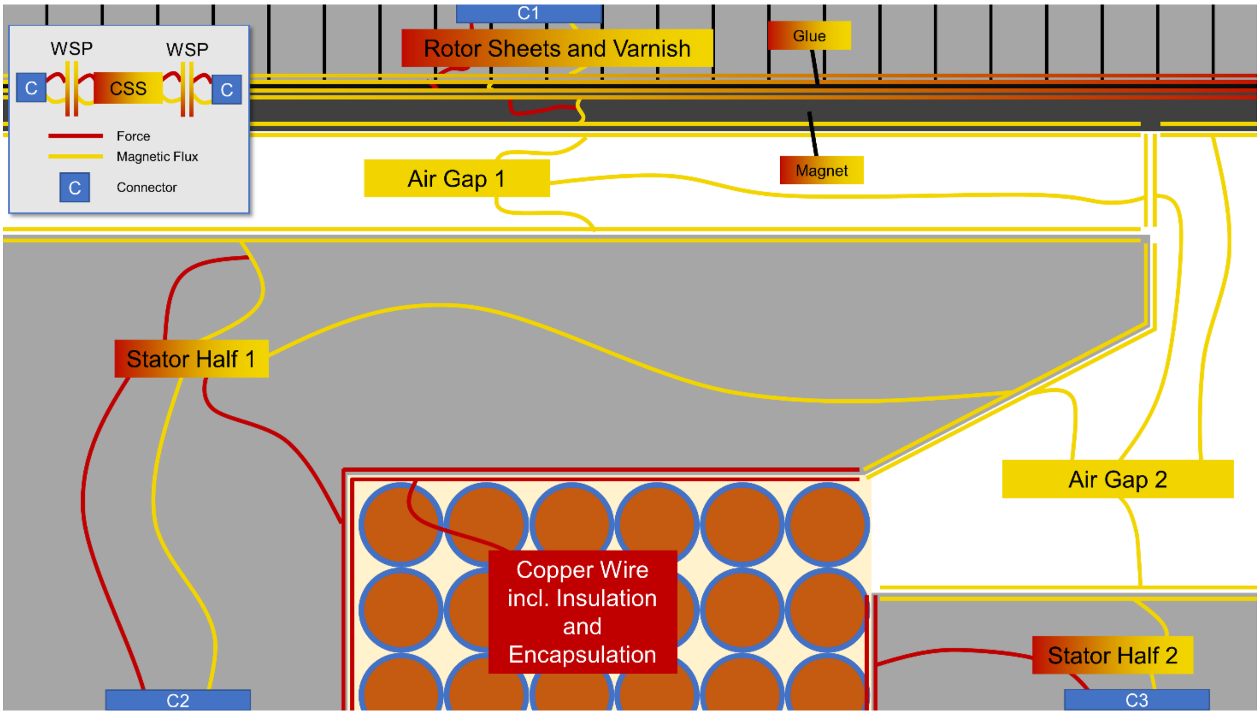


Fig. 12 C&C-M TFM “AM” cross section 1; Detail with a cross section perpendicular to the laminate sheets showing the force flow and magnetic flux between the copper wire, the stator and the rotor via the air gap

Focusing on the same cross-sectional view as shown in Fig. 10, distinct changes can be observed in Fig. 12. The stator halves are now built as one part, eliminating all the sheets and varnish layers. On the left one stator half is shown, while the separated right part shows the second half. As discussed, the wiring is assumed to still be standard electrically insulated copper wiring encapsulated after initial assembly. Two more changes to the overall structure stand out. On one side, the formerly U-shaped stator core now protrudes over the wiring, enlarging the surface area directly facing the rotor. Secondly, the magnet is now shown in this cross section as the switch to surface PM brings them into the cross sectional plane.

Looking at the previously segmented section with wedges and cross bars depicted in Fig. 13, there are now slots in the stator core going all the way through the part. As explained in chapter 4.1, these serve as electrical barriers, hindering annular eddy current along the inner circumference of the stator. The shortest electrical connection now leads all the way up and along the outer surface. The WSP at the slots shows, that magnetic flux can still pass through, but has to deal with multiple WSP and CSS with different sub-optimal materials like air. The power flow follows the stator core inwards along the slots. The copper wiring is depicted simplified here as a solid copper piece, as it is outside the cross sectional plane and detailing the wiring fully would draw attention from the slot geometries and clutter the view unnecessarily which lead to choosing a coarser level of abstraction.

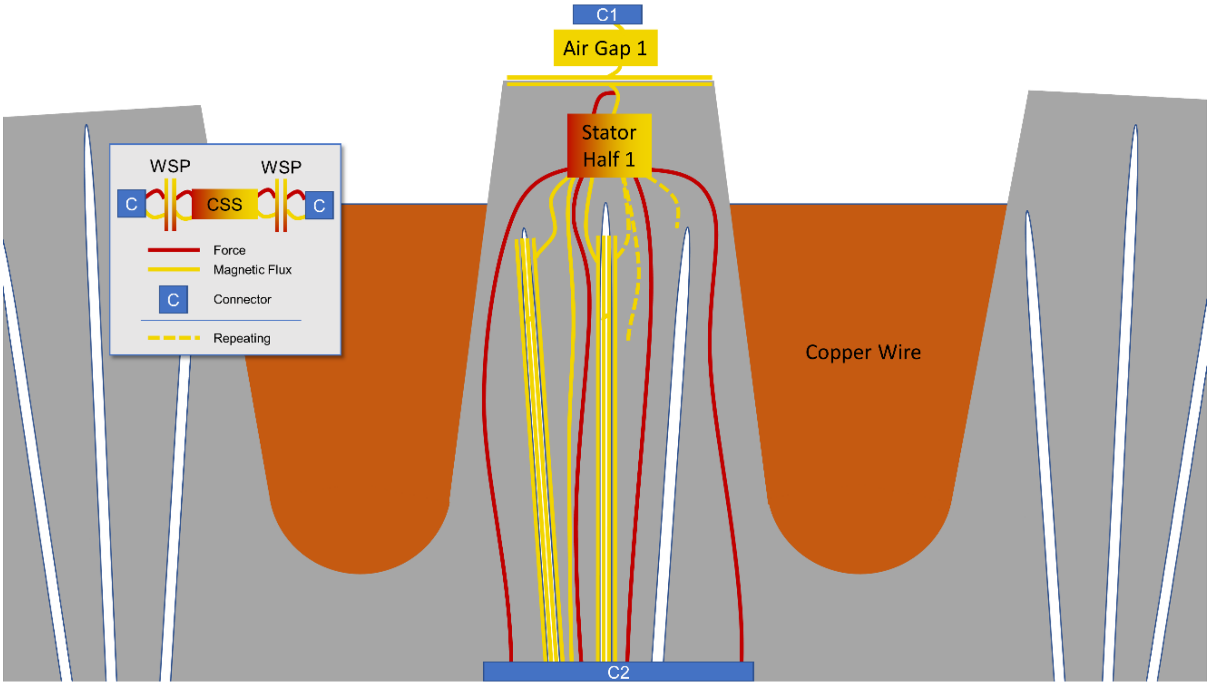


Fig. 13 C&C-M TFM “AM” cross section 2; Detail with a cross section perpendicular to the slots showing the force flow and magnetic flux

5. Results and Discussion

This chapter discusses the implementation of C&C²-A for a multi domain scenario and lays out the intended support and access to the gained knowledge. It then examines the two models and compares them to each other to highlight the advantages of this method by emphasizing the main differences and pointing out design synthesis possibilities.

5.1. Multi Domain C&C²-A and Support for future Engineers

Traditionally, C&C²-A was mainly used to describe the mechanical domain through force flows. By also covering the magnetic domain, interrelations and boundary conditions for a future product can be identified more efficiently.

As discussed in chapter 2.1, modelling of different views on a product, e.g. by mechanical or electromagnetic simulations, is usually done in-depth using specific tools. While multi domain simulation software like COMSOL Multiphysics exists for the creation of predictive models, the descriptive C&C²-M is utilized before that at the very early stages of product development to provide a common ground and base model for a product before branching out into specialized tools.

The process of using C&C²-A follows the workflow described in [3] and starts by close collaboration of all involved disciplines. All functions of the current or an external reference product, and the involved WSP and CSS for fulfilment are identified, for example in a workshop, and an initial C&C²-M for the sections in development on a sufficient level of abstraction and detail is set up together.

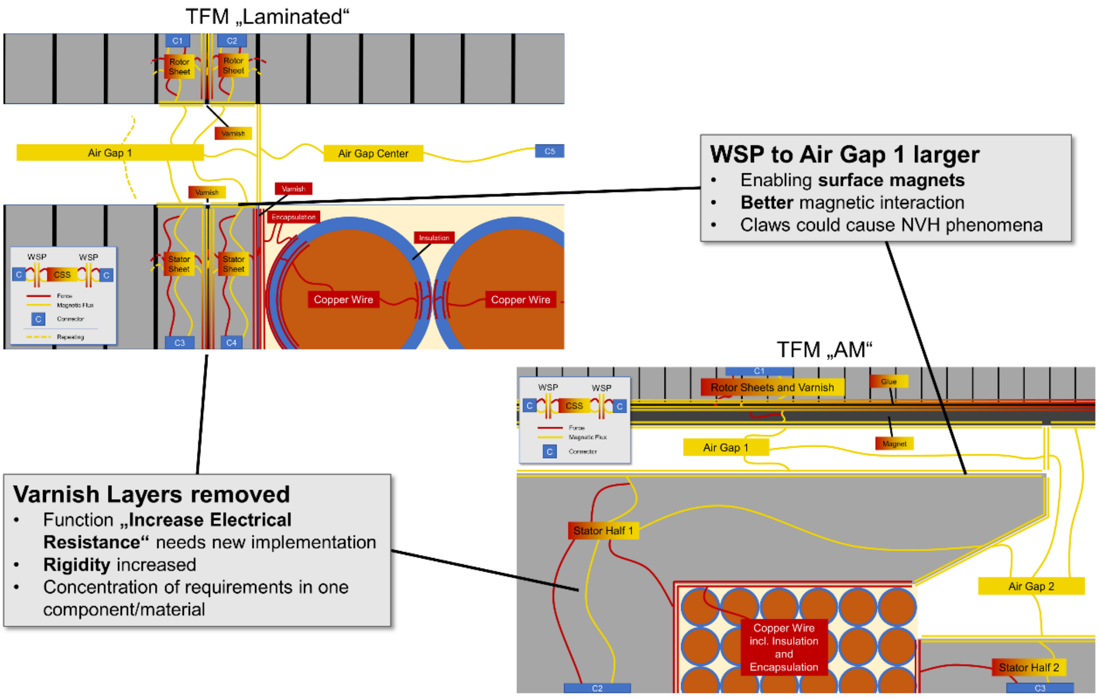
For the new product generation ideas, C&C²-M are created in the same way and the team can use both model generations by comparing them to extract the changes, additions or removals of or to WSP and/or CSS. By performing this analysis, the new requirements and boundary conditions for WSP and CSS can be identified. The strength of this approach comes from the integration of all views into one single model. Everyone on the team now knows the requirements of other views and the potential effects it has on the own view and the team can assess, if changes in one view have effects on others.

Another possibility to facilitate the new C&C²-M is for the synthesis of new solutions. By identifying challenges in the setup of WSP and CSS and solving them by changing the properties via addition/removal/alteration of WSP and CSS new solutions can be found. Both possibilities, the analysis but also the synthesis are exemplified in the next section using the previously developed models.

5.2. Comparison of the TFM Development Generations

When comparing both models side by side, it can be observed, that all ways to change the system (add, remove or alter WSP/CSS) have been used extensively. An excerpt of the comparison highlighting the integration of functions and changes in requirements is shown in Fig. 14 and discussed below.

Using a single material in the stator of the AM-TFM removes many WSP between the sheets and varnish layers. This, at first glance, seems like a positive change for the structure and rigidity of the system. Closer examination reveals, that this comes at a cost however. Removing the CSS “Varnish” completely means, that the function “Increase electrical



WSP to Air Gap 1 larger

- Enabling **surface magnets**
- **Better** magnetic interaction
- Claws could cause NVH phenomena

Varnish Layers removed

- Function **„Increase Electrical Resistance“** needs new implementation
- **Rigidity** increased
- Concentration of requirements in one component/material

Fig. 14 Comparison of the two C&C²-M to identify changes to WSP and CSS

resistance within the stator” now cannot be fulfilled the same way anymore. Instead, this function is now fulfilled by the stator itself, adding to the already substantial requirements for the stator material, which, among others, has to incorporate:

- High magnetic permeability and saturation
- Low magnetic hysteresis losses
- High thermal conductivity
- High stiffness and overall rigidity
- High electrical resistance (new)

As the fundamental processes within ferromagnetic material for heat conductivity and electric conductivity rely on the same physical principles, an immediate conflict of objectives becomes obvious. As the base assumption is using one single material for the whole stator core and not layering different materials in a layered structure, the problem has to be solved differently. As AM offers the capabilities to implement more granular and finer details, it was devised by the cooperating institutes, that radial slots (gaps filled with air from the environment) starting from the inner circumference (see Fig. 13) could be a potential solution. Electromagnetic simulations confirmed the lowering of eddy current losses while sacrificing only a small amount of torque. However, this change to the overall system introduces challenges outside the electromagnetic domain. While electric current has to travel around the air-filled slots, magnetic flux can pass through the slots albeit somewhat hindered by a worse magnetic permeability compared to ferromagnetic materials. Looking at the mechanical side of things, the rigidity and stiffness of the stator could suffer by reducing the area moment of inertia and essentially creating metal strings, which are prone to vibrations and NVH issues. On the other hand, these slots could be used for new function implementation, such as an internal cooling system using air or even a liquid or might be beneficial to insert sensors or actuators into the stator. Here, the power of the C&C²-M becomes apparent, as one can now focus on the desired functions of the future product and their relationship to the embodiment. Analyzing the WSP and CSS more deeply, it can be seen, that the main requirements for consideration of this generation were "high electric resistivity" and the mechanical requirements on rigidity, while new functionality was not considered at this development stage. Slots filled with air would fulfill this electric requirement, but they are not a good candidate from a more holistic perspective, including the mechanical domain. Instead, three new solutions were synthesized, devising them solely from their functionality.

One solution can be seen in Fig. 15. This would keep the slots and fill them with any electrically nonconductive, but solid material. Resins, already used for the encapsulation of the wiring, could be a good choice here, as no new process is required. This synthesis adds new WSP for the mechanical power flow through the slots and alters the properties of the slot CSS to now allow for force transmission. From an electrical perspective, the more slots there are, the better, although there are diminishing returns on efficiency gains when increasing the slot count. The mechanical behavior favors quite the opposite, as less slots are advantageous for the rigidity of the system. As for the slot width, magnetically they should be as narrow as possible, in order to minimize torque loss. This goes in line with the mechanic view, as narrower slots mean more solid material resulting in more rigidity. In this case, a lower limit to the width comes from the manufacturing process and needs to be considered. This solution's WSP and CSS are electrically similar to the first TFM generation, where the material between the slots represents the cross bars and the material within the slots mimics the varnish layers. Magnetically, filling the slots with non-magnetic material or leaving them unfilled makes no difference, so that the mechanical properties can be improved without any cost in the magnetic or electric domains.

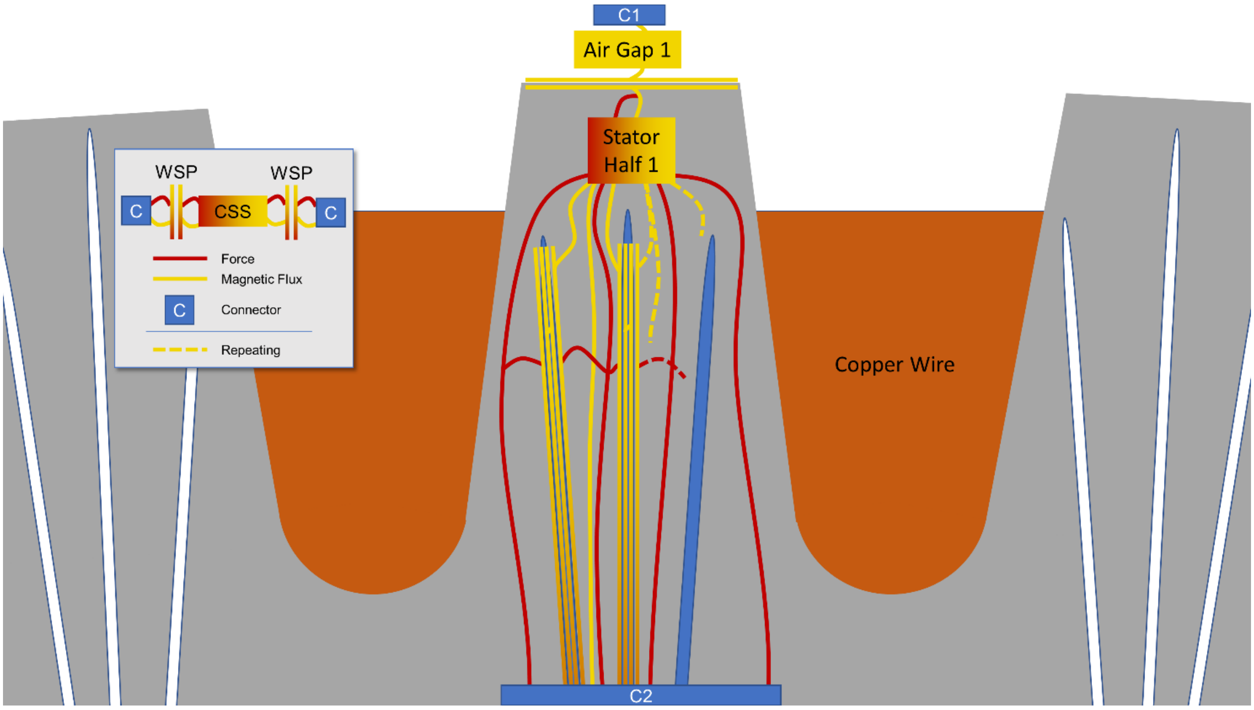


Fig. 15 C&C²-M of the synthesized solution for the lacking rigidity of the TFM stator filling the stator slots with a solid

A second solution seeks to implement the function “electrical insulation” in a different way by approaching the problem from a manufacturing process perspective. By altering the process parameters, one could potentially manufacture more porous sections within the stator, mimicking the behavior of the slots, but keeping the mechanical integrity intact. This of course imposes new challenges to the process itself and the electrical and magnetic behavior would need to be analyzed in more depth.

The third synthesis idea revolves around using the raw powder from the process directly to bring in new functionality. By leaving the powder within the slots and closing them of with resin or additively during manufacturing, one would create inner pockets of powder with potentially superior dampening characteristics from an NVH standpoint. However, the field of particle dampers made out of raw powder of additive processes is largely unexplored and especially the magnetic and electric behavior of this powder inside the pocket is not well understood. Also, the mechanical properties and the potential need for compacting the powder to achieve higher rigidity and the interaction of these parameters with the electric and magnetic properties needs further investigation before considering this novel approach. These identified possibilities represent an example analysis and synthesis process based on a TFM for research purposes. The designer(s) need to consider all the required functions carefully to arrive at the best multi domain tradeoff according to the desired machine specification.

6. Summary and Future Outlook

As Grauberger [2] already mentioned, the application of C&C²-A for the electromagnetic domain might pose some challenges. This research ventured out to investigate this very issue. By applying this method to a technical system, it was found, that Matthiesen [24] was right when he stated, that the C&C²-A can indeed be used for this domain also. By investigating the mechanical and the electromagnetic domain at the same within the same cross section the approach offers a more thorough understanding and highlights the requirements for each and every WSP and CSS much more clearly. Previously, one could deduce, that for example a certain Young's modulus for a CSS or a specific surface finish for a WSP was required in order to fulfill a function. The inclusion of electric and magnetic parameters, such as magnetic permeability or electric resistivity shows the difficulty of dealing with many requirements from different domains at the same time. By also including thermal requirements as well as material and process limitations, the results derived from these models are more complete, versatile and serve as a communication device between different disciplines in engineering. After all, the C&C²-A serves as a meta-model and expanding it to different domains establishes a powerful lingua franca, which eases communication and can potentially prevent mistakes from misunderstanding.

Visualizing the domain interactions also proved itself useful, as it opens up the engineer's mind to focus on the flows through the embodiment and link them to their underlaying function. With this, it is possible to break out of mental barriers or thinking in conventional and established designs and create solutions for necessary functions directly.

However, the C&C²-A has certain not fully addressed limitations that should be pointed out as well. One limitation of the C&C²-A is that the energy conversion between different domains, e.g.

mechanical to electrical and vice versa, is not fully specified in how it can be depicted in the models. Having forces appear seemingly out of thin air seems counter intuitive, as the closed force loop is missing at first glance. This was solved by connecting the force to the magnetic flux, indicating the energy conversion. This, however, requires further research and a more canonical approach.

Similarly, dealing with field penetrated volumes becomes a challenge by itself, as no clear and concise surface is available anymore for a Working Surface Pair. While the penetration happens at a distinct surface and proceeds into the volume, the generated forces from the field interaction do not have a clear surface, where they originate from. The depiction of this is also a topic for further research.

The analysis of the TFM with the C&C²-A in this work is carried out mainly on a qualitative level. The C&C²-M do not contain enough quantitative data to pinpoint the forces and the magnetic flux and its concentration. Therefore, assigning more quantitative data to every WSP and CSS would alleviate this and open up more synthesis possibilities, for example the quantitative description of necessary properties, allowing a full selection process.

This work presented the research on the C&C²-A by applying it directly to a technical product in the form of a transverse flux machine. In order to be able to carry out a clear analysis, individual aspects in the representation of the model are adjusted and simplified. Models of two different development stages are created, namely the conventionally manufactured TFM and the additively manufactured TFM. It is found, that analyzing the functionality of the system from a mechanical and magnetic view provides a deeper insight and reveals synthesis ideas by facilitating the embodiment design ideas of the C&C²-A. The level of abstraction was chosen to visualize the addition, removal and alteration of WSP and CSS throughout product development and understand the reasoning behind the decisions originally made from an electromagnetic perspective. The additively manufactured parts tend to carrying out more functions within the same part out of the same material when compared to their conventionally manufactured counterparts, which implies conflicting objectives. By incorporating the mechanical, material and process perspectives, new possibilities were explored and described as an example of application. It was found, that an electrically and magnetically optimized system can be enhanced to also satisfy mechanical requirements without influencing the electromagnetic domain negatively by introducing a new repeating CSS and WSP to strengthen the stator core. These small but impactful changes highlight the power of a common development and communication model between designers and the importance of working together and collaborating iteratively and not in sequence to one another.

In conclusion, the C&C²-A proves itself useful and valuable for multi domain systems and as a mutual lingua franca for product developers from different disciplines. The representation of the energy transformation as well as the interaction of volumes still requires further research. Also, the material properties with respect to the process parameters as well as the process itself need to be understood in more depth in order to inform the decision making and filter out infeasible synthesis ideas.

The work on this multi domain model has only begun and many questions remain. For the TFM itself, the implementation of further functionality such as an inner cooling system and the relationship between functions and embodiment for this addition as well as the introduction of sensors and actuators in stator and rotor for data collection and to inform the development process with a data foundation are currently investigated in follow up research projects.

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