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Systematic Review

Multidisciplinary Design Automation of Electric Motors—Systematic Literature Review and Methodological Framework

Niklas Umland [1,*], Kora Winkler [1] and David Inkermann [2]

[1] Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM, Wiener Straße 12, 28359 Bremen, Germany; kora.winkler@ifam.fraunhofer.de
[2] Institute for Mechanical Engineering, Technische Universität Clausthal, Robert-Koch-Straße 32, 38678 Clausthal-Zellerfeld, Germany; inkermann@imw.tu-clausthal.de
* Correspondence: niklas.umland@ifam.fraunhofer.de

Abstract: Electric motor development is a challenging task, as higher efficiency requirements and various interdependencies between different engineering domains must be considered. Established design approaches often lack the ability to address these interdependencies because they focus on specific domains and properties. Automated, multidisciplinary design approaches hold untapped potential for optimizing motors in terms of diverse requirements and advancing the development of more efficient and reliable motors. This paper presents a systematic literature review of the current state of research in the multidisciplinary design automation of electric motors. The literature basis comprises 1005 publications that are identified by a systematic internet search. The review of the existing approaches is based on twelve criteria that characterize the design automation task in general, such as knowledge representation or reasoning methods used, as well as criteria specific to electric motor design, such as domains considered and their coupling. The analysis reveals what current approaches are lacking: Consequent analysis and integration of domains, applicability of suggested methods, incorporation of established multidisciplinary design optimization (MDO) architectures, alongside the consideration of passive components in the motor. Aside from the introduction of twelve criteria for systematic charaterization of multidisciplinary design automation of electric motors, this article expands the state of the art by proposing an initial framework to establish process chains tackling the identified gaps in the review.

Keywords: electric motor; electric machine; design automation; multidisciplinary design optimization (MDO); knowledge-based engineering

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1. Introduction

Electric motors account for 53% of electricity consumption worldwide [1]. They are prevalent in a wide range of industrial and consumer products. Research focusing on electric motor development has gained momentum due to the ongoing electrification of various mobile applications, e.g., electric cars and more electric aircraft, as well as an increasing amount of mechatronic products. Subsequently, an increasing effort is invested in processes and methods in electric motor development, to meet ever-increasing requirements with regard to application-specific efficiency and power density [2]. Most applications require electric motors to be custom-tailored, resulting in the need to provide more flexible and efficient development processes [3].

Typical engineering domains involved in electric machine design are illustrated in Figure 1. In conventional approaches, design decisions are made in the electromagnetic domain first, often relying on the designers' assumptions and experiences [4]. Requirements and restrictions of further engineering domains like rotordynamics, structural mechanics or thermal design are considered at a later stage. Every time a design does not meet these requirements, several steps or the whole design process have to be revisited [5]. This often results in lengthy iteration cycles, increased project risks and prevents the inclusion of aspects from different domains in decision making. Various authors claim this to be a key factor for future electric motor development to meet rising efficiency standards [6–9].

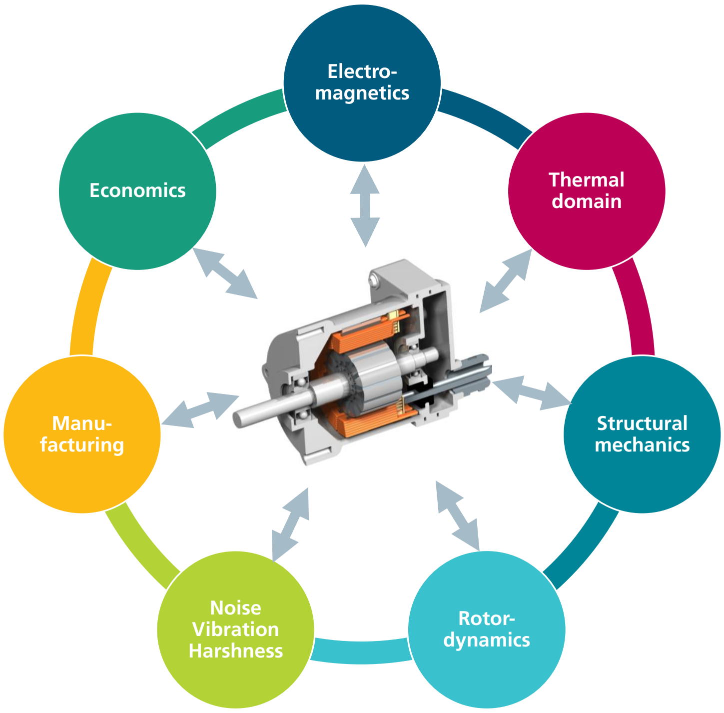


Figure 1. Engineering domains involved in the design of electric motors.

For this reason, new design methods are suggested in the literature, which will be summarized under the term multidisciplinary design automation (MDDA) in this work. These aim to overcome the weaknesses of conventional design approaches by systematically searching the solution space through automation. This allows decision-relevant information to be made available earlier and, thus, allowing for the design of a better electric motor from a multidomain perspective by breaking down domain silos [10,11].

In the literature, different approaches can be found for the application of MDDA in the development of electric motors. However, there is a lack of higher-level methods to set up MDDA processes. This paper systematically reviews the research conducted on MDDA in electric motor engineering. The main objective is to analyze and classify existing methods in this area. This allows to identify further research needs. Overall, this paper contributes by (1) presenting the state of the art regarding the adoption of MDDA, (2) identifying trends and gaps resulting from it and (3) deriving a generic methodological framework for the adoption of MDDA.

The article is structured as follows: Section 2 gives an overview of the used terminology in the scope of MDDA; Section 3 describes the review method; and Section 4 presents the employed review criteria. Section 5 presents the results of the systematic literature review. Section 6 presents the findings of the review in order to identify trends and gaps. Based on these findings, the authors present a methodological framework for setting up MDDA in electric motor engineering in Section 7. Section 8 concludes the paper by answering the research questions.

2. Multidisciplinary Design Automation in Electric Motor Design

2.1. Terminology

The most relevant terms for this publication will be clarified in the following text, since there is no uniform terminology. In general, design automation (DA) can be understood as computer-aided engineering support. It translates information and knowledge into solutions, tools or systems to support the progress of design processes through automation [12]. Since electric motor development involves different engineering domains, it is reasonable to extend the concept to multidisciplinary design automation as suggested by [13]. Another term that is often used in the context of DA is knowledge-based engineering (KBE). Van der Velden differs between KBE and DA and describes the former as a capture of engineering knowledge to emulate human decision making and automate engineering processes. Design automation is described as an automation of sequential steps in engineering processes. These are often only applicable to specific use cases, since they contain hard-coded rules and knowledge [14]. In more recent definitions, KBE has been described as a method within the context of DA [13]. These definitions emphasize that KBE leverages existing knowledge to automate repetitive tasks in product development [15,16]. As shown in Figure 2, three steps are necessary for the creation of a KBE system: knowledge capture, knowledge formalization and knowledge representation [17].

Figure 2. Steps necessary to build a KBE system [17].

Generative design and engineering is a term that is often used synonymously to DA. It describes methods and processes for generating a large number of solution variants, often related to geometries. This enables engineers to explore the existing solution space more thoroughly. There are different approaches to generative design, ranging from parameterized computer-aided design (CAD) templates [18] to leveraging deep networks to synthesize new designs [19]. The term computer-based design synthesis (CDS) is used in a similar context. It refers to tools and methods in the design process that support engineers to create design alternatives based on computationally encoded knowledge [10,20]. Another relevant term in the context of automated multidisciplinary design is multidisciplinary design optimization (MDO). The concept of MDO emerged primarily from the challenges encountered in aircraft design, which inherently involves intricate design and simulation processes due to its multidisciplinary nature. MDO addresses these challenges by executing coupled simulations and concurrent optimization of specified design variables [21]. In recent years, MDO methodologies have been applied to the design of electric motors [22,23]. Since MDO facilitates the automatic synthesis of geometries while considering multiple domains of analyses, it can be regarded as a distinct form of MDDA that leverages optimization algorithms as a reasoning approach. A typical process for setting up a MDO consists of five steps, as visualized in Figure 3 [24].

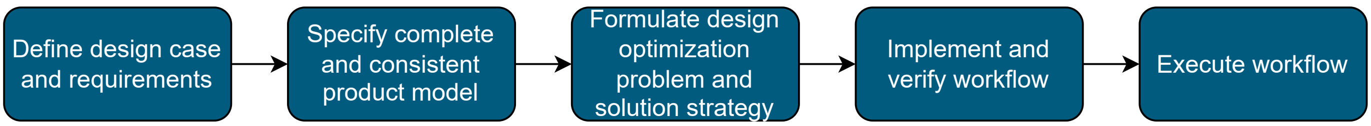


Figure 3. Steps for the creation and execution of MDO processes [24].

Design automation tasks serve different purposes in the design process. In his categorization—see Figure 4—Rigger groups DA task categories along the design process. Some of them contain multiple tasks, resulting in a total of 15 different design automation task categories. In early design stages, design automation tasks are focused on automatically decomposing the functional structure, i.e., functional synthesis, and on product architecture synthesis. This includes topology and parameter synthesis and analysis. However, at this early stage, the design takes place on a high level and does not yet include concrete geometric features and parameters. In embodiment design, tasks revolve around spatial synthesis and analysis and are grouped under the term spatial product/component architecture. These range from topology and parameter synthesis to analysis preparation, integration and simulation. A spatial topology optimization forms an integrated loop of these tasks. Typical MDO processes are an example of this. Automated design configuration can be applied both in embodiment design and detailed design. Tasks grouped under the term transformation process design focus on the planning of production processes in later stages of the design process. However, a co-evolution of products and processes can be implemented in early stages too [10].

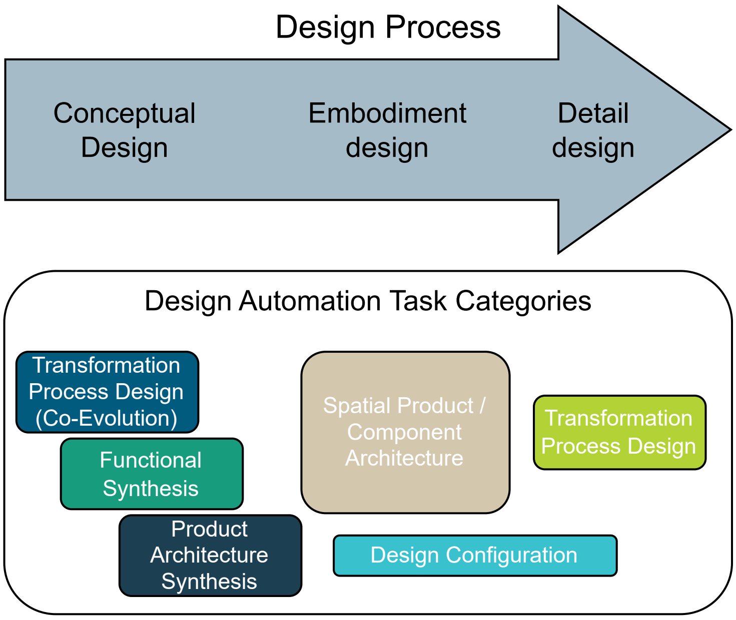


Figure 4. Categorization of design automation tasks along the design process [10].

Apart from the selection of a motor type, most decisions made in electric motor design are made during spatial product design. The focus of this review is therefore on design tasks involving an automated synthesis of geometries, i.e., spatial product/component architecture, design configuration and spatial topology optimization.

2.2. Existing Reviews

In order to ensure that there is no review already addressing the research goal, existing review papers in the field of MDDA for electric motors were searched in the lens.org database. The identified review papers are briefly presented in the following text.

Reference [2] gives an overview of modern optimization techniques within the development of electric machines. The authors present commonly used optimization algorithms and the basic idea of setting up the optimization problem. However, integrated multidisciplinary analyses are not in focus.

Reference [25] differentiates between component-level design and system-level design approaches and argue that the optimal solution can only be found following a multidomain perspective. Furthermore, aspects to be considered in each of the engineering domains, i.e., electromagnetic, thermal and mechanical engineering, are listed. However, no in-depth analysis of the state of the art in MDO for electric machines is presented.

Reference [26] highlights and categorizes couplings between engineering domains in the multidisciplinary optimization of electric machines. The proposed categorization was applied within the framework of the systematic review in this paper; see Section 4.3.

References [27,28] review current optimization procedures used within electric machine development, focusing on optimization algorithms. Since a profound analysis of optimization algorithms has already been carried out, the analysis of these algorithms will only be a secondary aspect in the paper at hand. In the systematic analysis, the associated data collection category is based on the categorization proposed by [27].

To summarize, none of the existing review papers comprehensively address the specific use of MDDA for electric motor development. Single reviews focus only on certain aspects, e.g., optimization algorithms, while in other reviews, MDDA is only considered as a side aspect.

2.3. Research Objectives and Focus

MDDA is increasingly relevant to address the need for more efficient development of electric motors, especially as solutions are required to meet increasing demands for power density, reliability or efficiency. Based on the experience gained in different projects at Fraunhofer IFAM, there is a need for a methodology for setting up application-dependent MDDA workflows. In order to provide a sound basis for this methodology, the research goal is formulated as follows:

Purpose	Collect and analyze existing approaches
Issue	on MDDA in electric motor development that explicitly take into account
Object	different engineering domains and their interactions
Perspective	both from the point of view of engineers and researchers.

Based on this goal, this article is guided by the following overarching research question:

What approaches for MDDA exist to support development of electric motors, which domains do these consider, what activities and methods do these include and in which application fields are they employed?

Since existing reviews do not answer this question, the contribution at hand extends the state of the art by

- Collection and analysis of state of the art MDDA in electric motor development.
- Introduction of criteria to distinguish MDDA workflows and associated methods.
- An initial framework to set up MDDA workflows for efficient development of electric motors for different applications.

These contributions are based on a systematic literature review. In line with the design research methodology (DRM) [29], this review is associated to the "descriptive study 1". It serves as a basis for detailed design support development in the prescriptive study in future work.

3. Method

The method of the systematic review is introduced in the following section. The applied methodology is based on [30], including the following steps: (1) research questions, (2) search process, (3) publication selection, (4) quality assessment, (5) data collection and analysis. For publication selection the PRISMA flow was adopted [31].

3.1. Research Questions

Based on the understanding of MDDA described in Section 2.1 and the DA tasks that are in focus in this paper, the following sub-questions are used to guide the review:

1. How is the multidomain analysis and automated geometry synthesis structured?
2. How are domain-specific aspects and constraints formalized?
3. When in the development process of electric motors are MDDA approaches being utilized?
4. For which application and type of electric motor is MDDA already employed?
5. Which parts and geometries of electric motors are automatically created?
6. Which domains are considered and implemented in the MDDA and at which fidelity level?
7. Which couplings between engineering domains are considered?

Based on these sub-questions, specific criteria for the review will be defined in Section 4.

3.2. Search Process

To ensure completeness of papers for a systematic review, the authors searched for relevant publications in a two-stage process, as depicted in the PRISMA diagram in Figure 5. In the first stage, the search was based on a search string, using the search databases lens.org, Web of Science and Scopus. These offer a large database and are able to handle complex search strings. In an iterative process, the search string was specified, considering three parts and their multiple synonyms: design automation, multidisciplinary, and electric motor. The finally used search string is given in Appendix A. The search was conducted within title, abstract and keywords of the publications. In the next steps, doublets were removed, inclusion/exclusion criteria were applied, and the database was extended by a forward and backward citation analysis. In Figure 5, the different steps of the literature identification and selection process following the PRISMA flow diagram [31] are illustrated.

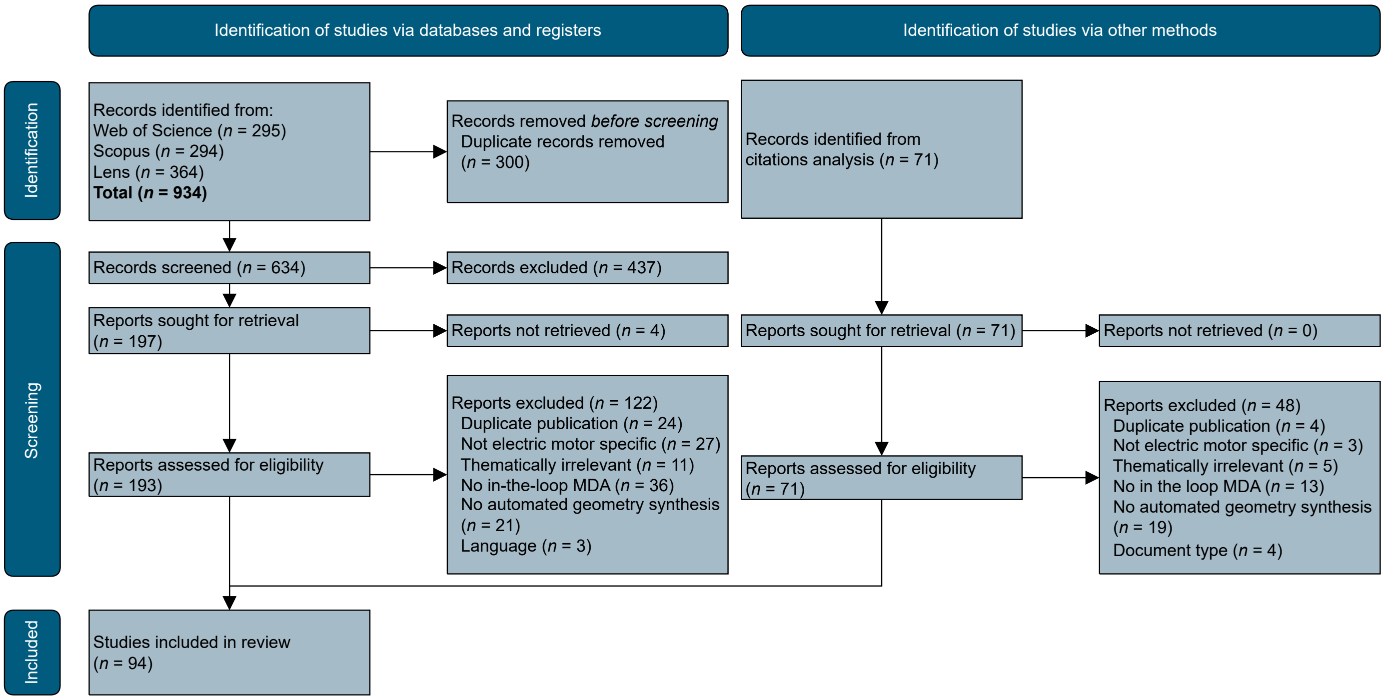


Figure 5. PRISMA flow of the conducted literature identification process and number of papers in each step.

3.3. Publication Selection

Following criteria were used to select papers for the review:

- Document type: Peer-reviewed conference or journal publications
- Language: English
- Date range: Years 2007–2022
- Electric machines: Only papers that focus on design activities of electric machines are included. Publications that consider electric machine design as a side aspect (system-of-systems) are not considered.
- Electric motor focus: Papers that relate to details of generators are excluded from the review unless the authors indicate the transfer to electric motors.
- Automated geometry synthesis: Only papers that employ methods for automated geometry synthesis are considered.
- Multidisciplinary: In the scope of automated geometry synthesis, analyses have to be presented in more than one engineering domain, see Figure 1.

A total of 934 papers were initially identified, as depicted in Figure 5. After removing duplicates, 634 papers remained for abstract screening. In this screening process, 437 papers were excluded. Four papers could not be retrieved and therefore had to be excluded from the review. Another 122 papers had to be excluded in the assessment of eligibility based on the full papers, either because they did not fit the inclusion criteria or turned out to be duplicates. In this step, publications are classified as duplicates if they only differ marginally in their content. This is often the case when publications were first published at conferences and then in a journal. In this case, the more detailed version of the paper is considered in the review. A forward and backward citation process was conducted based on the remaining studies. In this process, 71 additional papers were identified based on their abstract. All 71 papers could be retrieved and thus were assessed for eligibility, which resulted in an exclusion of 48 papers. As a result, a total of 94 papers were included in the review.

3.4. Quality Assessment

Three basic aspects were considered to assure high quality of the review during the literature selection phase:

1. Quality of paper identification;
2. Quality of papers;
3. Quality of review criteria

Moreover, the overall procedure of the review is based on well-known methods, i.e., Kitchenham's approach and PRISMA flow [30,31]. In order to address the three mentioned quality aspects, the following measures were taken. Literature identification was based on three well-established databases, namely Lens.org, Scopus and WebOfScience. A backward and forward citation analysis based on Researchrabbit and lens.org was conducted to assure that all relevant papers were found for the review. To ensure the quality of papers in the study, only conference and journal papers having passed a peer-review process were included. The quality of the review criteria—see Section 4—is ensured by two precautions. First, categories and items are based on existing works. Second, within two randomly selected samples (29 papers), the classification of papers was performed by two independent authors. Based on the results, discrepancies were identified and the review criteria were specified to reduce subjectivity of classification. The occurring discrepancies were divided into three categories: full match of review items, partial match and poor match. As a result of the iterative procedure, the average for all review criteria was 75.5% full matches, 15.3% partial matches, and 9.2% poor matches.

3.5. Data Collection and Analysis

To systematically analyze the papers and answer the research questions, twelve criteria were defined for the review; see Figure 6. Half of these criteria are based on [10] and extended by specific criteria relevant for design automation in electric motor development. For the definition of basic DA tasks, Rigger analyzed publications regarding inputs, outputs, goals and DA Methods. The analysis of goals is further split up in purpose, system level and requirements/constraints, while DA Methods consist of knowledge representation and reasoning methods. Since the review at hand focuses on MDDA for electric motors the following criteria were added for the review: considered domains, couplings between domains, machine type, part of the machine, and application. Considered domains were analyzed based on [32], couplings were introduced based on the classification in [26], and reasoning methods were adapted for electric motor specific reasoning methods defined in [27].

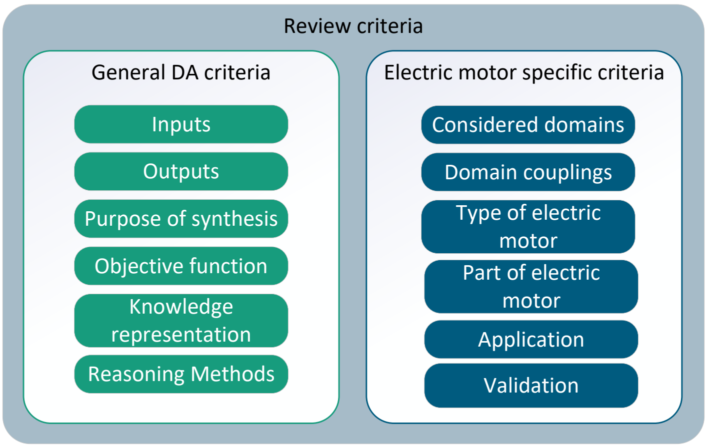


Figure 6. Review criteria employed in the review.

4. Review Criteria

The chapter below describes the criteria used for the systematic review and introduces the information to be extracted for each criterion.

4.1. Inputs, Outputs and Goals

The inputs and output types of a design automation task depend on the stage within the design process [10]. In this review, we distinguish between parameterized and non-parameterized geometry, as proposed by [2]. Instead of employing a fixed topology defined by parameters, the corresponding approaches utilize a non-parameterized geometry that discretizes design areas and achieves design optimization by element-wise material assignment. Furthermore, alternative geometry inputs, such as component libraries, were explored during the search process. An expected output of spatial synthesis tasks is finding (optimized) geometry parameters [10]. The goal criterion provides additional information regarding the purpose of geometry synthesis and its objective function. In this review, the authors assessed whether topology or parameter synthesis was performed, as well as the objective function and design variables employed in each respective paper. Given the multitude of potential design variables, specific variables were not identified. Instead, the review identified the overarching component they represented. For example, when stator slot parameters were included as design variables, the review noted the term "stator".

To define the process stage in which the MDDA is applied, the specific design variables were analyzed. Allocation of design variables to process stages of electric motor development is defined based on common guidelines, e.g., [32,33]. In both procedures, the first step is to determine the main machine dimensions, namely the air gap diameter and the active stack length. In order to determine the stage of the development process, this review evaluates whether the main machine dimensions were already fixed or considered as design variables in the MDDA. The former was defined as detailed design and the latter as preliminary design. Some papers describe a two-stage design process, where a preliminary design is found in the first stage and further elaborated upon. These papers were marked as preliminary and detailed design in the study.

4.2. Knowledge Representation and Reasoning Methods

Rigger highlights that the selection of knowledge representation methods in the context of design automation is influenced by the particular reasoning approach used. Hence, the review analyzed the way of representing knowledge based on the characteristics proposed by [10]. These include: graphs, object-orientated representations, ontologies, shape-based representations and procedural rules. The identification of reasoning methods was guided by Rigger's definition, while specific reasoning methods relevant for electric machines, as defined in [27], were added. In total, seven categories of reasoning methods were defined:

1. Evolutionary algorithms, e.g., genetic algorithms (GA);
2. Other intelligent optimization algorithms, e.g., ant colony optimization algorithm (ACO);
3. Multi-objective optimization algorithms, e.g., non-dominated sorting genetic algorithm (NSGA);
4. Gradient-based algorithms, e.g., sequential quadratic programming (SQP);
5. Inference engines, i.e., fixed decision procedures to guide rule application;
6. Statistical reasoning methods, e.g., response surface method (RSM);
7. Other reasoning methods.

4.3. Considered Domains and Domain Couplings

In this study, publications were only included when their automated geometry synthesis process follows an in-the-loop MDA; see Figure 7.

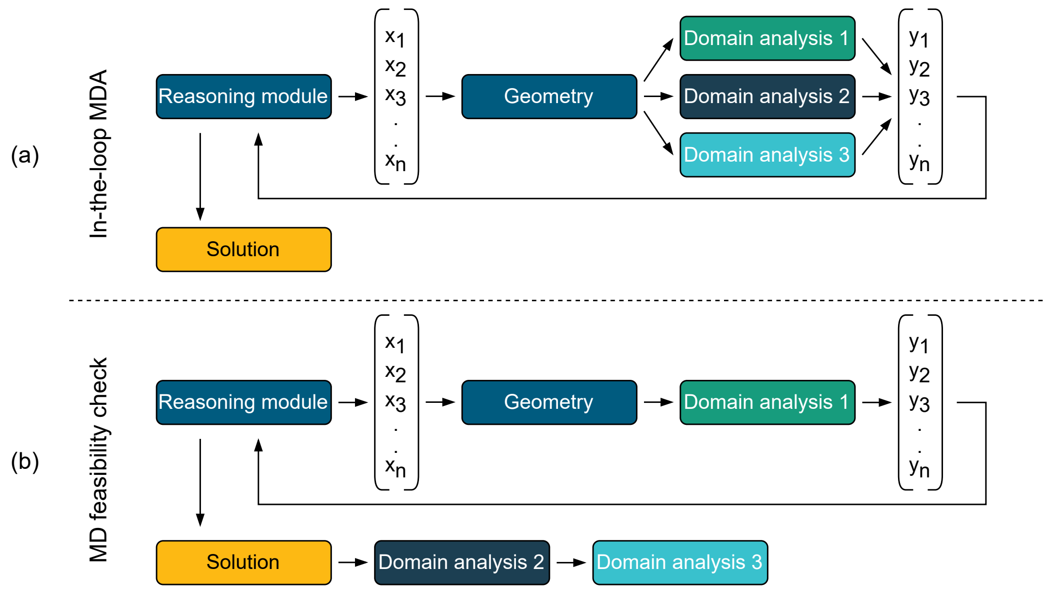


Figure 7. Difference between in-the-loop multi-disciplinary analysis (MDA) (**a**), where multidisciplinary aspects are considered in decision making and multi-disciplinary (MD) feasibility check (**b**), where a primary discipline is used for decision making, and other domain analyses are conducted to ensure the design's feasibility afterwards.

In conventional electric motor development processes, the design is optimized in one domain, mainly the electromagnetic domain. This single-domain optimum is then checked in other domains to ensure its feasibility. The term in-the-loop MDA, however, pertains to process frameworks that assess designs across multiple engineering domains for each design variant. This approach empowers engineers to make design choices by considering properties from multiple domains and facilitates more frequent iterations, thereby facilitating the identification of optimal designs within the solution space [6,7]. The review papers were analyzed regarding the following engineering domains considered in the in-the-loop MDA: electromagnetic, thermal, mechanic, manufacturing and economic domains. A variety of different engineering tasks can be summarized under the term mechanical design [32]. This is why it was decided to further split this domain in the study into rotordynamics, structural and NVH (noise, vibration, harshness) analysis.

In addition to determining the relevant domains to consider, setting up MDDA involves making decisions regarding the appropriate model fidelity. In this review, three fidelity levels across the different domains were specified. These are analytical calculations, lumped-parameter models (LPM), and finite element analyses (FEA) or computational fluid dynamics. Models with lumped parameters are very popular in the design of electrical machines to evaluate the thermal behavior of the machine. However, they can also be used to evaluate other physical relationships, such as noise characteristics [34].

These domain models are inherently coupled because they are based on the same geometry and material properties. In addition to that, the results of one domain model can affect the other model. To handle these influences, couplings between the different domains were analyzed in the review. These couplings in electric machine design processes describe the sharing of input and output data between different analyses [26].

There are different ways to handle domain couplings. The first one is to separate the analysis modules and not consider a coupling. The second one is to sequentially couple domains, i.e., use results of one domain in the other domain in a one-way fashion, called one-way coupling in this review. The third one is to consider a domain coupling in an iterative manner, meaning that the inputs and outputs of both domains are iterated until the error between inputs and outputs reaches a certain threshold. The latter will be called two-way coupling in this review. A special type of coupling is the so-called parameter split decoupled approach. In this approach, parameters are assorted to domains based on their sensitivity in order to reduce the impact of decoupling [26].

4.4. Type and Part of Electric Motor and Application

To assess the scope of the MDDA, the automatically designed geometries of the electric motor are noted in the review. Furthermore, the type of electric motor, e.g., permanent magnet synchronous motor (PMSM), is recorded. In order to find areas of focus for the use of MDDA, application fields were identified when indicated by the authors.

4.5. Validation

To evaluate the credibility of the proposed methods, the type of validation was also identified. This involved determining whether validation was conducted through simulations or experiments within the paper, after discovering a specific design using MDDA.

The described review criteria were applied to all publications and the classification was performed by one author.

5. Results

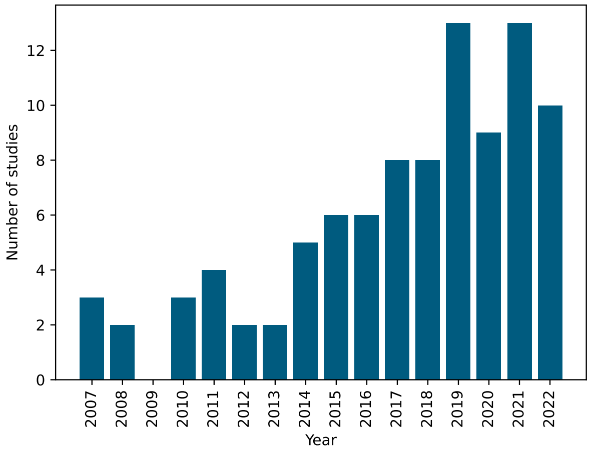
In this section, we summarize the results of the literature review.

5.1. General Results

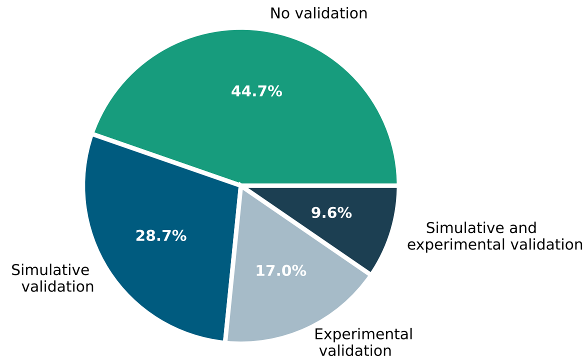
With regard to the evolution of MDDA as well as the validation of MDDA approaches, these are the following results.

5.1.1. Trend

In Figure 8a, the amount of papers for each year is given. The graph shows that over the analyzed time span of 15 years (2007–2022), the amount of publications regarding MDDA in electric motor development is constantly increasing. About 56% of the papers considered within the review were published in the last 5 years (2018–2022). Most of these papers are published by researchers, while only a small portion (30%) of the works include at least one author affiliated to an industrial company.



(a)



(b)

Figure 8. (**a**) Number of papers in the review by year published; (**b**) Share of papers with different types of validation in the review.

5.1.2. Validation

Figure 8b reveals that the majority of papers included at least one kind of validation. The highest form of validation is to use high-fidelity simulations and prototype tests to verify the MDDA results. The type of validation depends on the analyses conducted, i.e., if the MDDA included high-fidelity simulations of one specific domain, validation can only be performed by even higher fidelity simulations or experimental results. In [8], an FEA-based validation is conducted for each analysis module. Reference [35] compares the results of their optimization workflow with an analysis in the software Ansys Motor-CAD for validation. In [36], the applied design process is verified by applying it to an example and comparing it to detailed FEA analyses.

In [37], the design found by the MDDA is prototyped and tested physically. The results are close to simulation results, whereby the authors consider the proposed development methodology to be validated. Reference [11] validates their proposed MDDA tool in a similar manner by comparing properties of the realized prototype with analysis results.

5.2. Inputs, Outputs and Goals

5.2.1. Inputs

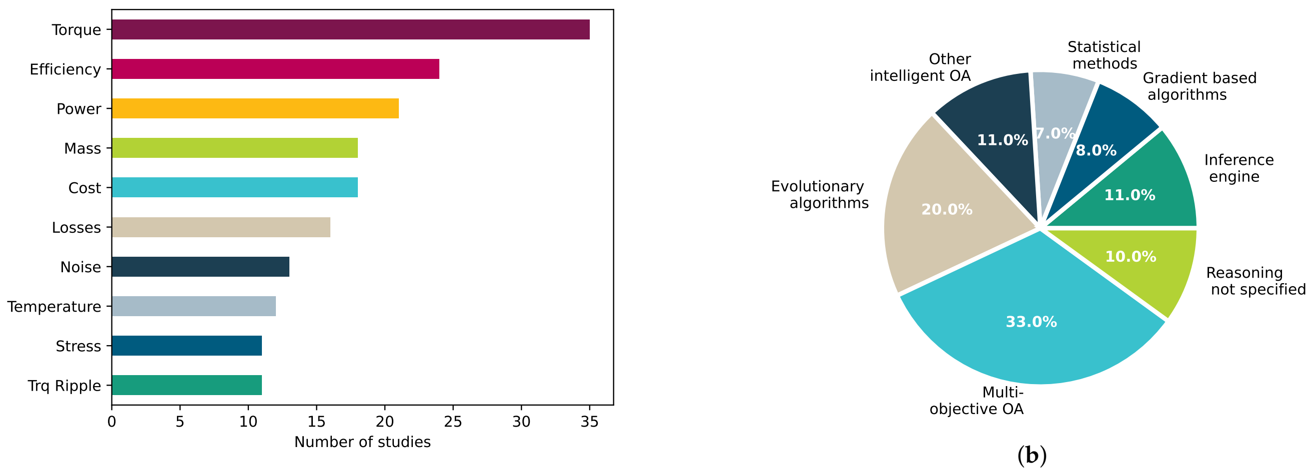
In this review, most papers used parameterized geometries as inputs for the MDDA. However, the level of geometry fidelity differs. Approaches that apply analytical analyses utilize a geometrical representation of their design variables, whereas the actual calculations are performed using only the parameters (e.g., [36,38,39]). Higher fidelity geometry representations, such as CAD models, are primarily employed for more detailed analyses, such as FEA simulations. In these papers, the CAD representation is generated and used for the analysis (e.g., [40,41]). While most authors use a parametrized geometry, some authors adapt non-parametrized geometries, enabling them to find new and unconventional designs. For instance, Reference [42] uses a level-set methodology to describe the geometry of a PMSM rotor and analyzes it in the thermal and electromagnetic domain. A similar approach is proposed by [43] for the joint electromagnetic and mechanical design of a rotor geometry for a synchronous reluctance motor.

5.2.2. Goals

Consistent with the inputs, the goal of most of the contributions is a parameter synthesis. It is noticeable that almost no paper analyzes different topologies within the MDDA. Exceptions are the papers applying non-parametrized geometries, since these will always result in new topologies. Furthermore, Reference [44] compares various rotor topology concepts for Synchronous Reluctance Motors (SynRM) that differ based on the positioning of supporting ribs and the use of a retaining sleeve. Similarly, Reference [11] uses a MDDA process to compare different PMSM topologies. In both cases, however, the optimization is performed separately for each topology. The results of each MDDA is then compared, leaving the topology decision to the machine designer.

5.2.3. Outputs

Since all MDDA approaches focus on geometry synthesis, geometry was identified as an output for all papers in the review. However, the aspects under which the design decisions or optimizations were conducted differ. These objectives describe a design's properties that the MDDA aims to maximize or minimize. The most common synthesis objectives are shown in Figure 9a.



(**a**) (**b**)

Figure 9. (**a**) The ten most frequently identified electric motor properties as a part of the objective function in each paper; (**b**) Share of papers with different types of reasoning methods in the review.

5.2.4. Objectives

A total of 21 papers employ a single objective, implying that most papers use a multi-objective function in their MDDA. From Figure 9a, it is apparent that the three most prominent objectives are the main performance objectives of electric machines, namely torque, efficiency, and power. These originate directly or indirectly from the electromagnetic analysis of the proposed design. Cost and mass can mainly be derived from a machines' geometry [45,46]. However, their calculation depends on the considered geometries and their fidelity. The majority of papers only take into account active parts for cost and mass calculation. Approaches that consider non-active parts for cost or mass calculations are only available in [11,46]. However, these examples demonstrate that the mass estimate for non-active parts is by no means negligible, as they account for 40% of the total mass of the machine. Losses in an electric motor consist of iron losses, winding losses and mechanical friction losses [47]. In some works, losses act as an indirect way of taking thermal aspects into account [48]. Some papers even abstain from adding a thermal analysis module for this reason. However, doing so prevents assessing temperatures and results in not fully exploiting a material to its limits [39]. Noise, temperature, stress and torque ripple are, again, domain-specific properties of a machine, stemming from NVH, thermal, structural and electromagnetic analyses.

5.3. Knowledge Representation and Reasoning Methods

5.3.1. Reasoning Methods

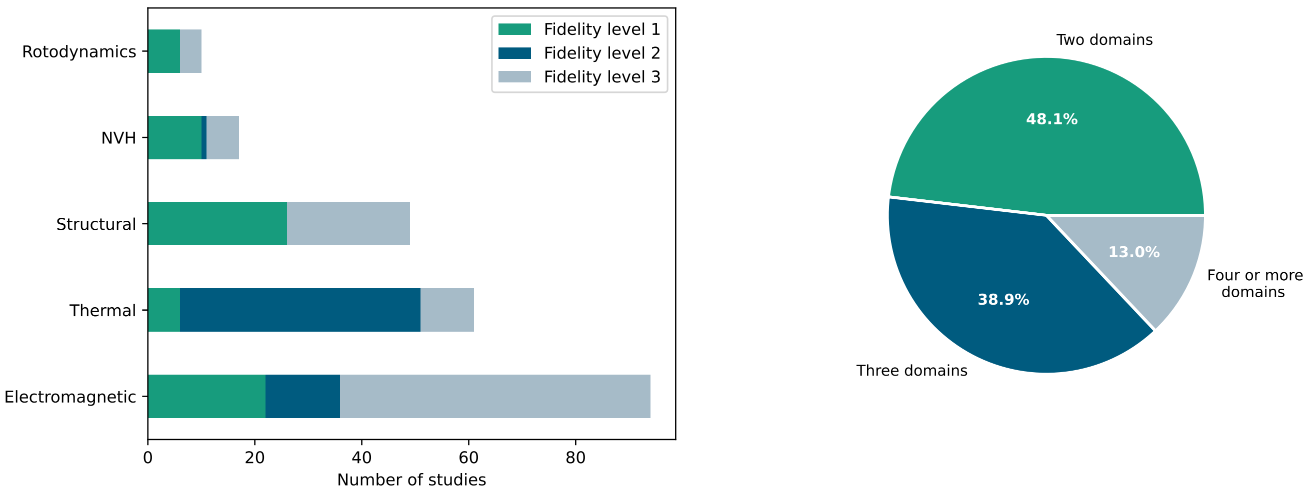
Figure 9b shows the reasoning methods employed in this review. Most reasoning methods in this review rely on optimization algorithms. Rule-based reasoning using inference engines can only be found in a small number of papers, e.g., [38,49]. Evolutionary algorithms make up a large proportion of reasoning methods in the scope of this review, with the genetic algorithm (GA) being most widely used [50–52]. Other intelligent algorithms, like the particle swarm optimization (PSO) method, are used less frequently, e.g., [53,54]. Most optimization algorithms have further developed counterparts to handle multi-objective optimizations better, e.g., the widely used non-sorting genetic algorithm (NSGA-II) or multi-objective PSO (MOPSO) [40,55,56].

5.3.2. Knowledge Representation

According to [10], the formalization of knowledge in the context of a general design automation task is strongly related to the reasoning methods used. In the reviewed papers, design dependencies were almost exclusively formalized as being shape-based or via procedural rules. As introduced in Section 2, the design automation tasks of the reviewed papers fall under the category of spatial product synthesis. For these tasks, typical knowledge representations next to shape-based and procedural formalization are graph-based formalization, object-oriented formalization and formalization based on the unified modeling language (UML) [10]. However, in the papers reviewed, these formalizations were not identified.

5.4. Considered Domains and Domain Couplings

Figure 10b shows how many different disciplines are considered in the MDDA of the reviewed papers. As it can be seen, most approaches are limited to two domains. Figure 10a illustrates the frequency of each domain and the corresponding fidelity level identified in this review.



(**a**) (**b**)

Figure 10. (**a**) Considered domains in the papers of this review and corresponding fidelity level; (**b**) Share of papers considering two, three or four and more domains. For this electromagnetic, thermal, structure mechanic, rotordynamic, NVH, manufacturing and economic analyses as part of the MDDA were searched for.

5.4.1. Electromagnetic Domain

From Figure 10a, it is apparent that nearly all reviewed papers consider the electromagnetic domain. This emphasis is primarily driven by the opportunity to calculate machine efficiency via electromagnetic models based on the calculation of electromagnetic losses and the machine power from torque and speed [57]. These parameters are crucial while designing electrical machines and explain the number of studies in Figure 9a that contain torque, efficiency and power as optimization objectives [58]. Some papers additionally mention the analysis of torque ripple and cogging torque [47], whose reduction together with keeping a minimum efficiency can also be a desired optimization criteria in the MDDA of electrical machines [59]. Overall, in this review, three major distinguishing criteria for the electromagnetic analysis were observed: analysis fidelity level, analysis dimension (2D/3D) and time dependency of the analysis. Within the electromagnetic domain, high-fidelity approaches prevail. In that case, most of the authors use numerical FEA concepts, like those demonstrated in [60,61]. Other numerical approaches for the electromagnetic analysis, e.g., using the finite-difference method, were not identified in this review. Next to numerical approaches, analytical models [48,54,62] and lumped-parameter models (often referred to as equivalent circuit approaches) [34,57] are also used in the reviewed papers. The required level of fidelity for the electromagnetic analysis depends on the machine type under investigation and possible compromises between computational effort and accuracy needed for the desired outcomes [63]. For instance, FEA has a high fidelity but entails a high computational burden. In contrast, analytical or equivalent circuit approaches have moderate computational effort but offer lower fidelity [64]. Nevertheless, in case of difficult structures, complex field distributions and nonlinearities, analytical models may fail to predict electromagnetic variables or are not accurate enough, necessitating the use of FEA despite the computational demands [47,65]. A possible way to reduce computational effort while keeping high fidelity in the electromagnetic analysis is the combination of different methods. In [47], an approach is proposed where parameters that are easier to model are analyzed using an analytical sub-domain model; then, the more challenging parameters are optimized using an FEA. The analytical model optimizes the PMSM's general geometry by calculating its electromagnetic and torque performances with high accuracy. To further optimize the torque ripple and cogging torque, the authors utilize FEA in computing the magnetic pole shift, magnet segmentation and eccentricity. On the other hand, the combination of an analytical approach and FEA can be applied when the analytical part is used for post-processing of loss data obtained from FEA [66]. In [57], they present a combination of a magnetic equivalent circuit (MEC) for the electromagnetic domain and an electric equivalent circuit (EEC) for the electrical domain and as extension of a loss model for calculating the copper and iron losses. In combination, these models are used to replace an FEA for the electromagnetic optimization of a switched reluctance machine. To calculate the static flux density, the static flux linkage characteristic data and the static torque, a magnetic circuit modeled by a reluctance network is applied. Figure 11 demonstrates an example for a reluctance network. The EEC is then used to calculate, for instance, the phase current, the torque ripple coefficient and the average torque from the static torque and the flux linkage characteristic data [57]. A similar way is chosen in [67], where a strategy is proposed to mitigate computational effort by substituting the FEA with an analytical method to calculate the torque, internal power factor and the internal voltage and combining that method with an EEC and a loss model. The choice to use a combination or a single EEC and MEC depends on the specific use case and the desired parameters as well as on whether only the electromagnetic or the entire electrical analysis is considered, which is also related to time dependency [63]. If a static model is sufficient to predict the behavior of a machine, as is the case for synchronous machines, the electromagnetic and electrical analyses can be combined in an FEA or MEC without requiring an extra EEC [63]. In this context, static or quasi-static analysis means an analysis for one or more static rotor position points [68], which results in lower computational effort [45] and faster analysis if it is used to replace a transient simulation [38]. However, in general, transient analysis serves to more accuracy [69] and is also utilized to analyze transient behavior caused by eddy currents [70]. Furthermore, the need for a transient analysis depends on the machine type. Induction machines, for instance, require transient analysis or the analysis needs to run until achieving a steady state [63]. This requirement leads to a significant increase in computational effort. Hence, for dynamic or transient performance analysis, an electrical analysis model such as an EEC is imperative to limit the computational effort [63]. The combination of an analytical model and a MEC is described in [36]. The authors utilize the methods separately, employing one for the stator field calculation aspects and the other for electromagnetic parameters relating to the rotor. Another approach to reduce the computational effort involves a combination of methods, such as implementing an analytical coarse pre-optimization followed by a more detailed FEA. In [71], this technique is used to analyze the electromagnetic characteristics of a PMSM. A similar approach is employed in [72]. The method described in [73] is comparable but incorporates a MEC for achieving a low fidelity and low computational effort. In [64], all three fidelity levels are combined. The analytical model is used for a pre-optimized design to filter out weak options. This is followed by a MEC analysis. The final accurate optimization is then made by an FEA.

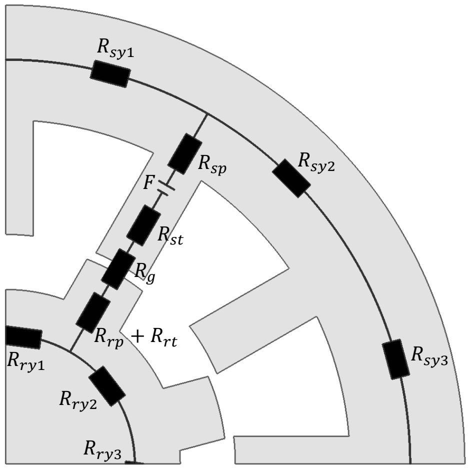


Figure 11. Example of a magnetic equivalent circuit (modified from [57]).

5.4.2. Thermal Analysis

The thermal domain is considered in about two thirds of reviewed papers; see Figure 10a. The purpose of the thermal calculator is to assess whether design candidates reach thermal limits [50,59]. Typical thermal limits are the maximum winding insulation and magnet deterioration temperature [22,45,59]. As it can be seen in Figure 10a, fidelity level 1 is applied less frequently for thermal calculations. The authors in [38] use analytical equations to derive cooling jacket dimensions and a heat exchange coefficient in the scope of a multidisciplinary automated scaling approach. The most prominent way of conducting thermal analyses are lumped-parameter models. Their execution times are usually very fast; however, it requires the developer to build a model to accurately describe the main heat flow [22].

For this purpose, the machine geometry is modeled by simple geometrical shapes for which the heat flow has been derived. Each of these are represented as a node in the LPM [56,74]. Heat flow between nodes are modeled using thermal resistances. For transient considerations, the heat capacity in each node must be taken into account [56]. Three different detailing criteria of LPMs were observed in this review: (1) The dimensionality, (2) time dependency and (3) assumptions for the thermal modeling. Most authors use a 2D representation of the machine for the thermal analysis by modeling an axial or radial section of the motor [56,75,76]. Three-dimesional LPMs combine these and have a higher accuracy [72,77]. Stationary thermal calculations are most often used in the papers of this review, i.e., calculation of temperatures under the assumption of reaching an equilibrium in each considered operating point [36,75]. However, not considering transient phenomena with respect to use scenarios can result in a significant limitation of the design space. Reference [39] compares in his MDDA application steady-state and transient thermal analyses for the design of an electric motor in a hybrid electric aircraft powertrain. The use of a transient thermal analysis with respect to the flight scenario results in a significant size reduction and thus an almost threefold power density increase. Some other detailing criteria of LPMs are the assumptions made in each study. Commonly, radiation heat transfer is not considered, and thermo-physical material properties are assumed to be temperature-independent [39,57,78]. However, more detailed LPMs encompassing radiation heat transfer in the scope of MDDAs exist [72]. Beyond that, higher fidelity numerical modeling for thermal analyses is usually avoided for computational efficiency reasons.

It is noticeable that there are only a few papers that not only examine the exceeding of thermal limits in the context of an MDDA, but also include components and parameters of the cooling system as part of the design variables. One example is the design of cooling ducts in the scope of MDDAs [79,80]. In [81], the thermal stress distribution in a double-skewed rotor for an induction motor is used to find the optimal design of the rotor.

5.4.3. Structural Mechanics

The overarching objective of structural analyses in MDDAs is to ensure that the geometry is able to withstand the mechanical loads that are imposed during operation. For the most part, structural analyses are focused on rotor geometries, including rotor shaft, rotor sleeves, magnets and machine-specific rotor lamination geometries, like flux barriers in synchronous reluctance machines. The structural-mechanical design is often in conflict with the electromagnetic design, e.g., when sizing ribs in SynRM rotors [75,82]. Structural analyses in this review utilized both analytical calculations and numerical FE calculations, as illustrated in Figure 10a. In order to perform an analytical calculation of the structural mechanics within a MDDA, authors utilize model reductions for which analytical calculation models are available, i.e., reducing the problem to two dimensions by assuming the stress and strain in the axial direction to be zero [70]. In [37], an analytical model based on rotating disks stress equilibrium theory is applied for the design of a high-speed PMSM. The contact pressure, the thermal expansion as well as the centrifugal forces are considered. Similar approaches to design rotor magnets and rotor sleeves are adopted in [8,39,55,73,75]. Some authors use analytical calculations for more detailed rotor and stator geometries as well, e.g., ribs in SynRM rotors by employing beam theory simplifications [36]. Since this form of geometry simplification is limited when dealing with more complex geometries, FEA calculations tend to be used for this purpose in the reviewed papers. Thus, there are a variety of papers that use 2D FEA simulations to evaluate detailed rotor geometries in synchronous reluctance machines [44,68,83] and permanent magnet-excited machines [22,43,66,84]. For the design of high-speed rotors that include retention sleeves, 2D FEA is also utilized [50,60]. Regardless of the fidelity of the calculation, the maximum speeds including a safety factor are generally used as a basis for the structural mechanics analysis within an MDDA.

5.4.4. Noise, Vibration, Harshness (NVH)

Another set of tasks that can be assigned to the mechanical domain involves the examination of generation of acoustic noise. In this review, a total of 17 papers considered NVH analyses. Radial electromotive forces of different spatial orders and temporal frequencies cause the stator teeth to vibrate. Resonance amplifies this effect, which occurs when the spatial orders and temporal frequencies of the radial electromagnetic forces align with a natural mode of the considered geometry, resulting in a significant noise level [85,86]. The vibration in the stator is transmitted to components that are rigidly connected to the stator, such as the housing [41]. Usually, only the stator is considered in NVH analyses, although the housing and other motor components can certainly have a dampening effect [87]. In [85] the stator is simplified as a cylinder so that a mass–spring equation system can be set up for each mode shape. Similar analytical analyses are conducted in [22,88,89]. In [41], an equivalent circuit model is used to account for the different areas and materials of the stator and housing in the vibration analysis. The main advantage of these analytical and equivalent circuit approaches is the significantly reduced computational time compared to an FEM analysis [41]. For FEA analyses, simplified 3D geometries of the stator or even of the stator and the housing are often used for NVH assessment [87,90]. On the basis of vibration analyses, an acoustic analysis is often carried out in order to find corresponding sound pressure levels [90,91].

5.4.5. Rotordynamics

In ten papers, tasks belonging to rotordynamic analysis are carried out in the scope of the MDDA. The rotordynamic analyses are performed to ensure that the rotor is not operated in a critical speed range. Similar to the resonance effect in the context of NVH, the critical speed is the speed at which the rotor excites the structure at its natural frequency [32]. Strong vibrations that are capable of destroying the motor are the consequence of the resonance effect [92]. High-speed motors are operating close to their physical limits [93], which explains why almost all papers that consider rotordynamics in the context of MDDA address high-speed motors. As can be seen from Figure 10a, all three fidelity levels were identified for rotordynamic analyses. In [94], only the first-order natural frequency of the rotor is determined analytically and considered as part of the optimization objectives. A similar approach is applied in [37]. Reference [69] uses an analytical estimation of the critical speed based on a simplified rotor geometry. Reference [73] uses a lumped-parameter model by dividing the rotor into disk segments, allowing the incorporation of multiple diameters and material properties. Some authors make use of higher fidelity analyses for the rotordynamics analyses. Reference [95] uses a 3D-FEA of the rotor with a cooling fan impeller to determine the first bending mode of a high-speed PMSM. Reference [92] uses a similar approach. A few authors use a campbell diagram for the analysis and visualization of critical speed ranges [73,96].

It is noticeable that other tasks that belong to the mechanical domain in the development of electrical machines are only considered in single works in the scope of MDDAs in this review. These tasks include the design of non-active parts, such as the housing, end flanges or bearings. In [11,46], simple analytical calculations are used for this purpose in order to be able to provide a better estimation of the mass and dimensions of the motor, including the non-active parts.

5.4.6. Manufacturing

Another engineering domain analyzed in this review is manufacturing. Manufacturing influences on the design are often not calculated by separate calculations as it is performed for the other engineering domains. Papers considering manufacturing aspects use statistical models to account for manufacturing deviations. This circumstance prevents to analyze the manufacturing analysis fidelity, which is why no data regarding the fidelity of the manufacturing analysis were derived from the literature study. The manufacturing analyses encountered during this review are often referred to as robust design optimization. According to [97], there are three common approaches to conduct robust design for electric motors: Taguchi parameter design, worst case design and design for six sigma. Performing a multi-objective robust design study always involves a high computational cost, especially when high-fidelity analyses are used [97]. For this reason, most robust design papers in the study make use of methods to improve the computational efficiency of the analyses, like surrogate models [98,99]. Manufacturing aspects are considered almost exclusively in combination with electromagnetic analyses. Thus, multidomain robust design was not identified in this review. The only exception to this was found in [99]. The authors make use of a multi-physics model for the robust design of a SMC (soft magnetic composite) motor consisting of electromagnetic, thermal and modal analyses as well as a production cost estimation model. To handle the computational cost, surrogate models are built and a multilevel design parameter approach is employed.

5.4.7. Economics

The costs of a design also play a major role in many papers. This is reflected in the choice of optimization objectives in Figure 9a. In order to determine costs, different types of cost determination are used. According to [99], the production cost of electric motors consist of material cost, buying parts cost, machinery cost, capital cost and personnel cost. Papers in this review predominantly reduce this to the material cost and calculate it by computing the masses or volumes and the corresponding market prices [45,47,71,100,101].

In this review, almost all authors restrict costs, and thus mass and volume, to active material cost, i.e., iron sheets, copper parts and magnets [45,47,67]. Reference [100] also includes the cost of the rotor-retaining sleeve. References [101,102] include the aluminum parts of the motor, making a simplified housing geometry necessary. Reference [99] calculates the material cost in dependence of production volume and also include the cost of scrap material and buying parts in their estimation. References [77,103] are the only works that include machining cost in their calculation for manufacturing of a specific component: in this case, the SMC core.

5.4.8. Surrogate Models

Especially in the more recent papers, surrogate models are frequently implemented in MDDAs to handle expensive calculations with a lower time effort [84,100]. The use of surrogate models fundamentally affects the setup of the MDDA. The models must be built in advance of the actual optimization. The steps for this usually consist of sampling to build the database, building the surrogate model, and checking the accuracy of the model including subsequent readjustment [52,73,96,100]. For the sampling stage, different methods exist, e.g., the Latin hypercube sampling plan [90]. In [96], a design of experiments sampling plan is used to maximize the amount of information acquired and minimize the bias error. Reference [73] proposes to combine low- and high-fidelity domain analyses in the sampling stage to achieve the best trade-off between computation time and accuracy. The actual surrogate model can be built using either artificial neural networks or interpolation methods. In [100], three neural network methods, multilayer perceptron, support vector regression, generalized regression neural network, are compared with the Kriging interpolation method, where support vector regression shows the best results for the considered application of a high-speed PMSM.

5.4.9. Domain Couplings

Figure 12 presents the results of the domain couplings analysis. For this analysis, the rotordynamic, structural and NVH domains were considered as one mechanical domain. This is valid, since no couplings between different tasks within the mechanical domain were identified. The figure depicts the percentage distribution of coupling types in papers that consider the respective pairs of engineering domains. Couplings between domains are not always reported in the reviewed papers. In ten papers, no specific couplings or the type of coupling implemented in the respective MDDA are described. The coupling between electromagnetic and thermal domain is described as a strong coupling in the literature, making it necessary to be considered for accurate results [72]. In particular, the magnetic and electric conductivity of materials in the electric motor are depending on the temperature in the system [40]. One of the outputs of the electromagnetic calculations are losses, which are necessary inputs for the thermal domain in order to calculate the temperatures within the system [11,37,66]. Figure 12 shows that most authors that consider both the electromagnetic and thermal domain implement set coupling as a one-directional coupling. References [79,80] use a one-way coupling between the electromagnetic analysis and the thermal analysis to design cooling ducts in both the stator and the rotor. Reference [40] states that the permeability of the laminations remain nearly constant with changing temperature. The temperature dependency of copper resistivity on the other hand should be incorporated in the analysis. The authors propose to update the copper losses according to the temperature variation instead of recalculating the electromagnetic analysis [40]. If the initial guess of machine temperature deviates strongly from the calculated values, the calculation of the magnetic field and thus the magnetomotive force has to be updated [72,85]. This is why some authors implement a bi-directional coupling and iterate between the domains until the error becomes sufficiently small [76]. Reference [72] combines a one-way coupling with a two-way coupling using a space mapping methodology for the design of a starter motor.

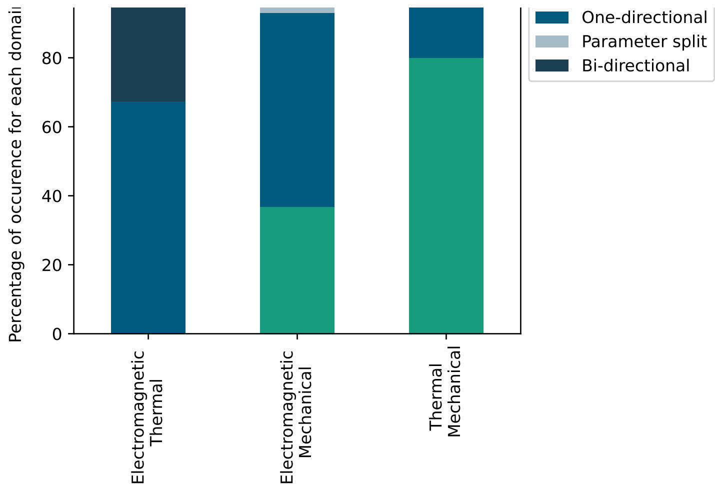
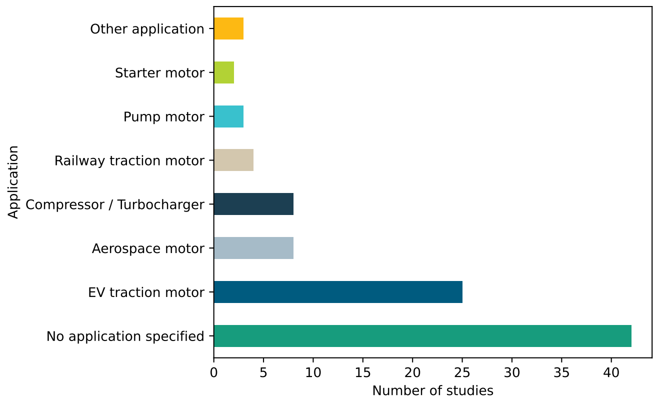


Figure 12. Different types of couplings between engineering domains employed in the MDDA of reviewed papers.

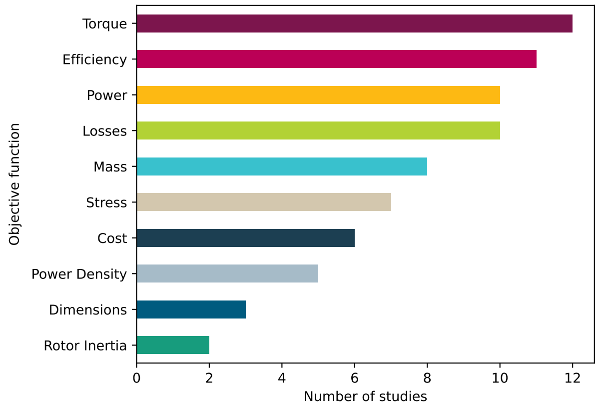
The properties for the mechanical analyses also depend on the temperatures in the system. However, most papers that feature both a thermal and mechanical analysis do not consider a coupling between these domains. In [37], the temperature dependency is integrated into the mechanical analysis of magnets in a high-speed motor. The authors conclude that the temperature rise can have a significant impact on the safety factor of the magnets. Between electromagnetic and mechanical domains, different dependencies exist. The NVH analyses start with a vibrational analysis, which is based on radial electromotive forces, as an output of the electromagnetic analysis. This is why for papers featuring NVH analyses, a one-directional coupling between the electromagnetic analysis and NVH analyses is considered in all cases, e.g., [41,87,91]. For rotordynamics and structural analyses, dependencies arise mainly from rotational speeds in the system. Most MDDAs in this review base their calculations in these domains on the maximum rotational speed that the system is designed for [70,95]. In these cases, no direct coupling between the electromagnetic domain and rotordynamic/structural domain was identified. A number of papers designing detailed rotor geometries address coupling strategies between the electromagnetic and structural mechanics domains. It is necessary that the small ribs or bridges within its geometry, see Section 5.7, provide a balance between being sufficiently robust to withstand loads and yet small enough to reduce their detrimental electromagnetic influence [104]. Reference [104] presents and compares different architectures of coupled electromagnetic and mechanical analyses. Reference [83] suggests a parameter-split decoupling (PSD) approach, where the design parameters of a SynRM rotor are split into two subsets. One subset will be part of the electromagnetic analysis, with the other being fixed, and vice versa for the structural analysis. The assignment of a parameter to a subset depends on its influence in each domain. Most authors conduct the electromagnetic analyses and check for structural integrity afterwards in their MDDAs. However, the mechanical stress in the rotor laminations influences its permeability. In [105], an approach is presented where the results of a stress analysis in a PMSM rotor is considered in the electromagnetic analysis.

5.5. Applications

Figure 13a indicates that mobile applications dominate, such as electric vehicle (EV) traction motors, electric machines in aerospace applications or railway traction motors. However, not all articles provide details regarding the utilization of the motor developed in the MDDA. In most mobile applications, space is limited, which results in the aim to realize high power while keeping the weight or volume of the motor as low as possible [11]. The correlation between application and objectives becomes evident in Figure 13b. It indicates the objectives applied for papers focusing on traction motor design. Compared to the numbers for all reviewed papers shown in Figure 9a, it can be concluded that losses, power density and dimensions of the motor are used more often as design objectives.



(**a**)



(**b**)

Figure 13. (**a**) Stated applications in the papers of this review; (**b**) Ten most frequently identified objectives of papers applying the MDDA to electric vehicle traction motor design.

Reference [39] even states that for aerospace applications, minimizing the mass has the highest priority. Some papers for mobile applications are also focusing on optimizing specific driving cycles or load profiles. Reference [66] integrates a WLTP cycle (worldwide harmonized light vehicles test procedure) into the MDDA for an electric vehicle traction motor. With the calculated losses map, the total lost energy for the driving cycle is calculated and applied as the main optimization objective. Reference [39] uses a reference flight mission profile to calculate the total losses in the scope of their MDDA for a hybrid electric aircraft powertrain. A total of 21 of the reviewed papers feature high-speed motors. These papers do not, in all cases, specify an application field such as compressors or turbochargers. Consequently, they make up a large part of the "no application specified" group in Figure 13a.

High-speed motors are particularly noteworthy because of distinctive characteristics regarding the MDDA application. On the one hand, the application of MDDAs is quite apparent for these motors, since the high speeds are accompanied by high structural-mechanical, thermal and rotordynamic loads. Thus, sequential development processes for the development of high-speed motors comprise numerous iterations [5]. On the other hand, this type of motor entails changes in terms of the geometric design of the components. For example, because of high speeds, the motors are typically built with smaller diameters, and rotor-retaining sleeves must be provided to secure the magnets mechanically, see Section 5.7.

Furthermore, the application significantly impacts the considered domains of the MDDA. In Figure 14a,b, domain fidelity levels for high-speed motors and traction motors are given. For both applications, the designers opted to employ high-fidelity electromagnetic analyses. However, the structure of the MDDA varies significantly for all other domains. In the case of high-speed motors, the emphasis is on structural and rotodynamic analyses, with no consideration of NVH analyses. Conversely, traction motors are analyzed with respect to their thermal characteristics and NVH behavior.

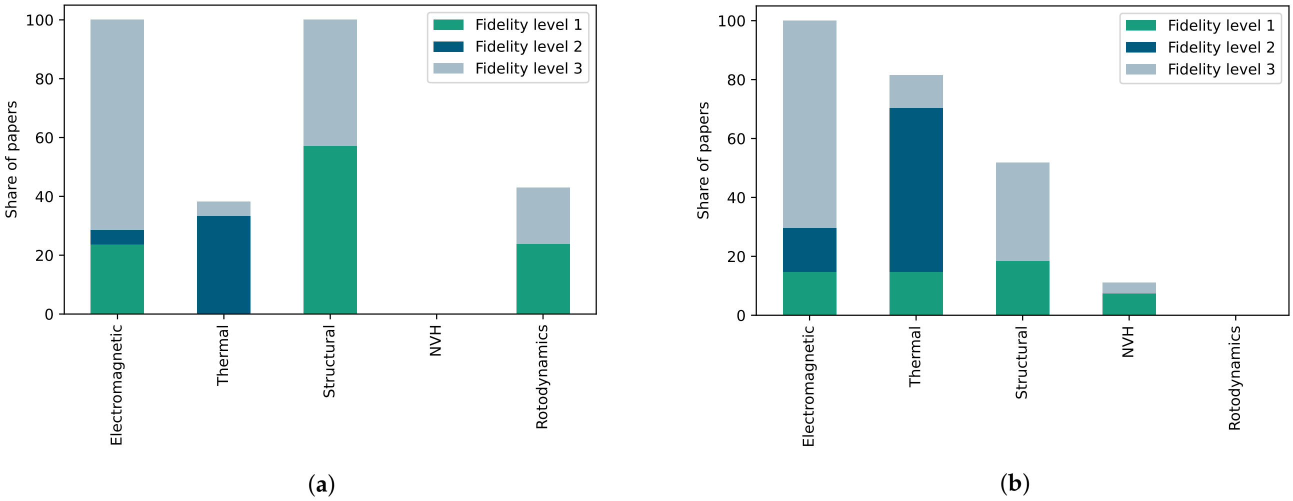


Figure 14. (**a**) Considered domains and fidelity levels in papers designing high-speed motors; (**b**) Considered domains and fidelity levels in papers designing traction motors.

5.6. Process Stage

In Figure 15, it is illustrated that both preliminary and detailed design studies were identified in this review.

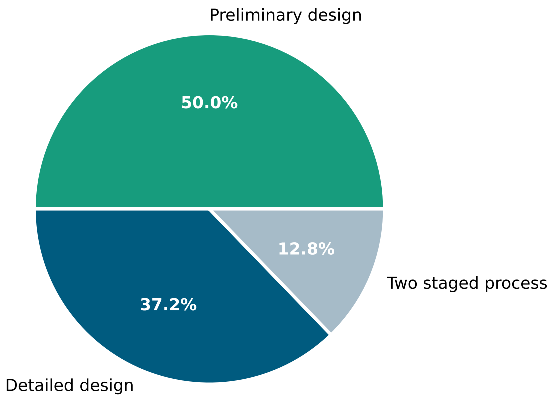


Figure 15. Share of papers presenting preliminary, detailed or two-staged design approaches.

Most of the papers focus on preliminary design aspects. In these papers, the multidisciplinary process primarily revolves around sizing the active machine part. This includes not only the main machine design parameters, but also the basic design of the stator and rotor geometries. More in-depth approaches start with fixed main machine design parameters and place emphasis on automating the design of more detailed geometries [66,83,104]. A small set of works combines a preliminary design step with a more detailed design [76,106]. From the bar graphs in Figure 16a,b, it can be seen that the process stage has a significant influence on the applied domain models and corresponding fidelity level. In preliminary design papers, all domains are present, drawing a similar picture as the findings in Figure 10a.

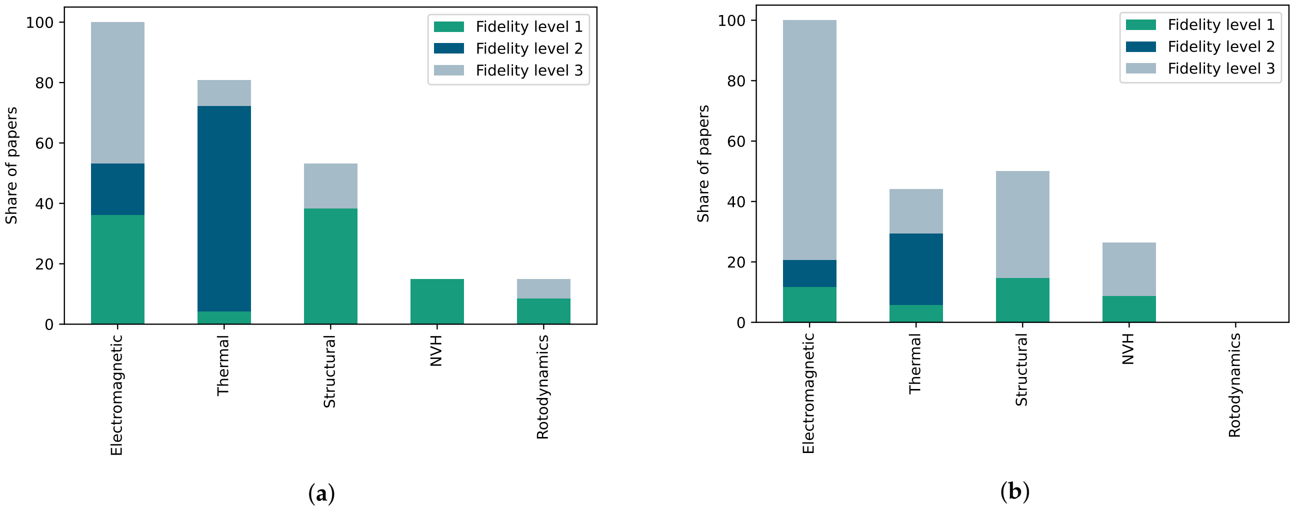


Figure 16. (**a**) Domains and corresponding fidelity levels of preliminary design papers; (**b**) Domains and corresponding fidelity levels of detailed design papers.

In more detailed designs, the focus of the analyses is on higher fidelity analysis models. For electromagnetic, structural and NVH analyses, FEA analyses are employed in the majority in MDDAs. For thermal analysis, LPMs are used for both preliminary and detailed design. Additionally, some detailed design papers tend to focus on component-level issues. Here, the analysis models are chosen depending on the component, e.g., structural and electromagnetic analyses for the design of PMSM rotor geometries [105] or SynRM rotors [43,65].

5.7. Type and Part of Electric Motor

5.7.1. Type of Electric Motor

As can be seen from Figure 17a, most authors (61.7%) apply MDDA to permanent magnet-excited motors. Overall, surface permanent magnet motors (SPM) predominate. The SPM motor type is often used for high-speed motors [8,55,73,75,100]. A general topology of SPM motors used in this review is shown in Figure 17b. A main feature of high-speed SPMs is that a rotor-retaining sleeve must be designed in the MDDA [37,60,70,75,95]. In [50], an MDDA approach is used to design an SPM for a traction motor application. In the process, optimal stator and rotor parameters are determined, including a rotor-retaining sleeve. In general, MDDAs applied for the design of permanent magnet motors often include modules to examine permanent magnet-specific boundaries and properties: With permanent magnets, the examination of the temperature is of utmost importance to prevent demagnetization [42,70]. Furthermore, permanent magnets in the rotor structure can be exposed to high mechanical stresses, which is why structural mechanics modules might be necessary [37,95]. Papers dealing with interior permanent magnet motors (IPM) often consider rotor topologies with a V-magnet arrangement, as is depicted in Figure 17b exemplary [22,41,66]. For IPMs, the rotor topology is frequently studied in great detail, i.e., the majority of design variables in the MDDA describe rotor geometries [22,78,105]. Reference [66] determines the optimal shape and orientation of a V-type permanent magnet rotor. The embedding of permanent magnets often results in narrow rib and bridge geometries, which is why the authors implement a structural analysis of the rotor geometry. Similar approaches can be found in [22,78,105].

Next to PM motors, reluctance motors are the second largest group in this review, making up 20.2%. Synchronous reluctance motors account for 12.8%, and switched reluctance motors are considered in 7.4% of reviewed papers. Similar to the MDDA of IPMs, papers applying MDDAs for SynRM again focus on the design of the rotor geometry. SynRMs also comprise fine ribs or bridges, as can be seen in Figure 17b. The design of these has a significant electromagnetic and structural mechanical impact [44,68,104,106]. Almost all induction motors (IMs) in the reviewed papers feature squirrel cages, an example of which is shown in Figure 17b. Consequently, the MDDAs in these papers often focus on the detailed design of the rotor bar geometry [101,107]. In addition to electromagnetic performance, the geometry of an IM rotor has an impact on thermal, structural, mechanical and NVH characteristics [81,93,108].

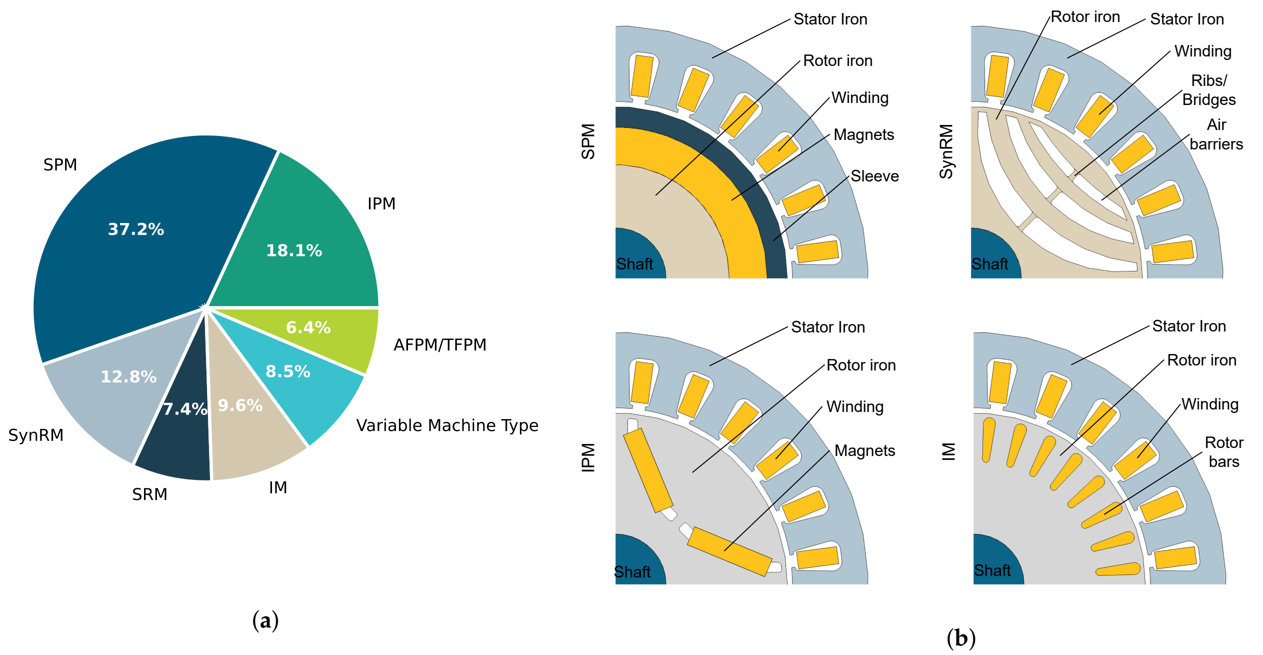


Figure 17. (**a**) Share of papers with applying MDDA for different types of electric motor topologies; (**b**) Typical geometries encountered in this review for the most frequently represented motor types.

Some authors intentionally keep their MDDA approach general, i.e., they do not refer specifically to one machine type. These papers thus claim that their approach can be applied to different types of electric motors [47,52,64,90]. One prerequisite for a general MDDA approach is, according to [47], to build the MDDA based on modular submodels, so that each can be replaced for the calculation of different machine types.

5.7.2. Automatically Designed Parts in the MDDA

Most reviewed papers are limited to the automated design of active parts, i.e., stator and rotor geometries. In some applications, the stator geometry is fixed and only an MDDA for the component specific parameters, e.g., rotor parameters, is performed. These papers take a more detailed look on the 2D-Geometry of PMSMs or SynRMs, often combining electromagnetic and structural mechanic calculations [66,83,104]. The majority of papers use simplified 2D geometries for analyses. If machine types are designed whose magnetic flux also has axial components, such as transverse flux machines or axial flux machines, 3D geometries are used [45,77,99]. Furthermore, the simplification of the motor geometry depends on the analyzed domains. In the case of NVH analyses, a simplified 3D geometry of either the stator and/or housing is often required, or a 2D simplification must be derived from the original geometry [41,88]. As mentioned previously, a significant number of papers focus on the design of high-speed motors. Consequently, it is common practice to incorporate a sleeve in addition to the typical stator and rotor geometries. This is because the presence of a sleeve directly affects the effective airgap in the magnetic circuit, thereby impacting essential optimization objectives such as power density and efficiency [55,75]. Non-active parts are rarely designed in the scope of an MDDA in the reviewed papers. In [94], magnetic bearings and the active parts are designed simultaneously as part of the MDDA for a high-speed motor. In [38,60,79,80], next to the active parts, a focus is put on designing geometries for the cooling system, e.g., cooling ducts in the stator or in the cooling jacket. In some MDDA applications, the shaft is designed simultaneously with the active parts [37,51,60]. In [11,46,51], non-active parts are automatically designed, like bearings, shaft and housing parts, e.g., by generating cylindrical shells and disks. The objective here is to obtain a better estimation of the non-active mass in the motor and consider it within the optimization.

6. Findings

In the course of this review, the selected papers were examined with regard to twelve criteria. As stated in Section 4, the review criteria were established by considering application-unspecific design automation tasks and electric-motor-specific criteria. The papers showed significant differences with regard to most of the criteria examined, indicating that the criteria can be used to analyze MDDA processes for the development of electric motors. In the following sections, the key findings drawn from the review will be presented.

6.1. Mdda Application Is Limited to Specific Use Cases or Machines; General Works Are Lacking

Overall, this review has shown that MDDA is already being used in the development of electric motors. The results in Section 5.5 showed that MDDAs can be employed for the design of electric motors in a variety of applications. However, in 64% of reviewed papers, MDDAs are employed for mobile applications or high-speed motors. Thus, MDDAs are not yet adopted for electric motors in all application fields. It can be assumed that the reason for this is similar to that of setting up design automation for the design of other systems. Studies have shown that the initial effort to create the models and interfaces is considered to be the main obstacle and requires a corresponding change in the organization [109]. In this review, authors often construct process chains for their specific case without adhering to any specific methodology or utilizing preexisting concepts and architectures, like MDO architectures. Thus, general works that developers can apply as a blueprint for their use case to build an MDDA process chain, or even works that provide methods for building MDDA process chains, are lacking. However, Table 1 provides a summary of five papers that address parts of this issue.

Table 1. Selection of outstanding papers in this review regarding the application of MDDA for the development of electric motors.

Source	Considered Domains	Highlighted Features of the Approach
[39]	Thermal (Level 2), Electromagnetic (Level 1), Structural (Level 1)	Transient state thermal optimization, Optimization based on mission profiles, Component design (winding insulation)
[37]	Electromagnetic (Level 3), Thermal (Level 2), Structural (Level 1), Rotordynamics (Level 1)	High level of multidisciplinarity, Design variables based on sensitivity analysis Thermal/Structural coupling considered Response surface based optimization
[73]	Electromagnetic (Level 2 and 3), Structural (Level 1 and 3), Rotordynamics (Level 1 and 3)	Multi-fidelity surrogate model Component design (Rotor, shaft, sleeve)
[110]	Electromagnetic (Level 1), Thermal (Level 2), Structural (Level 1)	System and component aspects considered Component specific modeling Application independent approach Surrogate modeling
[11]	Electromagnetic (Level 1), Thermal (Level 2), Structural (Level 1)	Design of passive components considered Comparison of different motor topologies Application independent approach

Reference [39] introduces a comprehensive Multidisciplinary Design, Analysis and optimization (MDDA) approach for designing an electric motor as an integral component of a hybrid electric aircraft powertrain. The authors integrate higher-level design considerations to design the motor's active components. Simultaneously, they address lower-level design aspects encompassing windings insulation design by including partial discharge analysis, since this component showed to be most critical for their application. Simultaneously, they address component-level design aspects related to the insulation of windings and partial discharges, since the winding showed to be critical for their application. In terms of thermal analysis, the authors emphasize the criticality of accounting for application-specific load profiles within a transient thermal analysis framework, particularly for optimizing objectives dependent on mass.

In [37], an approach for the design of high-speed motors for antenna applications is presented. While application specific, the approach shows the integration of a variety of disciplines, considering electromagnetic, thermal, structural and rotordynamic aspects in the loop of the MDDA. The authors systematically compile their optimization objectives and design variables based on a sensitivity analysis. Additionally, they make use of a surrogate model based on a response surface methodology and validate their design by simulations and experiments.

Reference [73] focus solely on the design of the rotor in a high-speed PMSM in their MDDA approach, showing that MDDA approaches can be employed both on a higher level and a lower level. Herein, they combine electromagnetic, structural and rotordynamic analysis and employ a multi-fidelity surrogate model for the optimization.

While most works in this review divide the design problem in their MDDA according to the domains considered, Reference [110] decomposes the system based on its components, considering shaft, yoke, slots, winding and pole design issues. To find a system-level design, the analytical component models are integrated in to a system-level model by simplifying them using a surrogate model.

Reference [11] stands out because of their consideration of active and passive machine parts alike in their MDDA approach. They highlight the importance for the mass reduction of the machine. Additionally, their approach is the only one using the MDDA to compare different motor topologies, in this case internal, external, dual stator and dual rotor topologies.

Overall, from this review, it can be drawn that the architecture of an MDDA process chain is a complex task that demands the developer to consider a variety of different aspects. However, this review indicates a lack of overall guidance for developers on how to setup MDDA process chains.

Thus, the support to be developed on the one hand has to give a general framework that can be adopted for different applications. On the other hand, it has to address the gap of lacking methodological support for the setup of MDDAs for electric motors.

6.2. MDDAs Are Relevant Both on a System and Component Level

This review has pointed out that MDDAs can be employed both on the system level and for more detailed examinations of specific components on the component level. The latter is necessary to explore the boundaries of a design and investigate the effects of material or manufacturing innovations on a particular component, e.g., soft magnetic composite cores [77]. Furthermore, only a detailed analysis of a component allows to consider resulting design variants, manufacturing constraints or necessary component analyses, e.g., partial discharge analyses in the winding [39].

A strict separation or decomposition of system and component design for the electric motor are found only in a few papers (e.g., [110]). Frequently, all aspects are examined at a single level, which limits the potential for parallelization [111]. Therefore, a methodological framework for the MDDA setup should enable the designer to consider both system and component design aspects within the overall design and provide assistance for their integration and parallelization.

Furthermore, this review showed that MDDA is relevant both for the system-level design and for the detailed design of parts in electric motors. Subsequently, a general framework has to consider both these aspects. For this type of framework, the methodological assistance should aid the developer in adopting concepts of integration or parallelization. Figure 18 presents the parts of the overall support concept that are based on the findings of this review.

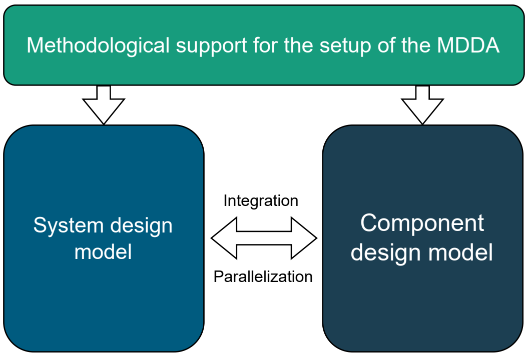


Figure 18. General support concept for the setup of MDDAs for the development of electric motors.

6.3. Systematic Approaches for the Architecture of MDDAs of Electric Motors Are Lacking

This review has revealed a multitude of interdependencies for the MDDA setup: for the architecture of an MDDA, a variety of decisions have to be made, i.e., the consideration and fidelity of domain analyses, the way of reasoning to implement, the arrangement and coupling of the automated procedure, and resulting interfaces, as well as approaches for a higher computational efficiency. This review demonstrated that architecture decisions depend on the application, the resulting requirements and design objectives, as well as the specific type of electric motor and process stage employed. However, approaches to set up an MDDA workflow taking these into account are lacking.

6.3.1. Objectives

The selection of optimization objectives, design variables and constraints is a crucial task while setting up an MDDA workflow. It lies in the nature of multidisciplinary design that a vast amount of possible design variables, optimization objectives and constraints can be considered. Selecting too many objectives or design variables can result in a large computational burden [63]. Even though laying this foundation has a major influence on the outcomes of a design study, only a small number of authors use systematic approaches in order to decide for design variables and objectives (e.g., [37,57,99,100]).

6.3.2. Procedure Arrangement

The MDDAs in the various reviewed papers can be classified as MDOs. However, most authors do not specifically state that they set up an MDO in their work. This indicates that existing methods in the literature have not fully advanced to the field of designing electric motors. This is also reflected by the fact that the vast majority of papers set up their MDO as the most straight forward architecture, called multidisciplinary feasible (MDF). In this monolithic architecture, analyses are simply conducted after each other in each optimization loop. Other monolithic MDO architectures, like All-at-once (AAO) or individual discipline feasible (IDF), or even distributed architectures, like concurrent subspace optimization (CSSO), were not identified in the scope of this review. The only exceptions are the following references: [23,112]. Reference [112] compares different monolithic architectures for its MDDA of a PMSM, proving that remarkable wall clock savings can be achieved compared to MDF. Reference [23] states that their framework is able to decompose the original optimization problem into smaller subproblems, making use of distributed MDO architectures like CSSO. A major advantage of a hierarchical breakdown is that it enables the developer to solve multiple optimizations in parallel [111]. In this review, however, systematic approaches on selecting an architecture for the MDDA are lacking. In other engineering disciplines, methods for this task exist, e.g., [113], who propose a question technique to determine MDO architectures for aerospace engineering.

6.3.3. Computational Efficiency Approaches

Adapting the MDO architecture is not the only way to achieve time savings. In the reviewed papers, surrogate-model-based approaches became more and more prevalent in recent years. In these approaches, analyses are conducted to gather data regarding the inputs and corresponding output responses first. Based on these data, a model is fitted, which can accurately predict the output across the input range. These models can then be used in the actual optimization of the system. Since surrogate models can be evaluated as fast as analytical models, this enables the designer to conduct optimizations with high accuracy and less time effort [84,100]. For the overall architecture of the MDDA, this means that the corresponding steps for setting up the surrogate models must be incorporated. Furthermore, it should be noted that the electric motor always is part of a system-of-systems context, meaning it is itself a component within a larger system, such as a powertrain in a vehicle [39]. Therefore, an MDDA framework should provide a basis for integration into higher-level design and optimization procedures. Surrogate model approaches can act as an enabler for this [110].

6.4. High Level of Multidisciplinarity Continues to Be the Exception

The utilization of MDDA is primarily motivated by the ability to consider interactions among engineering domains during the systems design in order to enhance performance and reduce time and cost in the design cycle [114]. To achieve these benefits, it is crucial to systematically include the relevant engineering domains within the MDDA framework. The reviewed papers primarily focused on the electromagnetic domain, which is evidently the most important domain and thus should always be considered in the system-level design. It is noticeable that either fully analytical models or FEA models were used. Across all papers reviewed, thermal analysis has also been shown to be a vital component of electric motor MDDA. Especially for power dense motors, the temperature is the main limiting factor [39]. For thermal analysis, LPMs are used almost exclusively at the system level. Structural-mechanical analyses were also prominently addressed, especially for PMSM or SynRM rotor geometries. Both high-fidelity FEA calculations and analytical models are employed within this domain. If the aim of the MDDA is to design the rotor geometry in more detail, the component design model should incorporate structural analyses. NVH analyses and rotordynamic analyses are clearly underrepresented compared to the other engineering domains. Nevertheless, this review pointed out that low-fidelity approaches to incorporate these domains with a small additional computational load do exist. Overall, this review showed that developers ranked the domains differently in terms of the trade-off between accuracy and computational cost. The majority of papers utilize FEA for electromagnetic analyses, whereas analytical and semi-analytical models are predominantly employed for other domains. Furthermore, this review showed that cost and mass estimation can play a major role for a wide range of developments; however, the evaluation of these is often restricted to active parts and thus are limited. For the general MDDA framework to consider rotordynamics and NVH analyses, geometric models of passive parts showed to be necessary, which then can also be used to obtain better estimation of cost and mass of the motor. Another aspect investigated in this review is the manufacturing domain. Overall, manufacturing-related topics are relatively scarce. In principle, MDDA approaches have the potential to take manufacturing aspects into account early in the development process. Robust design approaches are an example for this. However, the majority of these approaches are confined to investigating the interaction between the electromagnetic and manufacturing domains. Robust design analysis is also associated with potentially extensive computational requirements, restricting its application to only a small set of design variables and making the use of surrogate models necessary [99].

6.5. Knowledge for MDDAs Is Not Systematically Formalized, Limiting Reusability

As already laid out in Section 2, Reference [14] describes DA as an automation of sequential steps, while KBE involves a more systematic way of capturing engineering knowledge to emulate human decision making. Referring to this definition, this review revealed that MDDAs in the reviewed papers lack systematic ways of knowledge formalization. MDDAs mostly contain hard-coded knowledge in the form of geometries, topologies or procedural rules. Systematic ways of building knowledge bases for the setup of MDDAs were not found in this review. This limits the transferability and reusability of the approaches. Knowledge captured in knowledge based systems can be reused with CAD tools and simulation tools, reducing product development time and cost [115]. This is crucial, since one of the main factors stopping developers from setting up DAs is the initial effort required [109]. Systematic approaches to build up the knowledge base for MDDAs in the reviewed papers, including knowledge acquisition, knowledge formalization and knowledge representation [17], do not seem to not have found their way into the set up of MDDAs for electric motors. However, knowledge-based systems to support more conventional design approaches of electric motors exist.

Reference [116] presents a concept for building a knowledge-based system for the design of electric motors along the Verein Deutscher Ingenieure (VDI) VDI-2206 and VDI-2221 product development cycles.

Reference [117] presents a KBS to support the variant management of electric motors. By modeling variant and design knowledge, the system supports the designer by proposing design solutions in a semi-automatic manner.

6.6. Model Fidelity Decisions Depend on the Machine Type, the Application and the Process Stage

Analysis model decisions include the choice of domain models, their fidelity and couplings between them. This review, specifically Section 5.4, has shown that the application that the motor is designed for has a major influence on the MDDAs objectives and thus the analysis model decision. MDDA processes showed to be relevant at different stages in the spatial synthesis of a motor design. Therefore, MDDA processes should be adaptable to different process stages. Comparable multi-fidelity approaches have been presented in [64,73]. Consequently, in a systematic MDDA setup approach, the analysis model decision should be based on an analysis of the application and the process stage. This should be part of the systematic knowledge acquisition for the MDDA setup, which current approaches in this review are lacking. This review also revealed that analysis model decisions have an influence on the geometries to be generated. For example, while for the electromagnetic analysis, a 2D representation may be sufficient, for NVH analyses, simplified 3D representations might be necessary, as was discussed in Section 5.7.2.

6.7. Passive Parts Are Neglected in Most MDDAs

The review pointed out that a focus is put on the active parts of the electric motors in most MDDAs. However, this review also identified studies that emphasize the substantial impact of passive parts on specific optimization objectives, as discussed in Section 5.7.2. In addition to that, the synthesis of passive parts acts as an enabler for multidomain analyses, i.e., NVH analyses, rotordynamic and thermal analyses. This includes the shaft and bearings for rotordynamic analysis [37], as well as the housing for thermal [11] and NVH [88] analyses. Therefore, a general framework should be capable of considering these parts in addition to the active geometries. Moreover, this review showed that simple analytical models for multidomain calculations of these parts are already available. These suggest that the inclusion of non-active parts does not impose excessive computational burdens on the MDDA [37,41,51]. Structural analyses showed in this review to be motor-type specific, e.g., structural calculations for PMSM rotor geometries [22,36]. Furthermore, this review highlighted that the majority of MDDAs employ 2D geometric representations for electric motors. However, as already discussed for certain machine types, parts, and domain analyses, 3D geometries are necessary. Moreover, simplifying geometries for analysis purposes can help to reduce computational effort [88]. The MDDA framework should therefore be able to generate the parts with a high fidelity and derive low-fidelity geometries for analysis purposes.

7. Methodological Framework

This review points out a lack of guidance to set up MDDA processes within the development of electric motors in a purposeful manner. The works analyzed partially show general and systematic approaches and frameworks, but approaches that are only valid for individual use cases. A more generic framework addressing different fields of applications and their requirements, the different levels (system level and component level) as well as the different design stages and tasks of design automation is missing. To support engineers in setting up MDDA process chains, we propose a methodological framework that integrates the findings of this review—see Section 6—and addresses all tasks and decisions needed for MDDA in electric motor development.

The forthcoming section presents the methodological framework's structure, as it is visualized in Figure 19. The framework comprises two main components: The system-level design model (SDM) and a component design model (CDM). In addition, the framework provides methodological support to prepare and adapt the models needed for the MDDA.

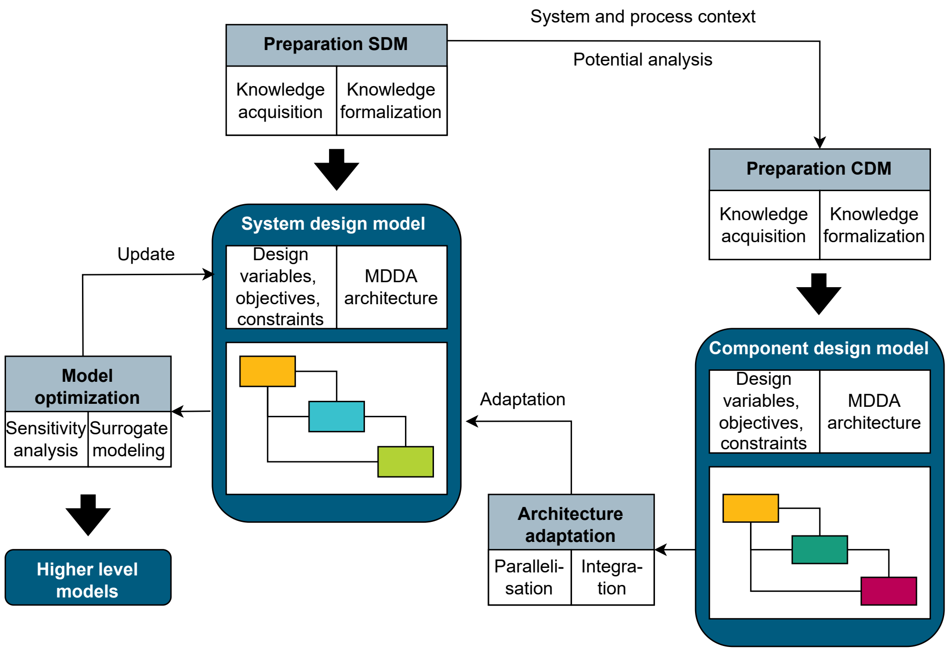


Figure 19. Methodological framework derived from the findings of this review.

7.1. System Design Model (SDM)

The system model describes a modular MDDA framework for the design of electric motors on system level. The aim is to give a general model of the motor that can be adapted to the specific circumstances, mainly depending on the application and the individual requirements, optimization objectives and design variables derived from the intended application of the electric motor. Moreover, the design process stage is specified with regard to the SDM. The SDM should be implemented in a modular way, so that it can be reused for new application scenarios. It represents a reference model of the electric motor and can be adapted to specific application scenarios, motor types and design process stages. This adaptation is enabled by exchanging or rearranging certain elements of the SDM, e.g., analysis models. This allows to reuse elements of the model, which is not supported by most of the existing approaches. As a starting point for the SDM, domain models that work for most applications have to be set up. These can be drawn from the results of this review, as they are presented in Section 5.4. The SDM features a central geometry generator, as proposed in different MDO approaches from aerospace engineering such as [118]. This allows to generate geometries and geometry parameters for the different analyses, enabling a high number of domains to be considered in the MDDA [119]. In the SDM, this also includes passive geometries of the motor, which current approaches often neglect.

7.1.1. SDM Preperation and Setup

The setup preparation is performed in a preparation step. In this step, knowledge for the architecture of the MDDA and the creation of corresponding models are gathered. This includes: system-level requirements based on the application at hand, information regarding the process stage and the considered motor type. The support for this task can be synthesized from a variety of existing methods, e.g., generic requirements engineering methods [120] or electric-motor-specific requirements engineering methods [121]. Furthermore, the SDM preparation addresses the formalization not directly related to the geometry by using, e.g., ontologies. For electric motor design, approaches for knowledge formalization exist (e.g., [122]); however, they have not been applied in the context of the setup of MDDA processes.

Based on these preparations, the SDM is set up. This includes the architecture of the MDDA, domain model and coupling decisions, necessary geometric models, as well as the derivation of design variables, objectives and constraints. This review revealed that methods for this task have not found their way in to the setup of MDDA processes for electric motors. However, in other disciplines, methods exist for this task, especially from aircraft engineering (e.g., [113,123]). Reference [113] gathers knowledge regarding the MDO architecture before formalizing it in a semantic web. This is used to derive the MDDA architecture for the design of an aircraft. Reference [123] presents a tool that allows MDO architects for aircraft design to quickly arrange MDO workflows and visualize them using a extended design structure matrix (XDSM). These methods are promising to be adapted for the setup of architectures for the MDDA in electric motor development in future works.

7.1.2. Model Optimization

After the MDDA process is set up, sensitivity analyses can be employed to find the design variables with the highest impact on the optimization objectives. Suitable methods for this task were identified in this review, e.g., in [124], and can be integrated into the proposed framework. Furthermore, the SDM can be used to build surrogate models. This is useful to increase computational efficiency before performing the actual optimization or for integration into higher-level system models. Methods for this were also identified in this review, which can be reused and adopted for this framework, e.g., [96,100].

7.2. Component Design Model (CDM)

The component design model (CDM) is the second part of the support framework. The purpose of the CDM is to detail certain components, while integrating the results into the SDM. This allows a component of interest to be deeply analyzed and designed early in the process. This way, component-level aspects, like manufacturing constraints, can be systematically considered, which existing approaches lack. As can be seen from this review, the decision for detailed modeling of a component can be driven by various reasons. It ranges from examining the impact of a particular manufacturing method or material innovation for a component, e.g., SMC rotor cores [97], to detailed examination of a component for exploiting it for a specific use case, e.g., the detailed examination of rotor geometries [22,36].

7.2.1. CDM Preperation and Setup

Similar to the preparation step of the SDM, the preparation of the CDM setup includes a systematic acquisition and formalization of knowledge about system and process context of the component, manufacturing constraints, necessary evaluations of the component as well as possible variations of the component, e.g., different rotor topologies. Since the goal of the CDM is to automatically design a component, existing approaches from the literature can be adopted for this. Reference [10] proposes methods for the identification, evaluation and formalization of design automation tasks. The proposed templates could be adapted to structure the process of the CDM. Reference [125] presents a part decomposition approach for the design automation of flow components, systematically considering manufacturing constraints in the process. A similar approach could be applied for the systematic knowledge acquisition and formalization for the CDM preparation.

7.2.2. Architecture Adaptation

For the integration of the CDM, the architecture of the SDM needs to be adapted. Depending on the component, the CDM can be either integrated or parallelized. Reference [110] proposed in his multilevel approach an integration procedure by building surrogate models. Another integration approach can be a parameter split decoupling, as is demonstrated in [83]. This review showed that existing MDO architectures are not employed for electric motor design. In other engineering disciplines, different works that tackle the systematic derivation of MDO architectures which could be adapted for the framework exist, e.g., [113,123,126].

8. Conclusions

In this paper, a systematic literature review was conducted to examine the current state of the art and research in the multidisciplinary design automation (MDDA) of electric motors. A total of 94 papers were selected and analyzed, considering general criteria for the characterization of design automation tasks as well as criteria that are specific for the development and optimization of electric motors.

8.1. Answers to Research Questions

This review revealed that existing implementations of MDDA are often focusing on specific applications or design criteria of electric motors, while more universally approaches are missing. The answers to the research questions given below summarize the findings of this review:

- How is the multidomain analysis and automated geometry synthesis structured? The majority of MDDAs encountered in this review can be classified as MDOs. However, it is evident that authors do not refer to existing MDO architectures, known from, e.g., aircraft engineering. This is reflected in the fact that most authors employ straightforward multidisciplinary-feasible architectures (MDF); other MDO architectures are often not considered. Additionally, numerous analyses are carried out on a sole level without differentiation between architecture levels, such as the system and component levels. Overall, this review indicates a lack of systematic and reusable approaches that can be utilized to establish an MDDA based on the given use case.
- Which parts and geometries of electric motors are automatically created? A focus in the reviewed papers is put on active parts of electric motors. This review showed that MDDAs are applied at both the system and component levels. In the former, the active parts are usually optimized as a whole, while in the latter, a component is considered in detail, such as the optimization of a rotor geometry. This review also revealed a lack of consideration of passive parts of the motor, which are often essential for non-electromagnetic domains, e.g., NVH, structural, thermal or rotordynamics, as well as higher accuracy mass and cost analyses.
- When in the development process of electric motors are MDDA approaches being utilized?
  This review points out that MDDA approaches are used at both the preliminary and detailed stages of the design process of electric motors. It has been shown that the process stage has a significant impact on the choice of domain models in MDDAs. Approaches that cover multiple stages or can adjust to them were found to be rare in the reviewed papers.

- How are domain-specific aspects and constraints formalized? In this review, shape-based and procedural rules were the only types of knowledge formalization used. Other expected forms for this category of design automation task, e.g., graph based formalization, object-oriented formalization and UML based formalization, were not identified for the setup of MDDAs.
- For which application and type of electric motor is MDDA already employed? The application of MDDA is mostly limited to high-speed drives and mobile applications, such as electric vehicle traction motors. This review demonstrated that the application has a significant impact on MDDA's architecture by affecting the selection of domain models and the objectives of the MDDA.
- Which domains are considered and implemented in the MDDA and at which fidelity level? MDDA process frameworks enabling the developer to analyze all relevant engineering domains remain the exception in the reviewed papers. Electromagnetic analyses build the basis of all MDDA process chains in this review, mostly being employed with high-fidelity models. Thermal analysis is the second-most frequently considered domain. Independent of the application and process stage, the majority of MDDAs adopted lumped-parameter models for thermal analyses. Structural analyses are mostly employed for detailed rotor geometries under high load, e.g., PMSM or SynRM geometries. NVH and rotordynamic analyses are often neglected in the reviewed papers.
- Which couplings between engineering domains are considered? Simple, one-directional couplings are usually implemented between the electromagnetic and other relevant domains for reasons of computational effort. The implementation of bi-directional couplings is almost exclusively implemented for the coupling between the electromagnetic and thermal domains and, even here, was rarely observed. The coupling between the electromagnetic and mechanical analyses are, if existent, one directional. Thus, the influence of mechanical loads and deformations on the electromagnetic analysis is neglected in most works. Couplings between thermal and mechanical analyses are mostly not considered. Instead, this physical coupling is represented in a simplified way by means of worst-case scenarios.

These findings are considered by different elements of the proposed framework for multidisciplinary design automation of electric motors introduced in Section 7.

8.2. Core Contributions

The reported systematic literature review expands the state of the art in the automated design of electric motors with the following contributions:

1. We present a set of twelve criteria to analyze the current multidisciplinary design automation approaches for designing electric motors. In addition to general criteria that characterize aspects such as knowledge representation or reasoning method, the classification criteria consider the type of electric motors, along with the related domains and their coupling. In particular, the specific criteria for electric motors can be used to build up MDDA process chains.
2. We provide a comprehensive overview of existing approaches in the field of multidisciplinary design automation for electric motors covering the period from 2007 to 2022. Based on this analysis, we indicate the main trends in the research field and limitations of existing approaches: consequent analysis and integration of domains, applicability and transferability of MDDA approaches, systematic incorporation of established MDO architectures, as well as the consideration of passive components in the motor.
3. Based on our assessment of the current literature and identified limitations, we suggest an initial methodological framework for establishing MDDA process chains tailored to specific applications, with a focus on integrating system and component-level design, as well as thorough domain consideration and coupling.

Following the design research methodology (DRM), the next research steps will focus on elaborating the methodological framework in more detail (prescriptive study), as well as validating its applicability through the development of electric motors within the stated framework (descriptive study II).

Author Contributions: Conceptualization: N.U. and D.I.; methodology: N.U. and D.I.; investigation: N.U. and K.W.; formal analysis: N.U.; writing original draft preparation: N.U. and K.W.; writing review and editing: D.I., K.W. and N.U. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

AAO	All-at-once architecture
ACO	Ant colony algorithm
CAD	Computer-aided design
CDM	Component design model
CDS	Computer-based design synthesis
CSSO	Concurrent subspace optimization architecture
DA	Design automation
DRM	Design research methodology
EEC	Electric equivalent circuit
EV	Electric vehicle
FEA	Finite element analysis
GA	Genetic algorithm
IDF	Individual discipline feasible architecture
IPM	Interior permanent magnet motor
KBE	Knowledge-based engineering
MDO	Multidisciplinary optimization
MDDA	Multidisciplinary design automation
LPM	Lumped-parameter model
MDF	Multidisciplinary feasible
MEC	Magnetic equivalent circuit
MOPSO	Multi-objective particle swarm optimization
NSGA	Non-dominated sorting genetic algorithm
NVH	Noise, vibration, harshness
PMSM	Permanent magnet synchronous motor
PSD	Parameter split decoupling
PSO	Particle swarm optimization
RSM	Response surface methodology
SDM	System design model
SMC	Soft magnetic composite
SQP	Sequential quadratic programming
SynRM	Synchronous reluctance motor
UML	Unified modeling language
VDI	Verein Deutscher Ingenieure e.V.
WLTP	Worldwide harmonized light vehicles test procedure
XDSM	Extended design structure matrix

Appendix A. Employed Search String

(“design automation ” OR “automat* design” OR “generat* design” OR “generative engineering” OR “Knowledge based Engineering” OR “Knowledge based System” OR KBE OR “design synthesis” OR optimis* OR optimiz*) AND (multi-physics OR “multi physics”

OR “multi disciplinary” OR multidisciplinary OR multi-disciplinary OR multidomain OR “multi domain” OR holistic OR multi-domain) AND ((electric OR “permanent magnet” OR synchronous OR asynchronous OR induction OR reluctance OR AC OR DC) AND (Motor OR Machine OR Generator)).

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