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Review

Overview of Identified Challenges in the Development Process of Superconducting Accelerator Magnets

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Abstract: Development challenges in the domain of superconducting magnets are concentrated on technical problems in the current literature. Organizational, domain-specific challenges are often seen as secondary but must be considered with new holistic development approaches like Model-Based Systems Engineering (MBSE) becoming more popular. This work quantifies the domain challenges and gives the foundation to derive success criteria for design support in the future. A systematic literature review has been conducted to identify the overall domain challenges, and extensive interviews in the CERN technology department have been carried out to identify the development challenges on a practical level. Problems in knowledge management have been identified as a major challenge in the development process and the general literature. The paper concludes by picking up the most important challenges from the interviews and literature and puts them into the context of the authors' knowledge of electrical magnet design.

Keywords: CERN; superconducting magnets; development process; challenges; design research

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1. Introduction

For a given radius of a proton–proton accelerator, the maximum attainable collision energy is limited by the strength of the dipole magnets. Thus, developing superconducting accelerator magnets with the highest magnetic field is one of the main objectives of future circular-collider projects [1] notwithstanding that the cost and complexity of the magnet and cryogenic system must be weighed against the cost of the civil engineering and general infrastructure for larger tunnels [2–4]. In the past decades, the Niobium-Titanium (Nb–Ti) superconductor was the widely used material; many accelerator machines currently operating rely on this proven technology. With the Nb–Ti superconductor, the achievable air-gap flux density in dipole magnets is limited to around 8–9 T [5]. Therefore, the research of accelerator magnets concentrates on new superconductor materials and technologies. The goal for accelerator-type magnets using Niobium-Tin (Nb_3Sn) superconductor is to achieve dipole fields of 12–16 T. Current research efforts worldwide are intended to improve the reliability and robustness of Nb_3Sn to make this technology viable for series production [6].

High-temperature superconductors (HTS) like Rare-Earth Barium Copper Oxide (REBCO) and Bismuth Strontium Calcium Copper Oxide (BSCCO) can reach fields of up to 45.5 T in small experimental settings. With HTS being in an early development stage, progress in this field of magnet Research and Development (R&D) is expected [7,8].

The accelerator magnet R&D programs face technical, organizational, and other challenges, such as long-term sustainability and accountability within international collaborations. Research efforts must be parallelized and coordinated while project durations are up to a decade [9]. In combination with the long lead times, the stability and continuity of research groups become difficult [8]. The high investment costs of large-scale infrastructure, coordination of interdisciplinary research teams, and industrial collaborations characterize the development of new generations of accelerators.

The available literature describes technical challenges in the general magnet development process extensively. Many academic papers cover new technologies and integration challenges, such as [10–13]. Identified problems and solutions in these sources are generally very detailed and technical. These technical challenges lead to computational needs in the design process, including electromagnetic and mechanical design and multiphysics simulations for quench studies and magnet protection [14].

To cope with the computational needs for electromagnetic design, the ROXIE (Routine for the Optimization of magnet X-sections, Inverse field calculation and coil End design) program package was created at CERN [15]. This program provides an easy-to-use interface to perform magnetic field optimizations. With the introduction of ROXIE in 1995, the need for a more integrated design process became clear early on. Recent extensions to the program aim to integrate the code with commercial programs and Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) systems and address more general problems related to the knowledge transfer process and the traceability of the simulation models [14].

In the year 2000, the Engineering and Equipment Data Management Service (EDMS) system was introduced as an official knowledge-management solution, providing CERN-wide document, engineering, and equipment databases [16]. EDMS is the official PLM (Product Lifecycle Management) solution at CERN for large-scale, long-term projects like the Large Hadron Collider (LHC) and Future Circular Collider (FCC). Experience from previous accelerator projects has shown that the relevance of production, test, and measurement data may become clear only at a much later stage during the operation of the accelerator. EDMS was created to make the data available to the next generation of engineers, bridging the gap between the system development cycles in accelerator projects. EDMS enables quality assurance processes and provides a variety of connections to other CERN services, such as the CERN Drawings Management System, the Enterprise Asset Management (EAM), and SmarTeam® [17]. User interfaces like the Equipment Management Folder (MTF) use the common EDMS database to provide convenient data access to documents in EDMS and monitoring solutions for the lifecycle of particular assets.

Apart from the challenges identified in the abovementioned references, various books about CERN-specific challenges within an international science environment have been written for the general audience [18,19].

With Model-Based Systems Engineering (MBSE) becoming more popular within Systems Engineering and the shift from the classic document-based development approach towards integrated system models, current best practices and existing tools need to be adapted. Organizational and structural challenges in the domain have become increasingly important in this shift. IT infrastructure and simulation software need to be more user-friendly to be accepted by scientists and technicians working in the field [20].

The first steps towards MBSE in numerical magnet simulation have been implemented in [21]. However, there is a lack of well-documented practices and challenges for the iterative design processes of accelerator magnets and related scientific instruments for test and magnetic measurements.

Following the examples of the space and automobile industries [20], defining these domain-specific challenges is essential to implement modern Systems Engineering approaches like MBSE in the field of superconducting accelerator magnets. These documented challenges can be used as measurement criteria for the future integration and success of general design supports.

2. Background

MBSE is a concept that uses models to support systems engineering processes. It has been applied in various fields and is seen as a way to manage complexity, maintain consistency, and assure traceability during system development [22]. It has been particularly effective in the aerospace industry, where it has been used to assist the development of systems such as rocket propulsion and thereby reduce costs and lead times [23,24]. Ref. [21] used MBSE in a project to manage the rising complexity of multi-physics simulations and used a custom software tool to interconnect the magnet system model to the different simulation tools for their respective simulation domains (mechanical, magnetic, thermal, and geometric). However, there is a need for further research to realize its potential benefits fully [22]. The engineering design community has a diffuse understanding of MBSE, and choosing the right standard for a practical application is a challenge [25,26]. MBSE and design research are closely connected, with MBSE providing a framework for integrating various design optimization tools, guidelines, and processes within a design methodology.

To understand the concepts in this paper, a short introduction to the domain of design research and its specific terms is required. According to "DRM: a Design Research Methodology" by Blessing and Chakrabarti [27], a widely applied methodology in the community of design research, design research is defined by including two main parts of the field: the development of understanding and support. These two fields are closely related, with a common goal of making design and development processes more effective and efficient. Design research is about developing more successful products by creating and following learned design practices. Two main objectives of design research can be identified:

1. Modeling the design process, including all related resources like products, knowledge, and organization.
2. Deriving design support based on the created models to improve design practice.

Both objectives include a validation process. According to [27], the models and supports are validated in practice to impact the design process positively.

In the context of design research, terms like methodology, process, method, guideline, and tools describing the design support are ubiquitous. As there is no universally accepted definition for these terms, we explain them as required for the understanding of this paper, closely following [28].

- A design methodology is a general, well-defined approach to producing designs for a particular class of systems. A design methodology describes design activities and their sequence, including methods, information artifacts, the management process, and priorities in design thinking.
- A design process is a series of organized and planned activities to develop a design or solution to a specific problem. The design process is defined within a design methodology. It typically includes phases such as research, ideation, prototyping, testing, and refinement and provides a systematic approach to creating and improving the system design.
- A design method is a specific technique or approach used to achieve a desired outcome within the design process. Design methods guide how to perform tasks, use information, and sequence actions to solve a problem.
- A guideline is a recommendation or principle that guides or advises approaching a particular task, situation, or decision. It is a standard and facilitates an information-based decision-making process following best practices.
- A tool is a physical or digital object that helps perform design-related tasks and create design elements. These tools can be tailored to specific methods, guidelines, processes, or approaches.

In summary, a design methodology serves as the foundation, while the design process applies or customizes that methodology to a specific problem. Design methods, guidelines, and tools support the design process, helping designers achieve their goals efficiently [28]. Figure 1 shows this relationship between the terms.

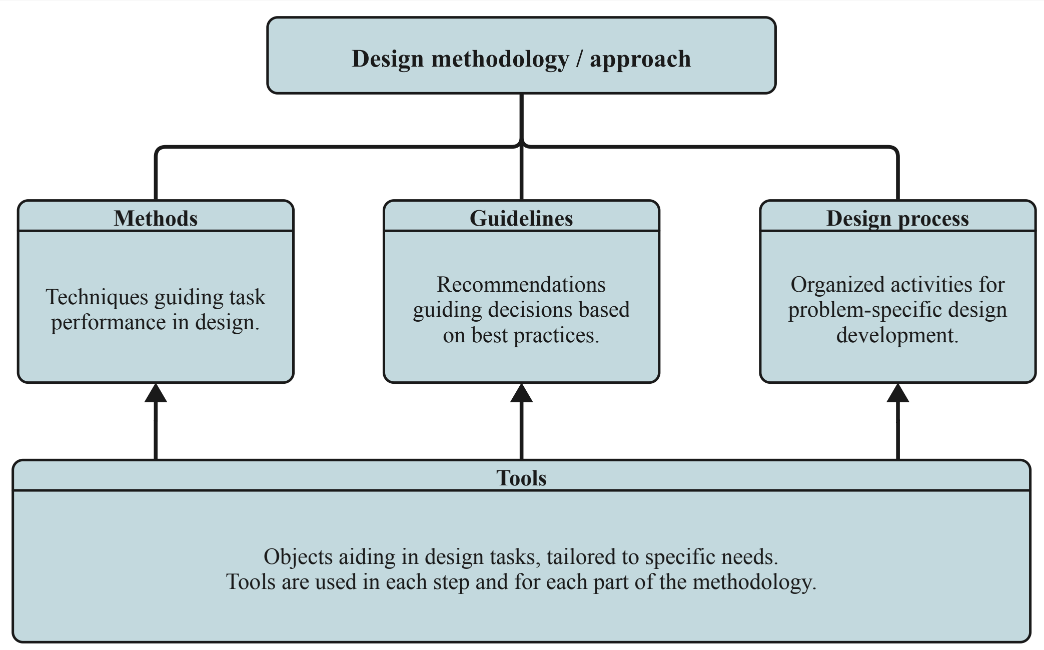

Figure 1. Relationship between the terms Design Methodology, Method, Guideline, Design Process and Tool (adapted from [28,29]).

3. Methods

This paper aims to identify the significant challenges in the development process of superconducting accelerator magnets. The challenges to be identified should not, like in the current literature, focus mainly on the technicalities but give a broad overview of general challenges, such as the typically long lead times, the large-scale infrastructure of high-energy physics applications, or the collaboration of international, cross-domain development teams. The research questions that should be answered in the present work are:

- What are the challenges in the domain of superconducting accelerator magnets?
- What are the challenges during the development process of accelerator magnets at CERN?

To answer these two questions, two research methods have been selected. An essential step is to perform a literature analysis to answer the first question, establish a general overview of the domain, and create a foundation for future work. For the second question, interviews are conducted with scientists and engineers in the technology department to develop insight into the daily magnet development processes at CERN.

3.1. Systematic Literature Review

A systematic literature review is being carried out to identify the general challenges in the domain and serve as a theoretical foundation. The literature search focuses on general challenges in the domain and specifically within the development process. The seven-step review method published in [30] has been used to filter the identified sources and only include relevant work. The results and identified general domain challenges are explained in Section 4.1.

3.2. Explorative Expert Interviews

Information about the practical challenges and influencing factors in the design process must be obtained by discussing with experts who have acquired hands-on experience. These discussions were conducted as explorative interviews with a constant set of open questions regarding the development process. The questions asked during the interview were in accordance with the checklist for stakeholder discussions in the Design Research Methodology (DRM) [27]. A total of 14 domain experts in CERN's technology department were interviewed. To not influence the experts' answers, they were given a brief introduction to the topic before starting the interview, but the identified challenges from the literature sources were not stated to them. The results and identified operational challenges are explained in Section 4.2.

Section 5 points out the interaction between the general challenges from the literature and the practical process challenges from the interviews. Section 5 puts them into the context of the electromagnetic design using simulation tools such as ROXIE.

4. Analysis of the Magnet Development Process

The Analysis section describes the results of the research methods above.

4.1. General Domain Challenges

Only articles published in the last five years were considered for the systematic literature review. The literature search was carried out using Google Scholar. The 'particle accelerator' search results in approximately 17,400 matches in the last five years alone. As explained in the introduction, the scope of the paper should be reduced to the domain of "superconducting accelerator magnet(s)", which gave 448 results. Specifically, the paper dealing with 'design' and 'challenges' should be considered. The keyword "motivation" proved helpful in filtering for paper considering the high-level challenges of superconducting magnets. The search string "challenges AND motivation AND design AND (Superconducting accelerator magnet(s))" delivered 93 results for the last five years. After removing duplicates and non-related papers, 85 papers were left for an in-depth review. The analyzed literature mainly focuses on the superconducting magnet technical challenges. Only a few papers explicitly list organizational challenges and development process challenges. Reviewing the papers' contents left 20 documents dealing with overarching problems and challenges. The content of all 20 documents is analyzed, and all challenges are listed on the way. Technical challenges related to the change in superconducting technology, such as using HTS materials, are being summarized under the common *Change of Technology* challenge. All other structural, organizational, or procedural challenges are summarized and grouped under common challenge topics. A total of 14 challenges were identified from the 20 sources. These challenges are listed and explained in the sections below.

4.1.1. Change of Technology

The LHC at CERN has reliably utilized Nb–Ti accelerator magnets. Still, this superconducting material has approached its theoretical limit of around 8 T for the main magnetic field, prompting a demand for higher magnetic fields in upcoming accelerator projects [31]. Crucial for collider performance, the magnet system must now look beyond Nb–Ti. Alternative superconductors like HTS and Nb_3Sn are eyed for future High-Energy Physics (HEP) applications. However, they come with challenges such as high costs, the absence of industrial partners, and material complexities like the brittleness of Nb_3Sn [5,32]. High-temperature superconductors offer a promising solution for achieving higher magnetic fields. Nevertheless, their early stage and the shift away from tried-and-tested Nb–Ti superconductors necessitate overcoming design and fabrication challenges [33].

4.1.2. Long Lead Times

The development and implementation of new technologies for accelerators and HEP projects are marked by long lead times, often spanning a decade or more [34,35]. Specifically, R&D programs for developing the next generation of superconductors can take around seven years to improve industrial products, and an additional five years are expected to extrapolate results with full-length magnets [36]. These protracted timelines make it crucial to conduct R&D in parallel with studies for future accelerator projects to ensure the readiness of new technologies when the projects are approved [31]. For instance, the preparation and construction phases for an ambitious program like the FCC-hh are anticipated to consume 8 and 15 years, respectively, with overall operation and construction taking nearly half a century [8]. These points highlight the need for long-term planning and parallelization in the field.

4.1.3. Large Scale Infrastructure and Investment

The development and production of superconducting accelerator magnets demand considerable investment in large-scale, specialized infrastructure that spans multiple domains such as cryogenics, electronics, and civil engineering [31,36]. These costs are not one-time but ongoing, needed to maintain and upgrade existing facilities [32]. Additionally, the high costs extend to the new superconductor materials like HTS [37]. For instance, about 39% of the total cost of the FCC-hh project is expected to occur for the production of the 16 tesla dipole magnets, making cost optimization a key consideration in magnet and collider projects [34,38]. As such, current R&D efforts must focus on more effective and cost-efficient methods, including modular components and the capability for maintenance by service suppliers instead of highly specialized personnel [35,37]. To utilize this costly infrastructure effectively, a sustained R&D program is essential [35,39]. With limited resources for producing essential accelerator components such as superconductors, dampers, and radiofrequency sources, sustainability, resources, and power efficiency have become prominent in large-scale production for future applications [38].

4.1.4. Maturity of Technology

Current advances in superconductor technologies, which are pivotal for the scientific field of particle colliders, mainly arise from laboratories with only limited industry involvement [31]. As a result, high-field applications of HTS and Nb_3Sn have yet to reach the maturity necessary for large-scale production [5]. The particle collider field constantly innovates and evolves, necessitating new technologies to produce high-field magnets of up to 16 T in the future [34]. However, reaching production maturity for these novel superconductor materials is an extended process, estimated to take at least 15 to 20 years [37]. Even though Nb_3Sn superconductors have been under development and research for 25 years and are now more widely used, their potential has not been fully realized, indicating they have not yet reached maturity [5]. The future generation of particle accelerators requires magnets capable of producing 16 T or even higher magnetic fields [34]. New superconductor technologies like REBCO are necessary to achieve this [37]. However, to date, no REBCO-based magnet has been able to generate a dipole field higher than 5 T, creating a significant technology gap between the present and future that poses a major challenge for R&D programs [34].

4.1.5. Continuous, Cross-Domain Teams

Developing new magnet technologies requires a multi-disciplinary approach, with teams possessing a broad spectrum of competencies across various scientific areas [31,40]. This multidisciplinary approach requires collaboration across academia and industry and benefits from continuity over prolonged periods [35]. Special R&D programs are advantageous in maintaining expertise, attracting new talent, and fostering early-career scientists to advance the HEP field [38,41]. Optimal scientific progress is achievable by ensuring continuity in development teams, which involves recruiting and training various roles, including scientists, engineers, and technicians [31,40]. However, declining accelerator R&D budgets pose challenges in training and maintaining a skilled workforce [38]. Building and maintaining strong, diverse teams are vital to supporting future accelerator facilities and advancing new technologies [41]. Given the multi-domain nature of high-field magnet research, it is imperative to form stable teams with a wide array of skills [35]. This team building necessitates substantial investment, and optimizing continuity becomes a vital success factor [38].

4.1.6. International Collaboration

The future of accelerators hinges on superconductor technologies yet to be fully developed or matured for mass production, necessitating robust international partnerships across laboratories, universities, and industry [31]. International cooperation is crucial to progress in magnet research, and both competitive and collaborative international programs are necessary [40] to effectively overcome technical and scheduling challenges [34,42]. Rapid development in the domain can only be achieved through frequent knowledge exchange [34,42]. Tightly coordinated collaborations across different universities, laboratories, and industry partners globally are needed, particularly for integrating new infrastructure for testing and manufacturing [35,36,39]. The magnet domain relies on the critical role of international collaboration in managing the cost and complexity of large-scale particle accelerator projects and the importance of strong ties to industry for long-term projects and cost reduction [37,38]. International collaboration efforts must be well coordinated and cost-effective. The need to focus on modular basic components and maintenance by service suppliers instead of highly specialized personnel carries on globally [37].

4.1.7. Parallelized R&D Efforts

The development of future HEP applications depends on current and future R&D programs being in line with international programs and organizations [31]. It is, therefore, crucial to align global collaborations with the demands of superconducting technologies [31]. Strategic R&D planning and significant financial investment are important to create a competitive ecosystem for maturing existing and introducing new superconductor technologies, crucial to the overall performance of accelerator magnets [40]. Ref. [32] stresses how neccessary Magnet R&D programs are for uncovering new insights into a critical technology for future accelerator generations [32]. It is important to expand the general scope and resources of current research programs to meet emerging domain needs [32]. Sustainability and inclusiveness are success factors for dedicated, well-planned programs, given the long timescales expected for future R&D activities [36].

4.1.8. Cross-Cutting Activities

High-field magnet development is a multi-disciplinary domain involving a vast range of expertise in areas such as material science, cryogenics, and numerical modeling [36]. In the context of future research and development programs, those related to HTS and magnets, these cross-cutting activities are key to innovation. The development of new modeling tools is required to align these diverse domains. Large projects like the FCC face design challenges spanning multiple fields and necessitate numerous cross-domain development activities over many years, as outlined in the FCC-hh design reports [8]. Future accelerator-based high-energy physics projects, with their increasing size, cost, and timescales, encompass a diverse array of research fields, from beam physics to magnet design, making them some of the most challenging scientific research projects [41].

4.1.9. Production Scale

The needed magnets for different accelerator projects range from one unit to a few thousand units. Both cases have their specific challenges. To achieve a high field level in magnets, exclusively producing in a laboratory can be a plus since technology transfer from academia to industry is challenging, and industrialization only becomes cost-efficient after passing a certain unit number. Lab production works well for a low number of magnets. For a more considerable magnet number, industry involvement is necessary to control the cost and reach production uniformity at scale. However, with the industry involvement, the mentioned difficulties in knowledge and technology transfer come into play [39]. CERN's standard policy is to procure from and involve industry whenever possible. Inhouse industrial productions are only taken on if there are external hindering factors, like the lack of competence in industry or the lack of suitable suppliers. This was the case, for example, for the construction of cryogenic test stations for the LHC superconducting series magnets.

Procurement from industry on the other hand needs to be balanced between cost savings and industrial returns to the CERN member states. The purchasing and production process for magnets poses a challenge specific to the respective development stage and situation and needs to be controlled and constantly adapted through clear procurement rules [43].

4.1.10. Multi-Physics Model

The fast transients in superconducting magnets during a quench can induce high mechanical stress, and protecting against quenching becomes more complex as the quest for higher magnetic fields intensifies [44]. The challenges require interconnected simulation models across domains, emphasizing the increasing relevance of multi-physics numerical models that link thermal, mechanical, and electromagnetic components [45]. The issue of simulating non-linear transient effects in superconducting accelerator magnets is characterized as multi-domain, multi-physics, multi-rate, and multi-scale, involving the magnet, its circuits, and the power converter controller [46]. These domains involve multiple interconnected physical phenomena demanding a simulation infrastructure allowing model-order reduction while facilitating information exchange between different software packages. Quenches in the operation of superconducting magnets can cause damage to the surrounding infrastructure and circuitry, requiring special protection systems whose interactions with the magnet must be simulated, incorporating multi-physical properties, heat propagation equations, and mechanical models [45,47]. This modeling process, complicated by domain coupling and multiscale phenomena, necessitates using multiple simulation tools like Ansys® and COMSOL® in tandem to model the electromagnetic and thermal domain couplings.

4.1.11. Standardization of Simulations

Future modeling must establish communication between models and services within different domains. A container-based micro-service infrastructure with standardized query capabilities is proposed to reuse different data from different data sources. Jupyter notebooks used as magnet system models should centralize these query capabilities and make them available to the user [21]. To answer complex research questions involving multiple tools and domains requires fully integrated simulation practices. To enable communication between tools and packages, an effort to standardize software interfaces must be made. The input and output formats need to move away from individual file-based exchange towards a unified workflow using defined community standards. For example, multi-physics simulations with multiple linked models would greatly benefit from easier information sharing and standardized software interfaces [48].

4.1.12. Usability of Tools

The domain of accelerator magnets is highly diverse and complex. Code and software tools evolve to meet the steadily increasing requirements. With the code changing over time, the user interfaces require updates along the line. Sustainable code maintenance approaches must be established to identify and fix breaking changes between the logic layer and the user interfaces. Only that way can the usability of the current tool versions be assured [48].

4.1.13. Knowledge Management

The development of superconducting accelerator magnets is a complex, multi-faceted process that spans decades, integrates multiple domains, and involves globally decentralized teams [48]. Ensuring effective traceability of design decisions and magnet models, particularly given the multitude of models and variants created during future project studies is crucial [21]. A shift toward model-based system engineering, away from classical document-based approaches, is necessary to ensure model traceability and repeatability [48]. Suggested methods include versioning models and creating variants as branches in a code repository [21]. In multi-project settings, the documentation and traceability of each team's models are vital [48]. Automatically generated reports and a direct link between the model and documentation can help maintain a record of results and design history [21]. Knowledge transfer between teams and stakeholders, as evidenced by the 11 T dipole project, is critical for success, particularly in managing technical and managerial challenges [39]. Access to historical data is essential to enhance modeling quality and productivity, enabling reuse and iterative improvement of past designs [48]. With increasing modeling complexity, data management becomes crucial [21]. Currently, models are often stored in non-retrievable formats such as figures or texts in publications [48]. Software tools developed by individual researchers are often abandoned upon their departure, highlighting the need for knowledge transfer practices for the continuity and modernization of simulation tools [21]. As part of knowledge management, code documentation is a central aspect of software usage [48]. Additionally, establishing sustainable code practices is crucial to building knowledge over time and dealing with limited development resources. Despite their short-term efficacy, past uncoordinated software package designs have proven unsustainable in the long run [48]. Ensuring community-wide access to information about issues, limitations, and capabilities of existing modeling software is essential for researchers to stay informed [21]. Lastly, the collaboration between laboratories and industry is necessary for mass magnet production, with knowledge and expertise transfer posing a significant challenge to achieving high-quality results [39].

4.2. Development Process Challenges

The 14 interviewed experts were asked the following questions which are relevant to this analysis:

1. "What problems/challenges occur to you during a typical project at CERN?"
2. "Which problems/questions are important to you to solve?"

The experts are all part of the technology department at CERN and have a deep understanding of the magnet development process. With an average of 14.53 years ($\sigma = 9.84$) of experience in development projects at CERN, the experts are considered to have sufficient knowledge about the company-specific challenges to answer the posed questions. The following explains the challenges identified by the experts by looking at their answers to these two questions. The numerical results of the interviews are given in Table 1.

During the analysis of the interviews, it became clear that the majority (12 out of 14) of experts identified problems related to knowledge management. This is why the challenges in Table 1 are grouped into general and knowledge management challenges. The absence of standardized knowledge management is a problem for most experts. Documentation is often missing or has low quality. Eight experts further identified problems related to historical data and documents, including missing data, inaccessible data, and missing links between data and documents. Other identified knowledge management problems are, unclear and/or changing requirements during a project, missing knowledge and data transfer in general, and repeating errors from past projects. Other identified problems are the low quality of documentation and the missing knowledge and data transfer, especially after the end of a project or the offboarding of a leaving employee. The most common general problems are unclear and/or changing requirements during development and missing standards and best practices. Other problems are in decreasing order: difficulties in the project planning, error repetition, communication problems, unclear onboarding process, staff turnover, use of unsuitable tools, and the frequent change of personnel.

With Question 1 asking for the general occurrence of challenges and Question 2 asking for their importance, a two-dimensional diagram with the occurrence of the challenges as the x-axis and their importance as the y-axis can be created from the results given in Table 1. This diagram with all identified challenges is shown in Figure 2.

Table 1. All challenges with their according number of mentions during Question 1 and 2 in absolute numbers and relative to the number of interviewed experts (n = 14). The challenges are grouped in Knowledge Management and General challenges.

	Question 1 *		Question 2 **	
Challenge	**Absolute**	**Relative**	**Absolute**	**Relative**
Knowledge Management				
Process Quality	11	79%	8	57%
Knowledge/data transfer	6	43%	8	57%
Unclear and/or changing requirement	6	43%	3	21%
Lessons learned/ improvement implementation	4	29%	5	36%
Missing and/or low-quality documentation	9	65%	9	65%
Problems with historic data/documents	9	65%	12	86%
General				
Communication problems	8	57%	4	29%
Unclear staff onboarding and turnover process	6	43%	3	21%
Frequent staff turnover	6	43%	2	14%
Problems related to standards and best-practices	10	71%	5	36%
Planning difficulties	6	43%	3	21%
Unclear responsibilities	6	43%	1	7%
Inconventient and/or inefficient tools	3	21%	9	65%

* Mentions in Question 1 are interpreted as Occurrence later on. ** Mentions in Question 2 are interpreted as Importance later on.

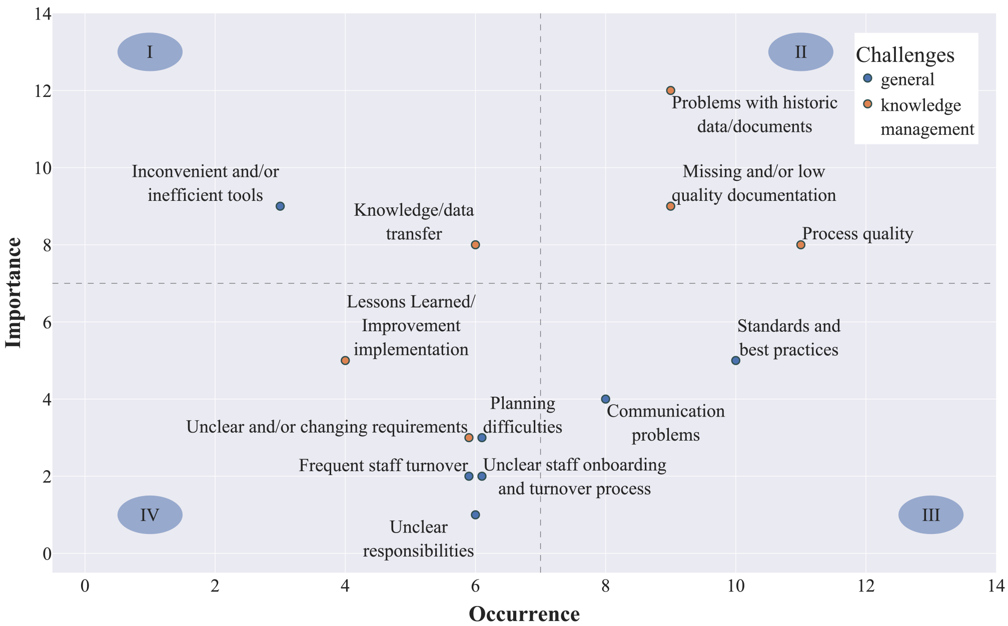

Figure 2. Identified challenges during the explorative expert interviews. The challenges are shown according to the number of mentions in Questions 1 and 2. The mentions in Question 1 are defined as the "Occurrence" of the challenge and Question 2 as the "Importance" of the challenge.

Challenges with high importance and occurrence (top-right in the diagram) are predicted to impact the current situation significantly. Vice versa, challenges with low importance and occurrence (bottom-left in the diagram) are expected to have less impact.

The diagram in Figure 2 is divided into four quadrants: I, II, III, and IV. The top right quadrant (II) contains all important challenges that occur frequently. This quadrant contains three challenges: Problems with historical data/documents, missing and/or low-quality documentation, and knowledge management process quality. Two challenges (Inconvenient and/or inefficient tools and knowledge/data transfer) are in the top-left quadrant (I). These challenges occur less often but are of high importance. The problems with lower importance and a high occurrence frequency include communication problems and challenges related to standards and best practices.

5. Discussion

Although the paper focuses on the magnet development and knowledge management processes at CERN, the identified challenges are representative of any large-scale scientific project.

A possible limitation of the systematic literature review is the focus on superconducting accelerator magnets, disregarding possible solutions and implementations in other domains, such as high-field Nuclear Magnetic Resonance (NMR) or fusion magnets.

The domain and practical challenges identified in both the literature review and interview studies shall be interpreted in view of electromagnetic modeling, particularly using the CERN field computation program ROXIE, for which the source codes are available. The focus shall lie on the practical challenges that have a high occurrence and/or importance in the magnet development process (quadrants I, II, and III in Figure 2).

Communication problems (III) appear frequently during a typical design project. This is in line with the general challenges mentioned in the literature. With extensive international collaborations and heterogeneous teams performing cross-domain activities, communication difficulties naturally occur. In the electromagnetic design process with ROXIE, communication problems are mostly related to the missing, common communication basis. Magnetic models are often not versioned and do not have a single source of truth regarding data storage. This makes data-driven communication and decision processes difficult and aggravates the traceability of design decisions.

Challenges related to standards and best practices (III) become more relevant with the need for multi-physics models and the long lead times in magnet development. An increasing number of simulation tools need to interface with each other to perform complex multi-physics modeling processes. Over a long development cycle with changing tools and personnel, these missing simulation standards become critical. As described above, to mitigate this problem, the first attempts towards MBSE are being made. The magnet literature also identifies missing standardization of simulation processes and tools.

Inconvenient and inefficient tools are a challenge that occurs less frequently during the design process but is highly important. The usability of tools, not only for developers and experienced users, is also mentioned as a challenge in the literature. To ensure the constant usability of in-house simulation tools like ROXIE, the user interface must be kept up-to-date to match the implemented changes to the software functionality over time. With the rising requirements for simulation tools and the increasing complexity of magnet designs, this constant improvement process can only be faced with sustainable code maintenance practices and strategic planning.

Four of the five identified challenges with high importance (I and II) are related to knowledge management. The process quality of the knowledge management process is insufficient for normal and superconducting magnets. ROXIE users are not provided with a standard process description for storing simulation models. This leads to problems with historical data and documents at later stages of the development process. Simulation models are often stored on local machines and become inaccessible when the project engineer leaves the organization. This makes the knowledge and data transfer difficult, especially over multiple generations of engineers. Missing and/or low-quality documentation is a challenge for the electromagnetic models, related design decisions, simulation software, and user interface. These challenges in knowledge management are clearly identified in the literature and are experienced by researchers in every scientific domain. Results and new implementations are often published incrementally with page constraints, particularly when published at conferences. These publications make it difficult to replicate and build on top of past breakthroughs. A good step towards reproducibility and traceability of published results is open-data approaches. For example, the interviews for this paper are formatted consistently, written in an open standard file format (Markdown), and publicly accessible. The link to these data can be found below in the Data Availability Statement.

With high-occurrence and high-importance (II) challenges as a subset of the knowledge management cluster and the call in the general literature for improved knowledge management, the authors are convinced that this domain should be a focus in design research for future magnet projects. The interview results conclude that deficiencies and improvements within knowledge management could have the most significant negative and positive impact on the current state of the development process within the CERN technology department.

A design methodology using the MBSE concept is developed at the magnet group at CERN in view of data-driven modeling of accelerator magnets and field transducers by combining numerical field simulations with tests and magnetic measurements. Model-based systems engineering must be supported by the appropriate database and project management layers, which requires the integration of many disciplines and heterogeneous user groups in electromagnetics and mechanics, metrology, and software engineering. The aim is to create numerical models of magnets that are updated by magnetic measurements and allow the extrapolation of performance parameters regarding different powering cycles, manufacturing defects, and varying material parameters. These models comprise six constituents: the physical objects (magnets and field transducers), data layers (numerical models and measured data), and software tools for design and analysis.

It has become clear that using MBSE and a design methodology requires a solution-driven approach towards the challenges identified in this paper. Within all mentioned constituents, clear processes must be identified to create a foundation for implementing such a design methodology. For example, without standardized knowledge, management system models cannot be stored and retrieved, and without standardized simulation interfaces, these models cannot be used in complex multi-physics simulations.

A detailed description of these constituents will be presented together with the design methodology in a future paper.

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Abbreviations

The following abbreviations are used in this manuscript:

BSCCO	Bismuth Strontium Calcium Copper Oxide
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
DRM	Design Research Methodology
EAM	Enterprise Asset Management
EDMS	Engineering & Equipment Data Management Service
FCC	Future Circular Collider
HEP	High-Energy Physics
HTS	High-Temperature Superconductor(s)
LHC	Large Hadron Collider
MBSE	Model-Based Systems Engineering
Nb–Ti	Niobium–Titanium
Nb_3Sn	Niobium-Tin
NMR	Nuclear Magnetic Resonance
PLM	Product Lifecycle Management
R&D	Research and Development
REBCO	Rare-Earth Barium Copper Oxide
ROXIE	Routine for the Optimization of magnet X-sections, Inverse field calculation and coil End design

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