Forschungsberichte

Institut für Produktentwicklung
am Karlsruher Institut für Technologie

Jens Kaeske

Methodology for the Electromagnetic Design of Superconducting Accelerator Magnets based on the Integrated Product Engineering Model - iPeM

Methodik für den elektromagnetischen Entwurf von supraleitenden Beschleunigermagneten auf der Grundlage des integrierten Produktentstehungsmodells - iPeM

Band 187

Systeme ▪ Methoden ▪ Prozesse

Univ.-Prof. Dr.-Ing. Dr. h.c. A. Albers
Univ.-Prof. Dr.-Ing. S. Matthiesen
(Hrsg.)

Forschungsberichte

IPEK

Institut für Produktentwicklung
am Karlsruher Institut für Technologie

Jens Kaeske

Methodology for the Electromagnetic Design of Superconducting Accelerator Magnets based on the Integrated Product Engineering Model - iPeM

Methodik für den elektromagnetischen Entwurf von supraleitenden Beschleunigermagneten auf der Grundlage des integrierten Produktentstehungsmodells - iPeM

Band 187

Herausgeber Univ.-Prof. Dr.-Ing. Dr. h.c. Albert Albers
Univ.-Prof. Dr.-Ing. S. Matthiesen

ISSN 1615-8113

Methodology for the Electromagnetic Design of Superconducting Accelerator Magnets based on the Integrated Product Engineering Model - iPeM

Zur Erlangung des akademischen Grades eines

DOKTORS DER INGENIEURWISSENSCHAFTEN (Dr.-Ing.)

von der KIT-Fakultät für Maschinenbau des

Karlsruher Instituts für Technologie (KIT)

angenommene

DISSERTATION

von

M.Sc. Jens Kaeske

Tag der mündlichen Prüfung:	31.03.2025
Hauptreferent:	Univ.-Prof. Dr.-Ing. Dr. h.c. Albert Albers
Korreferent:	Dr.-Ing. habil. Stephan Russenschuck

Vorwort der Herausgeber

Wissen ist einer der entscheidenden Faktoren in den Volkswirtschaften unserer Zeit. Der Unternehmenserfolg wird mehr denn je davon abhängen, wie schnell ein Unternehmen neues Wissen aufnehmen, zugänglich machen und verwerten kann. Die Aufgabe eines Universitätsinstitutes ist es, hier einen wesentlichen Beitrag zu leisten. In den For- schungsarbeiten wird ständig Wissen generiert. Dieses kann aber nur wirksam und für die Gemeinschaft nutzbar werden, wenn es in geeigneter Form kommuniziert wird. Diese Schriftenreihe dient seit mehr als 20 Jahren als eine Plattform zum Transfer und macht damit das Wissenspotenzial aus aktuellen Forschungsarbeiten am IPEK - Institut für Produkt-entwicklung Karlsruhe* am Karlsruher Institut für Technologie (KIT) verfügbar. Die Forschung des IPEK ist dabei strukturiert in die Kategorien Systeme, Methoden und Prozesse, um so der Komplexität heutiger Produktentwicklung ganzheitlich gerecht zu werden. Erst die Verknüpfung dieser drei Kategorien ermöglicht die Synthese innova-tiver Systeme durch Nutzung neuester Methoden und Prozesse. Gleichzeitig werden durch die Systemsynthese die erforschten neuen Methoden und Prozesse validiert und deren Mehrwert für die Praxis abgesichert. Dieses Forschungskonzept prägt nicht nur das IPEK-Leitbild, sondern auch den Charakter dieser Schriftenreihe, da immer alle drei Kategorien und deren Wechselwirkungen berücksichtigt werden. Jeder Band setzt hier individuelle Schwerpunkte und adressiert dabei folgende Forschungsgebiete des IPEK:

- das Entwicklungs- und Innovationsmanagement,
- die Entwicklungs- und Konstruktionsmethodik,
- der Leichtbau von der Ebene des ganzen Systems bis hinunter zur Optimierung des Bauteils,
- die Validierung technischer Systeme auch unter Berücksichtigung der NVH Aspekte (Noise, Vibration, Harshness) mit dem Fokus auf Schwingungen und Akustik an Komponenten und in den Gesamtsystemen sowie deren subjektiver Beurteilung durch den Menschen,
- die Antriebssystemtechnik mit den Schwerpunkten komplette Antriebslösungen für Fahrzeuge und Maschinen,
- das Design, die Tribologie und Erprobung von Kupplungen und Bremsen sowie
- die Gerätetechnik mit dem Schwerpunkt auf Power-Tools.

Die Forschungsberichte stellen Ergebnisse unserer Forschung sowohl anderen Wissenschaftlern als auch den Unternehmen zu Verfügung, um damit die Produktentwicklung in allen ihren Facetten mit innovativen Impulsen zu optimieren.

Albert Albers und Sven Matthiesen

* Eh.: Institut für Maschinenkonstruktionslehre und Kraftfahrzeugbau, Universität Karlsruhe (TH)

Vorwort zu Band 187

Das Feld der Produktentwicklung ist gekennzeichnet durch eine enorme Breite. Produkte, verstanden als von Menschen erschaffene Artefakte zur Lösung von Aufgabenstellungen mit einem Beitrag zur Gesellschaft, findet man in allen Lebensbereichen. Während die Produktentwicklung für insbesondere Konsumprodukte, die in großen Stückzahlen hergestellt werden, wie zum Beispiel Fahrzeuge oder auch Mobiltelefone, seit jeher ganz besondere Randbedingungen und Herausforderungen an die Strukturierung und Durchgestaltung der Prozesse erfordert, gibt es andere Bereiche der Produktentwicklung, insbesondere dort, wo es um Sonderanlagen, Sondermaschinen, Einzellösungen, Speziallösungen geht, bei denen häufig eine vollständige methodische Durchdringung des Entwicklungsprozesses und eine Steuerung und Begleitung noch nicht wirklich realisiert sind. Die zunehmende Komplexität und Kompliziertheit der Produkt- bzw. Systemlösungen in allen Bereichen führen aber nun dazu, dass wir im 21. Jahrhundert einen generellen Trend zu einer stärkeren, systemorientierten Betrachtung technischer, mechatronischer oder cyberphysischer Produktlösungen und Systeme angehen müssen. Die notwendigen Methoden und Prozesse dazu sind neu zu gestalten. Im Rahmen der Karlsruher Schule für Produktentwicklung – KaSPro – arbeitet die Gruppe um ALBERS unter den Stichworten Systemgenerationsentwicklung – SGE, Advanced Systems Engineering – ASE, Integriertes Produktentstehungsmodell – iPeM und XIL-Validierungskonzepte durch eine intensive, grundlagenorientierte, aber dann auch in die Praxis eingebundene Forschung, an Lösungsvorschlägen für diese Produktentwicklungswelt des 21. Jahrhunderts.

In diesem Kontext ist auch die Arbeit von Herrn Dr.-Ing. Jens Kaeske angeordnet. Herr Kaeske war als Doktorand am CERN in Genf tätig. Das CERN ist eine internationale Gemeinschaftsforschungseinrichtung, wo insbesondere der große Beschleunigerring betrieben wird. Das CERN unterstützt mit den dort zur Verfügung gestellten Forschungsmöglichkeiten im Beschleuniger weltweit die Grundlagenforschung im Bereich der Physik. So kommen in jedem Jahr viele hundert Wissenschaftler für einen Forschungsaufenthalt an die Einrichtung. Den Beschleunigerring bezeichnet man oft auch als „die Maschine". Sie stellt ein technologisches Unikat dar, das seit mehreren Jahrzehnten kontinuierlich weiter optimiert und entwickelt wird. Diese Entwicklung erfolgt zu großen Teilen durch einen betreuenden Engineering-Bereich des CERN und mit Hilfe von Zulieferern, wobei auch große Fertigungsmöglichkeiten im Bereich des Apparatebaus zur Verfügung stehen. Kernstück der Beschleuniger sind die Magnete. Diese Magnete sind Speziallösungen, die stetig weiter an die Grenzen des Möglichen verschoben werden müssen, um so die Performance des Beschleunigers weiter zu verbessern. Obwohl es sich hier um einen absoluten Sonder-Maschinenbau handelt, der noch dazu in einem extremen grundlagenorientierten Forschungsbereich angeordnet ist, werden auch diese Teilsysteme und Komponenten des Beschleunigers in Generationen - wie es das Modell der Systemgenerationsentwicklung beschreibt - entwickelt.

Herr Dr.-Ing. Kaeske hat seine wissenschaftliche Arbeit im Bereich der Magnetentwicklung am CERN durchgeführt. Hier konnte er durch eine tiefe Analyse der Entwicklungsprozesse und durch eine Lösungssynthese auf Basis der Elemente der Karlsruher Schule für Produktentwicklung – KaSPro den Entwicklungsprozess grundlegend methodisch neu durchdringen. Im Rahmen des Konzepts der Mitarbeitenden Forschenden hatte Herr Kaeske in der Forschungsumgebung des CERN einen ausgezeichneten Zugang zu den relevanten Daten sowie zu den Personen, die in diesem Kontext als Entwickelnde tätig sind. Herr Kaeske hat im Rahmen seiner Forschung eine ganzheitliche, neue Methodik für den elektromagnetischen Entwurf supraleitender Beschleunigermagnete entwickelt und diese mithilfe prototypischer Werkzeuglösungen umgesetzt und eingeführt. Wissenschaftlich für die Forschung in der Entwicklungsmethodik ist der gelungene Nachweis, dass die Konzepte und Ansätze der KaSPro auch im Kontext dieser Anwendung im Sondermaschinenbau genutzt werden können, ein wichtiger Beitrag der Arbeit.

September, 2025 Albert Albers

Abstract

In this thesis, a methodology for the electromagnetic design of superconducting accelerator magnets is introduced. This methodology is based on the integrated Product engineering Model (iPeM) and describes the formalized design steps during the simulation process of such a magnet. To implement the methodology in current simulation workflows, a software tool, the so-called Magnet Model Management Layer (3ML), is prototyped and implemented. The thesis project is carried out at the European Organization for Nuclear Research (CERN), which is at the heart of superconducting accelerator magnet development to provide infrastructure for international High Energy Physics (HEP) experiments. The thesis aims to fill the gap of missing organization-wide, holistic magnet design support methodologies at CERN.

Development challenges in the domain, at CERN as an organization and in the CERN TE-MSC group are identified and quantified. These challenges and their influence on each other are visualized, and success criteria for future magnet design development projects are derived. Knowledge management and transfer are identified as a critical challenge in the superconducting magnet development process. Based on these findings, the methodology, tool support, and integration are carried out. A methodology for the electromagnetic magnet design is introduced. This methodology is in line with existing Systems Engineering (SE) and Product Management (PM) standards at CERN. A dedicated tool support is developed and introduced during a validation test to teach the methodology to its users. Focusing on knowledge management, the model management layer has been implemented with a web interface, enabling all users to organize simulation models and identify reference system elements without having to open a dedicated simulation tool. The Routine for the Optimization of magnet X-sections, Inverse field calculation and coil End design (ROXIE) simulation software is used as an example to demonstrate the integration of Magnet Model Management Layer (3ML) in real-world simulation workflows. Advanced modeling use cases enabled by the new 3ML are explained.

The outlook highlights the improvement potential of 3ML and gives motivation for further tests and validation studies.

Kurzfassung

In dieser Arbeit wird eine Methodik für den Entwurf der elektromagnetischen Aspekte von supraleitenden Beschleunigermagneten vorgestellt. Diese Methodik basiert auf dem integrated Product engineering Model (iPeM) und beschreibt die formalisierten Entwurfsschritte während des Simulationsprozesses eines solchen Magneten. Zur Implementierung der Methodik in aktuelle Simulationsabläufe wird ein Software-Tool, der sogenannte Magnet Model Management Layer (3ML), konzipiert und implementiert. Das Dissertationsprojekt wird am CERN durchgeführt, welches im Zentrum der Entwicklung supraleitender Beschleunigermagnete steht, um die Infrastruktur für internationale HEP-Experimente bereitzustellen. Die Dissertation hat das Ziel, die Lücke der fehlenden organisationsweiten, ganzheitlichen Methodiken Entwicklungsunterstützung in diesem Bereich im Allgemeinen und am CERN im Besonderen zu schließen.

Entwicklungsherausforderungen in der Domäne, dem CERN als Organisation und in der CERN TE-MSC Gruppe werden identifiziert und quantifiziert. Diese Herausforderungen und ihr Einfluss aufeinander werden visualisiert und Erfolgskriterien für zukünftige Entwicklungsprojekte in diesem Bereich abgeleitet. Wissensmanagement und -transfer werden als kritische Herausforderung im Entwicklungsprozess für supraleitende Magnete identifiziert. Basierend auf diesen Erkenntnissen werden die Methodik, der Tool-Support und die Integration durchgeführt. Eine Methodik für den Entwurf elektromagnetischer Magnete wird vorgestellt. Diese Methodik steht im Einklang mit den bestehenden Systems Engineering (SE) und Product Management (PM) Standards am CERN. Ein Tool-Support wird entwickelt und im Rahmen eines Validierungstests eingeführt, um den die Methodik den Anwendern zu vermitteln. Mit dem Fokus auf Wissensmanagement wurde der Magnet Model Management Layer (3ML) mit einer Webschnittstelle implementiert, die es allen Benutzern ermöglicht Simulationsmodelle zu organisieren und Referenzsystemelemente zu identifizieren, ohne ein spezielles Simulationswerkzeug öffnen zu müssen. Das Routine for the Optimization of magnet X-sections, Inverse field calculation and coil End design (ROXIE) Programm wird als Beispiel verwendet, um die Integration von 3ML in reale Simulations-Arbeitsabläufe zu demonstrieren. Es werden fortgeschrittene Modellierungsanwendungsfälle erläutert, die durch die neue Software ermöglicht werden.

Der Ausblick zeigt das Verbesserungspotenzial von 3ML auf und motiviert zu weiteren Tests und Validierungsstudien.

Acknowledgements

This thesis is the result of my time as a doctoral student at CERN in Geneva. During this time, I was fortunate to be part of a vibrant and supportive research section within the organization. Both I and this thesis greatly benefited from that environment, and I am convinced it was one of the main reasons the project could be completed successfully.

I would like to express my deepest gratitude to **Stephan Russenschuck**, the leader of this research section, for fostering such an open and productive atmosphere. Throughout my time at CERN, he was always present for his students and contributed to every aspect of our work—not only with his extensive expertise but also with his humor and personal commitment. I could not have wished for better guidance.

Special thanks go to **Professor Albers**, whose efforts made the collaboration between IPEK and CERN possible across national borders, overcoming the challenges that come with such a decentralized project.

I am deeply grateful to **my parents**, who supported me throughout my time at KIT and have been a cornerstone of my education—both in general and in the specific context of this thesis.

To **my best friend Patrick**, thank you for always being there for me. From countless relocations to maintaining our friendship over the years, your support has meant a great deal.

Finally, to **my partner Francesca**, who stood by my side throughout my time at CERN—thank you for being there during both the beautiful moments and the difficult ones. Your presence and support made Geneva feel like home.

This work has been sponsored by the Wolfgang Gentner Programme of the German Federal Ministry of Education and Research (grant no. 13E18CHA).

Lucerne, the 18th of April 2025
Jens Kaeske

Perfection is attained not when there is nothing more to add but when there is nothing more to remove.

(Antoine de Saint-Exupery, 1939)

Contents

List of Figures

List of Tables

List of Abbreviations and Acronyms

3ML	Magnet Model Management Layer
API	Application Programming Interface
ARC	Areas of Relevance and Contribution
ASE	Advanced Systems Engineering
BSCOO	Bismuth Strontium Calcium Copper Oxide
CERN	European Organization for Nuclear Research
DRM	Design Research Methodology
EDMS	Engineering & Equipment Data Management Service
FCC	Future Circular Collider
HEP	High Energy Physics
HTS	High-Temperature Superconductors
IDSDM	Integrated Design Support Development Model
INCOSE	International Council on Systems Engineering
IPEK	Institute of Product Engineering
iPeM	integrated Product engineering Model
ISTQB®	International Software Testing Qualifications Board
KaSPro	Karlsruhe School of Product Development
KIT	Karlsruhe Institute of Technology
LHC	Large Hadron Collider
MBSE	Model-Based Systems Engineering
Nb_3Sn	Niobium-Tin
Nb-Ti	Niobium–Titanium
PGE	Product Generation Engineering
PLM	Product Lifecycle Management
PM	Product Management
REBCO	Rare-Earth Barium Copper Oxide

ROXIE	Routine for the Optimization of magnet X-sections, Inverse field calculation and coil End design
SE	Systems Engineering
SEM	Systems Engineering Management
SGE	System Generation Engineering
SoS	System of Systems

1 Introduction

Particle accelerators are crucial tools in various fields, including physics, chemistry, and medicine (Amaldi, 2000). They are used to accelerate charged particles to high energies and provide these sped-up particles to various experiments (Carter, 2011). Such accelerators have contributed to numerous Nobel Prizes and have a wide range of applications, such as cancer treatment, isotope production, and radiation processing of food (Resta-López, 2022). In high-energy physics research environments, such as CERN, they are used to investigate subatomic matter and help gain insights into evolution since the Big Bang (Mazzitelli, 2011).

The maximum collision energy in a circular accelerator is directly related to its radius and the strength of the main dipole magnets. Hence, developing magnets with the highest possible magnetic field for a given accelerator radius becomes one of the key objectives in circular collider research projects (Kalmus, 1986). With this pursuit, historically used and proven superconductor materials need to be replaced, and new technologies must be constantly evaluated and introduced to keep up with the high collision energy requirements of the accelerator machines. Pursuing these constantly increasing magnetic fields presents significant challenges for accelerator magnet research and development programs, such as long-term sustainability, accountability within international collaborations, and organizational hurdles. These research programs require parallelization and coordination, which can be difficult due to project durations lasting up to a decade (Prestemon et al., 2020). Additionally, the stability and continuity of research groups become difficult due to the long lead times required for these projects (the FCC Collaboration et al., 2019). The development of new generations of accelerators is characterized by high investment costs for large-scale infrastructure, coordination of interdisciplinary research teams, and industrial collaborations. Managing and transferring knowledge in a large-scale, high-tech environment with multi-decade projects is a significant challenge.

CERN introduced the Engineering & Equipment Data Management Service (EDMS) system in the year 2000 as the organization-wide knowledge-management solution (Boyer et al., 2002) to cope with a growing amount of documents and engineering data. EDMS is CERN's official Product Lifecycle Management (PLM) solution used for every project, from small research studies up to large-scale, long-term projects such as the Large Hadron Collider (LHC) and Future Circular Collider (FCC). With the growing complexity of accelerator projects and international collaborations, the data stored on EDMS grew exponentially. By 2015, EDMS reached over 2 million files by over 6 thousand active users (Wardzinska et al., 2015). It has been observed that in previous accelerator projects, the significance of production, testing, and measurement data may not be immediately apparent until a later stage in the accelerator's operation. To bridge the gap between system development cycles in accelerator projects, EDMS was created to make data available to the next generation of engineers (Wardzinska et al., 2015). EDMS provides a capable, interconnected tool to store documents and data. To date, standardized methods and best practices for organizing these documents have been missing, resulting in heterogeneous data structures and difficulties retrieving historical data.

To replace these traditional document-based development approaches, Model-Based Systems Engineering (MBSE) becomes more popular in Systems Engineering (SE). The shift towards MBSE in industry is driven by the need to manage complexity in developing integrated systems. Advanced Systems Engineering (ASE) empowers enterprises to cope with complex developments and brings together three key components: Advanced Systems, Advanced Engineering, and Systems Engineering (Dumitrescu et al., 2021). ASE provides a context for integrating modern engineering approaches and tools to develop intelligent, cyber-physical systems with high autonomy, interconnectedness, and socio-technical interaction, often as part of a larger System of Systems (SoS). MBSE is a widely used approach to implement ASE, conquering complexity by integrating IT or data management with different views of organizational structures and processes and enabling use-case definitions and validation of systems in several industries from small to large companies (Masior et al., 2020).

In the field of superconducting accelerator magnets, the adoption of MBSE practices is not as widespread as in industries such as aerospace and automotive (Dumitrescu et al., 2021). While initial steps towards MBSE in numerical magnet simulation have been taken (Maciejewski et al., 2023), they are still in the early prototype phase and have not been widely implemented within CERN's research environments.

However, document-based approaches and MBSE practices alone are no silver bullet for holistically handling rising system complexity. Enterprises and organizations are generating an increasing number of system model files through MBSE. With the increasing amount of data, there is a need to solve the issue of how to acquire the knowledge conveyed by the system model and reuse it effectively across system generations (Fu et al., 2021). Effectively handling the system models and iteratively improving them requires tools, best practices, customized methods, and an aligned company strategy. At the moment of this writing, no specified solution or database management tool exists to store, manage, and retrieve magnet system models for the organization-wide adoption of MBSE at CERN. During the shift towards ASE and MBSE, organizational and structural issues in the domain become increasingly important, and acceptance by experts and technicians in the field can only be reached by simplifying IT infrastructure and making simulation software more user-friendly (Dumitrescu et al., 2021).

The successful integration of MBSE practices in an organization requires a tailored approach that addresses specific challenges and opportunities. Papke et al. (2020) emphasizes the need for an enterprise approach, guided by enterprise architecture, to address issues such as skill and competency requirements, model and data management, and integration with other engineering tools and processes. Mabrouk et al. (2018) further underscores the importance of integrating agility into MBSE methodologies, particularly for multidisciplinary systems design. Pratt and Dabkowski (2022) identify key factors and moderators, such as upfront investment, legacy methods, and organizational support, that influence the adoption of MBSE in the aerospace industry. These sources underscore the need for a tailored methodology considering the organization's specific context, challenges, and opportunities.

This thesis aims to carry out the foundational work for such a tailored methodology for superconducting accelerator magnets and provide prototype tool supports that enable and promote the adoption of MBSE for the magnet development process. Tailored methodologies and tools to handle the rising complexity in the magnet development domain will improve the design process at CERN and support magnet designer during their daily workflows. The respective customization and modeling methods introduced in this thesis serve as a starting point for other research institutes to create similar, tailored methodologies. The validation studies and motivation for this thesis project can be used to raise general awareness of the need for customized design support and streamlined knowledge management to cope with the growing complexity of accelerator systems.

1.1 Thesis Focus

The development of magnets is a complex process that involves several new technologies leading to various technical and integration challenges (Barna et al., 2019;

Ferchow, 2021; Ferrentino, 2020; Hoell, 2022). These sources provide detailed technical information on identified problems and their solutions. To overcome these technical challenges, computational support is required in the design process, including electromagnetic and mechanical design and multiphysics simulations to study quenches and respective magnet protection systems. The importance and computational needs of these simulations in the design process are described by (Russenschuck, 2025).

A software package called Routine for the Optimization of magnet X-sections, Inverse field calculation and coil End design (ROXIE) was developed at CERN in 1995 to meet these computational demands of the electromagnetic design. It offers an easy-to-use interface for magnetic field optimization. The introduction of ROXIE highlighted the need for a more integrated design process. The program has since been extended to integrate with commercial programs and Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) systems and now addresses more general problems related to the knowledge transfer process and the traceability of the simulation models. (Russenschuck, 1995, 2025).

The focus will be on the electromagnetic simulation within the magnet design process to achieve tangible results within the research project's time frame. It would not be feasible to focus on all the parts of the multiphysics simulation needs of modern magnet design, including mechanical and thermal simulation, for example. Carrying out the project in the TE-MSC group at CERN, where the active software development of ROXIE is carried out, is in line with the focus on electromagnetic design. New findings can be directly validated in this environment by integrating them as beta features within the ROXIE simulation software. In contrast to the majority of research articles in the domain of superconducting magnets, the thesis should not exclusively focus on technical minutia but include the foundational and theoretical work required to integrate a design methodology. Integration studies should be carried out for the practical parts of the projects, proofs of principle should be introduced, and the scope of the thesis should stay at a conceptual level.

The Design Research Methodology (DRM) by Blessing and Chakrabarti (2009) introduces the so-called Areas of Relevance and Contribution (ARC) diagram. ARC diagrams have proven useful in past research projects by helping to clarify the foundation and areas of contribution (Blessing & Chakrabarti, 2009). Such a diagram is shown in Figure 1.1 and was created based on this section to serve as a guide for the prescriptive steps of the present thesis.

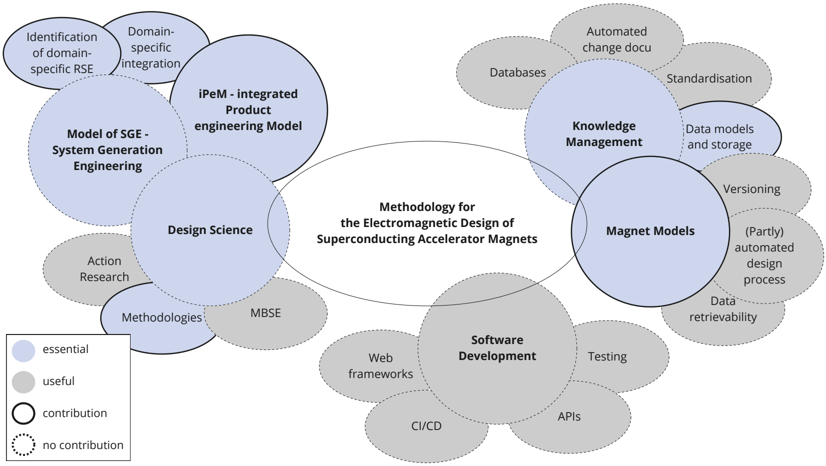

Figure 1.1: ARC diagram with this thesis project's most relevant research areas. The acronyms used in this figure are *Model-Based Systems Engineering (MBSE)*, *Continuous Integration and Continuous Delivery/Deployment (CI/CD)*, *Reference System Elements (RSE)* and *Application Programming Interface (API)*

1.2 Thesis Structure

This thesis is structured in seven chapters. The thesis structure follows the stages and artifacts of the Integrated Design Support Development Model (IDSDM). The IDSDM is a heuristic design support to structure and carry out thesis projects and will be explained in detail in Chapter 3.3.1. These chapters and their dependencies on each other are explained below, starting with Chapter 2.

Chapter 2 explains the *State of Research* and provides the necessary background and general concepts for the thesis. It covers various aspects of the domain of design science, Systems Engineering, and superconducting accelerator magnet design to help grasp the context and foundations of the research.
Chapter 3 outlines the *Research Design* that was taken throughout the thesis project to obtain the desired results. It explains the research objectives, guiding questions, empirical methods, and overall research methodology that structures the thesis. CERN and the magnet and superconductor group are briefly introduced as the research environment. The outcome of Chapter 2 and Chapter 3 in combination is, in

the parlance of IDSDM, the initial system of objectives and the research project plan.
Chapter 4 quantifies the *Identification of Magnet Development Challenges* in the domain of superconducting accelerator magnets and the specific research environment at CERN. These challenges are used to understand the initial situation and to derive success criteria for this and other future projects. The chapter starts by describing the development process of magnetic transducers during two separate case studies. The initial challenges identified during these studies provide an entry point for the research project and are being extended and quantified later. During the quantification part of the chapter, the domain challenges, organization-specific challenges, and practical design challenges are identified and explained. The chapter concludes by creating a reference model to determine the relationship between the challenges and derive success criteria for the research project. In the IDSDM, Chapter 4 corresponds to the activity of analyzing real-world design processes.
Chapter 5 builds on the findings from the quantified development challenges and explains the foundation and steps to create a *Concept of an Electromagnetic Design Methodology* for the design of superconducting accelerator magnets. An IDSDM transfer study is carried out to find a way to communicate and explain the magnet design methodology to the involved personnel, as it is key to each theoretical methodology.
Chapter 6 takes the foundational work from Chapter 5 and introduces *Development of an Integrated Tool for Magnet Model Management* with an according database as the central storage and management place for magnet models. This integration and development is based on challenges identified in Chapter 4 and provides a way to conduct an experimental study of the methodology to analyze the outcome and achieved impact of the design support. With the methodology and tool support in Chapter 5 and the magnet model management tool in Chapter 6, both chapters contain a design support embodiment step which the IDSDM classifies as the core synthesizing activity of the operation system.
Chapter 7 builds up on the findings from throughout the research projects and gives a final *Conclusion*. A critical view of the results and motivation for work to be done in the future is given.

A visual representation of the thesis structure is shown in Figure 1.2.

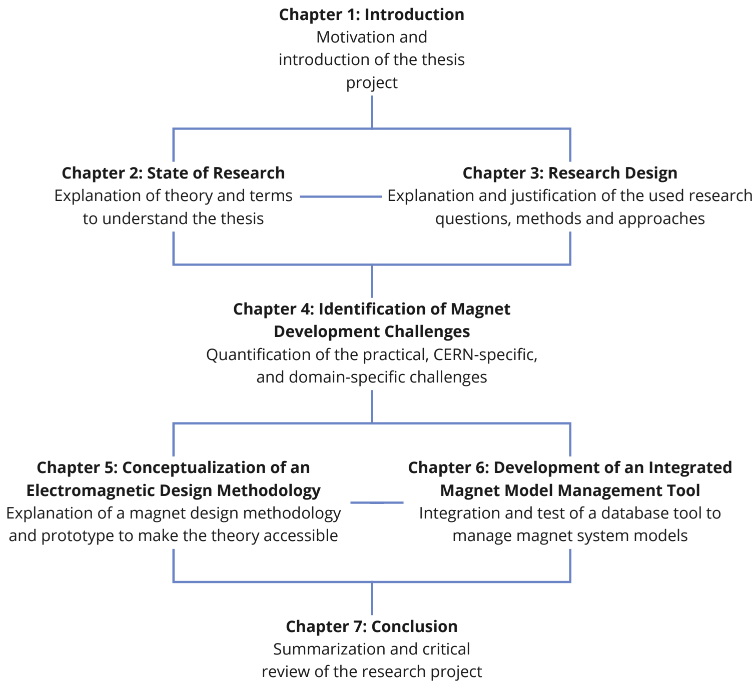

Figure 1.2: Structure of the present thesis and the dependencies between the chapters.

2 State of Research

The explanation of the current state of research starts with superconducting accelerator magnets, their periphery and test, measurement, and their development at CERN. With the knowledge gained about high-field magnets, the field of design research will be investigated, and existing approaches to integrating design science in magnet development will be explained.

2.1 Superconducting Accelerator Magnet Design

High-field accelerator magnets are crucial for advancing high-energy physics (Russenschuck, 2025). They enable circular accelerator operation by guiding and confining particle beams within a defined trajectory and volume. With the accelerator energy directly related to the collider radius and the magnetic field strength of the dipole, these magnets are essential for collider projects and, thus, for expanding the potential for physics discoveries.

Traditional electromagnets face limitations due to Joule heating, which restricts their maximum achievable current density. Superconductivity, discovered in 1911 by H. Kamerlingh-Onnes, was first usable decades later in the form of superconducting magnet coils and revolutionized the domain (Van Delft & Kes, 2010). Zlobin and Schoerling (2019) report that over time, stable and protected superconducting materials and designs could be developed by overcoming challenges like quenches and flux jumps. These advancements include the introduction of composite superconductors that combine small superconducting filaments within a conductive matrix to manage heat and ensure stability against magnetic disturbances. Innovations like this have enabled the creation of superconducting accelerator magnets that meet the rigorous demands for field uniformity, cooling efficiency, and performance crucial for exploring fundamental physics.

Barzi and Zlobin (2019) state that historically, Niobium–Titanium (Nb-Ti) was the most commonly used superconducting material within accelerator magnets and is used today in most operating accelerators. In the past decades, the Nb-Ti superconductor was the widely used material; many accelerator machines currently operating rely on this proven technology. The maximum air-gap flux density with this proven Nb-Ti superconductor reaches its limit at around 8-9 T. This creates the need to search for new superconducting materials and technologies with higher theoretical and technical flux density limits. One such new superconducting material is Niobium-Tin (Nb_3Sn).

The goal for accelerator-type magnets using Nb_3Sn superconductor is to achieve dipole fields of 12-16 T (Todesco et al., 2021). Current research efforts worldwide are intended to improve the reliability and robustness of Nb_3Sn to make this technology viable for series production. High-Temperature Superconductors (HTS) like Rare-Earth Barium Copper Oxide (REBCO) and Bismuth Strontium Calcium Copper Oxide (BSCOO) 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 (Ferracin et al., 2023; the FCC Collaboration et al., 2019).

2.1.1 CERN

CERN, the European Organization for Nuclear Research, is a leading particle physics research center that aims to understand the fundamental particles of the universe and their behavior (Turner, 2000). Its most significant accelerator, the LHC, is a key tool in this pursuit. CERN's work has led to significant scientific advancements, including the development of the Worldwide Web. The organization's commitment to peaceful research and collaboration is evident in its international membership and partnerships (Robertson, 1981). Apart from its groundbreaking discoveries like the internet, CERN is currently mainly in the spotlight for the operations of circular colliders. The largest circular collider in the world, the LHC, has a circumference of 27 km. It is part of CERN's accelerator complex and made big news, observing an entirely new particle, the so-called Higgs boson (Aad et al., 2012). CERN continues its constant advancements in fundamental research, the first-ever antimatter cooling using laser light in the Alpha experiment (CERN, 2021), or the discovery of another new particle, the so-called doubly charmed baryon (CERN, 2017). To reach higher collision energies, CERN is currently conducting a feasibility study for the ambitious 100 km circumference FCC collider (the FCC Collaboration et al., 2019). A size comparison between these two colliders is shown in Figure 2.1.

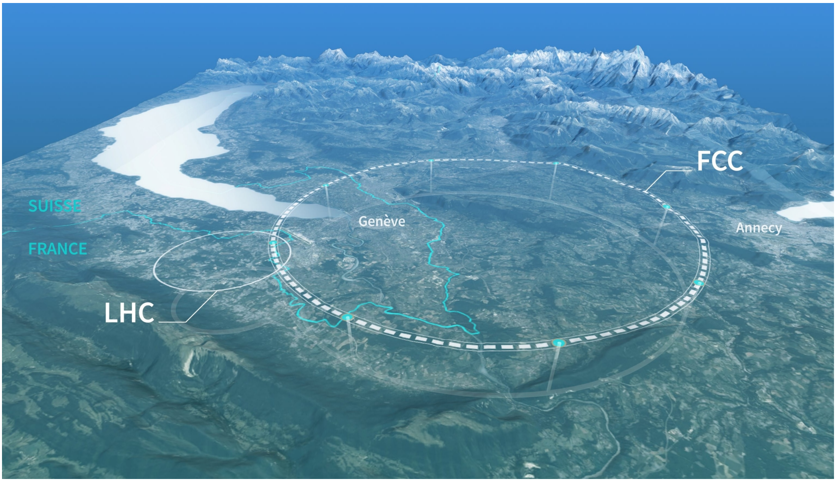

Figure 2.1: Size comparison between the LHC and FCC illustrated on top of a map of Geneva (CH) and its surroundings. From "Future Circular Collider" by CERN (2024a).

Particle accelerators can be considered Systems of Systems (SoS) due to their complex nature involving multiple interacting systems (Friedrich et al., 2017). These accelerators consist of various components, such as acceleration cavities, control means, and multipole magnets, that work together to accelerate particles effectively. Figure 2.2 shows the accelerator SoS and highlights the superconducting magnets and respective measurement devices, the so-called transducers, as the project-relevant subsystems.

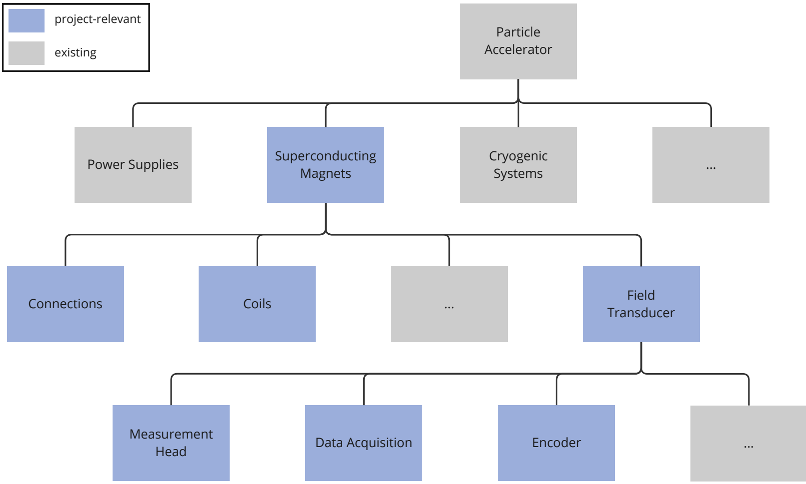

Figure 2.2: The accelerator complex is a System of Systems, including the accelerator magnets and field transducers as subsystems.

Being one of the most expensive accelerator subsystems, the magnet system is the main cost driver for the domain of HEP research. Developing these magnet systems requires complex multi-physics simulations. Because of this scientific interest in magnet systems and the conduction of the thesis project in the group for magnets, superconductors, and cryostats at CERN, the thesis focuses mainly on the magnet system as a subsystem of a particle accelerator (Russenschuck, 2025). The research environment in which the results for this project have been obtained is introduced in Chapter 3.1.

2.1.2 Field Simulation

With all their peripheral subsystems and protection systems, accelerator magnets encompass multiple disciplines. The successful magnet design thus requires simulations in the magnetic, thermal, geometric, and mechanic domains. Various simulation tools such as ROXIE, ANSYS, or Steam with different purposes exist for these diverse simulation needs and domains. The common outcome of these simulation domains is a system model with a certain degree of accuracy and complexity.

The operation of superconducting magnets can result in fast transients during a quench. These transients can cause high mechanical stress and amplify with superconductor advances, resulting in higher magnetic fields. With the rising magnetic fields, quench protection becomes more complex, and interconnected simulations across multiple domains are needed to mitigate the risks and design challenges. These so-called multi-physics numerical models link the domains from above and include geometric, thermal, mechanical, and electromagnetic components (Brouwer et al., 2019; Maciejewski et al., 2023). Combining these domains and simulating non-linear transient effects in superconducting accelerator magnets is a complex issue. It is characterized as multi-domain, multi-physics, multi-rate, and multi-scale, involving the magnet, its circuits, and the power converter controller. The resulting models must regard multiple interconnected physical phenomena, which is only possible with a simulation infrastructure that allows model-order reduction and information exchange between the different involved software packages (Brouwer et al., 2019; Maciejewski, 2019; Troitino et al., 2021).

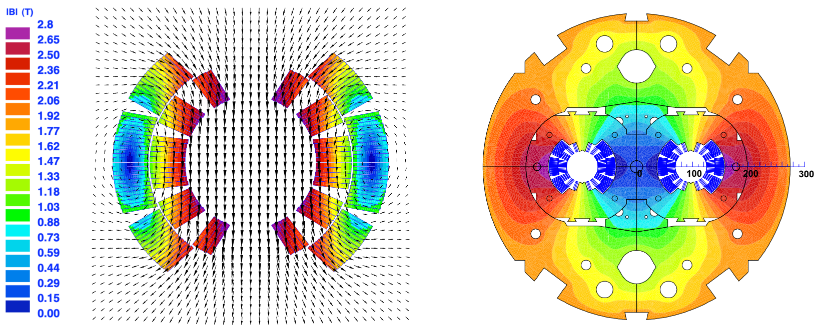

Figure 2.3: ROXIE simulations of LHC dipoles. The coil cross-section with the field map is shown on the left and a different variant of the cross-section as a two-in-one magnet version with the iron yoke and common mechanical structure on the right. Adapted from “Field Simulation for Accelerator Magnets” by Russenschuck (2025).

To give an example of the described simulations, Figure 2.3 shows two 2D simulations of LHC dipole magnet cross-sections. The simulations originate from the ROXIE simulation environment and show the magnetic field distribution in the coils, collars, and yoke.

2.1.3 Test & Magnetic Measurement

Simulations alone are often insufficient to characterize and understand the dynamic behaviors within a superconducting magnet. Lack of information, the coupling of dynamic and hysteretic effects, or the need for magnet production quality assurance make magnetic testing a vital part of the magnet development workflow (Mierau et al., 2018; Russenschuck, 2025).

Magnet measurement devices are often referred to as *field transducers*. A general transducer is defined as a device that converts one form of energy into another. Following this definition, a field transducer converts energy as a magnetic field into an electrical signal measurable as a voltage. Post-processing calculates the measured voltage back into the field strength, measuring important magnet characteristics such as field conformity, overall field strength, and magnetic flux values. Multiple types of magnetic transducers exist, and there is no ”one size fits all” type for the various measurement objectives. The type of transducer needs to be selected according to the desired measurement values and external boundary conditions, such as the shape and size of the magnetic field domain and the environment in which the measurement has to be performed. A combination of the results of multiple types of transducers type is a common practice and is referred to as *sensor fusion*. The most common transducers are single stretched wire systems, induction coil magnetometers, nuclear magnetic resonance probes, and hall sensors (Russenschuck, 2025).

Figure 2.4: Cryogenic, horizontal test benches with different LHC magnets in different measurement stages. From "LHC dipole testing facility completed" by Brice (2004).

Measuring the magnetic field of superconducting magnets, such as the LHC dipole of which the simulation is shown above, is not straightforward. Large infrastructure is necessary to perform these kinds of tests. Special measurement test benches, sophisticated data acquisition hardware and software, various power converters, and a cryogenic system providing cooling with liquid helium are needed. A laboratory providing the necessary measurement infrastructure, the so-called SM18 at CERN, is shown in Figure 2.4.

2.2 Design Science and Systems Engineering

Design science is a research field that investigates the design process and its components. It focuses on collecting and improving design-related knowledge, while also conducting research to support practical designers and design organizations (Gregory, 1966).

This definition provides a comprehensive understanding of the field but might not be easy to comprehend. Taking a step back to the motivation for design science, Benavides (2012) argues that a product can only be successful if the design process has been successful. He points out that a poor design process always leads to a poor product. Design science aims to answer the question of how to design such a good design process. It provides a framework for establishing a common language for the design process and the lessons learned throughout it. Design science makes these lessons sustainable and applicable for future design cycles in the form of derived principles or best practices. Benavides (2012) states that ”design science can be understood as the body of knowledge obtained through observation and reasoning, which is systematically structured and from which general principles and laws are deduced”. With this definition, two general objectives can be defined for design science projects (Blessing & Chakrabarti, 2009):

1. Modeling the design process, including resources such as systems, knowledge, and the organization that are related to it.

2. Improving design practice by deriving specialized design support based on the created models from the previous objective.

Marxen (2014) also mentions various difficulties of design science due to its missing maturity as well as missing terminologies or standard methodologies in the field. These missing standards make it difficult for researchers to prove the usefulness of their design science research and lead to general criticism, especially in industry. He states that humans have a central role in design science and development projects and that new design support always needs to be empirically validated in practical projects to mitigate the often overly theoretical nature of design support. Development projects of such sort can be commonly classified as systems engineering projects.

The International Council on Systems Engineering (INCOSE) defines SE as ”a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods” (Sillitto et al., 2019, p. 5).

While SE and design science are closely related and depend on each other, the distinction between the two terms becomes apparent in the INCOSE definition. SE is used to develop systems and encompasses all executive steps along the whole system development lifecycle using previously validated methods and best practices. These methods and best practices are artifacts resulting from formal design science research. Combining the two fields during a system development project is often referred to as *action research*, in which the findings from a development project are translated into theoretical knowledge and methods that, at the same time, can also be validated during the development lifecycle (Blessing & Chakrabarti, 2009).

SE can be described as a holistic approach to engineering new systems, and the outcome of a SE project is always an engineered system. A system does not necessarily have to be technical. It can include people, services, or other types of information. The purpose of this system is to function effectively within its anticipated operational environment and to achieve one or more predetermined objectives while adhering to all relevant boundary conditions (Sillitto et al., 2019). In the context of this thesis, the main engineered systems of concern are the superconducting accelerator magnets and their peripheries.

After this introduction to design science and systems engineering, we want to explore the project-relevant aspects of these domains further. To begin with, some general terms and wording conventions shall be given to make the design support and artifacts developed in this thesis understandable. After that, models and systems will be introduced in the context of accelerator magnets, and a general introduction to process and product models will be given. This thesis mainly focuses on the magnet design process and the potential improvements that can be made. The following introductions and term definitions will mainly be given in the context of the Karlsruhe School of Product Development (KaSPro). This is to avoid giving extensive explanations for certain aspects that are not of primary importance for this project.

2.2.1 Terms and Wording

Gerrike et al. (2017) provided explanations for the terms *methodology*, *process*, *method*, *guideline*, and *tool*, which were later summarized by Kaeske, Fiscarelli, et al. (2024). These terms are frequently used in the context of design science and are central to the discussions in this thesis. Despite their ubiquity in the domain, there is no universally accepted definition for these terms. The definitions provided by Gerrike et al. (2017) are just one of many interpretations but will be used consistently throughout this document. To establish a common understanding for the reader, the summarized definitions by Kaeske, Fiscarelli, et al. (2024) will be revisited in this chapter.

- A **design methodology** is a defined approach for creating designs for specific types of systems. It includes information artifacts, design activities, methods, management processes, and priorities in design thinking. The methodology can be seen as the overarching supersystem of all the here-defined terms.

- A **design process** refers to a set of structured and intentional actions taken to create a design or solution for a particular problem. This process is established within a design methodology and usually involves research, ideation, prototyping, testing, and refinement phases. Following a systematic approach enables the creation and enhancement of a system design.
- A **design method** is an approach or technique used to solve a specific design problem or, more generally, achieve a desired outcome. Methods guide the task performance, describe how to use information, and define the sequence in which the tasks should be performed. A well-defined method can effectively answer the questions of who, what, when, where, why, and how.
- A **guideline** is a set of recommendations or principles. These recommendations guide the designer's approach to a particular task or situation and help the decision-making. A guideline adheres to industry best practices, making it a standard for data-driven decision-making processes.
- A **tool** is an object, physical or digital, that is used to execute design-related tasks. Since they can be specifically made to implement and support certain methods, guidelines, processes, or approaches, they are often referred to as tool supports. Design elements or artifacts, in general, are the outcome of using such a tool support.

In summary, a design methodology provides the foundation for the design process, which customizes the methodology for a specific problem. Design methods operationalize the design process and describe the execution of a process's steps. Guidelines help the designer to make decisions according to best practices. Tools are used actually to perform a design process step; this could be, for example, a software tool like Excel to perform a certain analysis. Figure 2.5 shows this relationship between the terms.

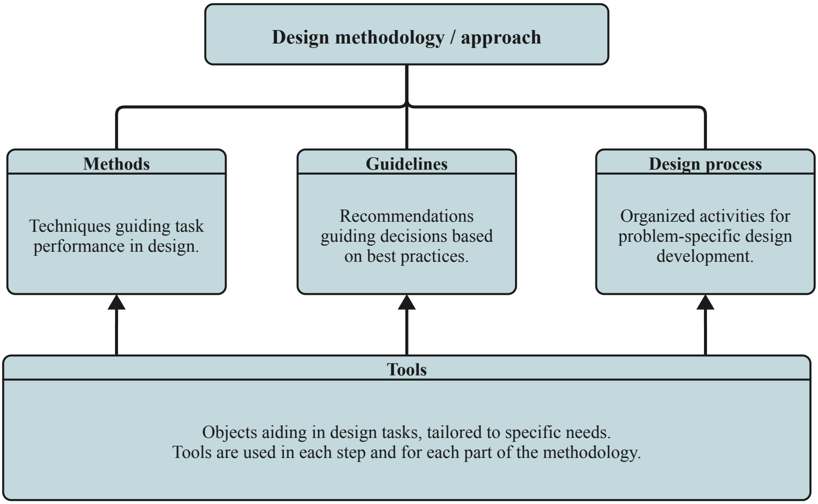

Figure 2.5: Relationship and hierarchy of the frequently used terms *methodology*, *process*, *method*, *guideline*, and *tools*. A short description is given for each of them. From "Overview of identified challenges in the development process of superconducting accelerator magnets" by Kaeske, Fiscarelli, et al. (2024).

2.2.2 Models and Systems

Systems

Systems are the fundamental building blocks of SE. In the classic, general system theory, Bertalanffy (1969) realized that a higher order system cannot be characterized by simply summing up the characteristics of lower order systems. Rather, the relationships between the constituents need to be considered to derive a higher-order system. These findings were summed up to the classic system theory providing the linchpin for the modern design of systems and its subsystems (Bertalanffy, 1969). These generic findings were used in a technical sense to create the classic system theory, which is referred to as the widely spread term Systems Engineering (SE).

According to the technical interpretation of system theory, three distinct concepts can be identified: functional, structural, and hierarchical (Ropohl, 2009).

- The **functional concept** describes the system as a black box. The characteristics of this black box are described by its interaction with the environment through inputs and outputs and by its internal state.
- The **structural concept** introduces the term "emergence", describing the fact that a system is more than the sum of its constituents. The system is described by its elements and the relationships between them.
- The **hierarchical concept** introduces the concept of subsystems and supersystems. The fact that each system can be successively split into smaller and smaller subsystems is called the "fractal character" of a system.

Ropohl (2009) used these concepts to define a general system:

> A system is a model of a whole that (a) has relationships between attributes (inputs, outputs, states, etc.), (b) consists of interlinked parts or subsystems, and (c) is delimited from its environment or a supersystem.[1]
> (p. 77)

Only looking at the systems and development artifacts is not a suitable strategy to fully understand technology. Technology needs to be understood as a socio-economical system in which the technical system corresponds and interacts with the surrounding nature and society. In this socio-technical system and the associated development process, Albers et al. (2013) emphasize the central role of human participants. New development of systems and methods is only possible with understanding the human as a central element of this development process (Albers et al., 2013).

Models

In the context of SE, models play a vital role. Models are used in every aspect of the design process, for example, to simulate systems and gain knowledge about them or to describe development processes and make these processes available as knowledge throughout the entire organization.

According to the general model theory defined by Stachowiak (1973), a model can be described using three characteristics. These characteristics are called reduction

[1] Direct translation from original German source.

characteristic, mapping characteristic, and pragmatic characteristic[2], and will be explained below.

- The **mapping characteristic** states that models are always representations of an original. These originals can also be models, either natural or artificial.
- The **reduction characteristic** states that models do not capture all attributes of the represented original, only those deemed relevant by the creators or users of the model.
- The **pragmatic characteristic** states that they are not necessarily associated with a specific original but rather serve as a substitute for the original by fulfilling a certain purpose within a specific period, for certain subjects, and with certain operational restrictions.

Bringing this back to the context of accelerator magnets, a model representing a physically existing magnet is classified as an ”as-built” model. The fact that the model models an existing magnet is contributed to the mapping characteristic. A model of this as-built model that only represents the 2D cross-section of the magnet and disregards other parts and effects is an example of the original being a model by itself. Referring back to Chapter 2.1.2, a ROXIE model for optimizing the coil windings to achieve a desired magnetic field describes the reduction characteristic by leaving out other effects, such as the thermal influences. Neglecting the thermal influences or only simulating certain magnet parts, such as the end spacers or the windings in a two-dimensional simulation, can be a valid option in certain magnet design steps and describes the pragmatic characteristic of magnet models.

However, complex development processes and large organizations like CERN require more than single, independent magnet models to build the required accelerator infrastructure. The steps in the development process itself need to be modeled, and system models[3] need to be linked to simulate the beam operation and gain further insights by coupling multiple simulation domains.

[2] Direct translation from the German words: Verkürzungsmerkmal, Abbildungsmerkmal, and pragmatisches Merkmal.

[3] System models are often referred to as product models in the design science literature. In this thesis, the term *system models* was chosen since physical magnets and non-physical objects such as software packages or databases are of interest.

2.2.3 Model-Based Systems Engineering (MBSE)

Novel concepts and approaches are necessary to achieve this coupling of different system models and handle the growing complexity of magnet modeling. Advanced Systems Engineering (ASE) serves as the context for combining the approaches and tools needed in today's magnet design and engineering. ASE combines three key components: Advanced Systems, Advanced Engineering, and Systems Engineering (Dumitrescu et al., 2021). The MBSE concept is a discipline within ASE and is used to achieve a paradigm shift from unrelated, document-based models to linked models with a consistent data structure (Mandel, Wäschle, et al., 2021). MBSE utilizes formalized system models to support and enhance SE tasks throughout a system's life cycle (Kossiakoff et al., 2020). Developing a comprehensive system model requires three fundamental components: a modeling language that provides a standardized means of expressing the system's characteristics, a modeling tool that facilitates the creation and manipulation of the model using the chosen language, and a structured method or framework that guides the effective application of the modeling language to represent the system accurately (Mandel, Böning, et al., 2021). These models, typically expressed in a standardized language such as SysML, consolidate system information and provide primary SE artifacts, enabling the standardized integration of system knowledge across engineering disciplines and subsystems (Delligatti, 2014; Matthiesen et al., 2014). MBSE is increasingly recognized as a crucial aspect of systems engineering projects, with a growing emphasis on its application at the system of systems (SoS) level (Holt et al., 2015).

MBSE brings benefits to development projects by providing a common knowledge exchange medium for engineering processes and tasks. MBSE aims, as a holistic modeling approach, to establish a central, single source of truth and enables a fully integrated system modeling process (Madni & Sievers, 2018). The International Council on Systems Engineering (INCOSE) defines MBSE as "the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases" (INCOSE, 2007, p. 15). The key modeling concept of MBSE lies in the separation between the actual model and the so-called views. A view takes the data from a model and displays them in a certain context, only using the necessary data. This has the advantage that the model itself stays consistent and serves as a single source of truth for the views, which can be adapted according to the different use cases within the organization (Berschik et al., 2023; Guo et al., 2022).

In the domain of superconducting accelerator magnets, the first steps towards the use of MBSE have been made by Maciejewski et al. (2023). With the goal of tracking the used magnet simulation models and their change history Maciejewski et al. (2023) introduces a model query mechanism using Jupyter notebooks. Each notebook encapsulates a magnet simulation domain and serves as a queriable data repository. Other notebooks can then query the results recursively to link them and perform more complex multi-physics simulations. These dependencies can be specified in a configuration file, and the separate models can be executed when the results change is made using a micro-service architecture that executes the underlying solver for each simulation domain. A cache is used to store dependent results after execution to save computing time temporarily. The notebook versions and, therefore, all simulation data can be versioned, and an automated report creation simplifies the traceability of the results (Maciejewski et al., 2023). This architecture and workflow are shown in Figure 2.6.

The models created as part of MBSE are used and updated throughout the entire development lifecycle and beyond as so-called ”as-built” models to track the adaptions necessary due to discrepancies between the physical object and the created system model before the production. Even though the concept MBSE helps and enables data-driven engineering processes, this does not magically solve all problems along the development lifecycle. The approach proposed by Maciejewski et al. (2023) goes in the right direction but falls short in terms of knowledge management and organization of the multitude of created magnet models. The cache is an effective way to improve simulation efforts, but it is not usable as persistent storage for the simulation models. Without this type of storage, versioning of models across multiple system generations and the traceability of changes becomes impossible. The manual effort to organize the individual notebooks and magnet models is unfeasible, especially for organizations with a scale like CERN. While MBSE becomes an increasingly popular approach to mitigate these challenges, its adoption is limited to early adopter companies, and existing MBSE methodologies are often too complex and abstract to provide real benefit. As a result, more user-friendly customized methodologies are proposed in recent literature (Mandel et al., 2023).

After coupling simulation domains and implementing persistent storage for the magnet models, the development itself still needs to be modeled. This goes beyond creating system models and relies on proven process models in design science.

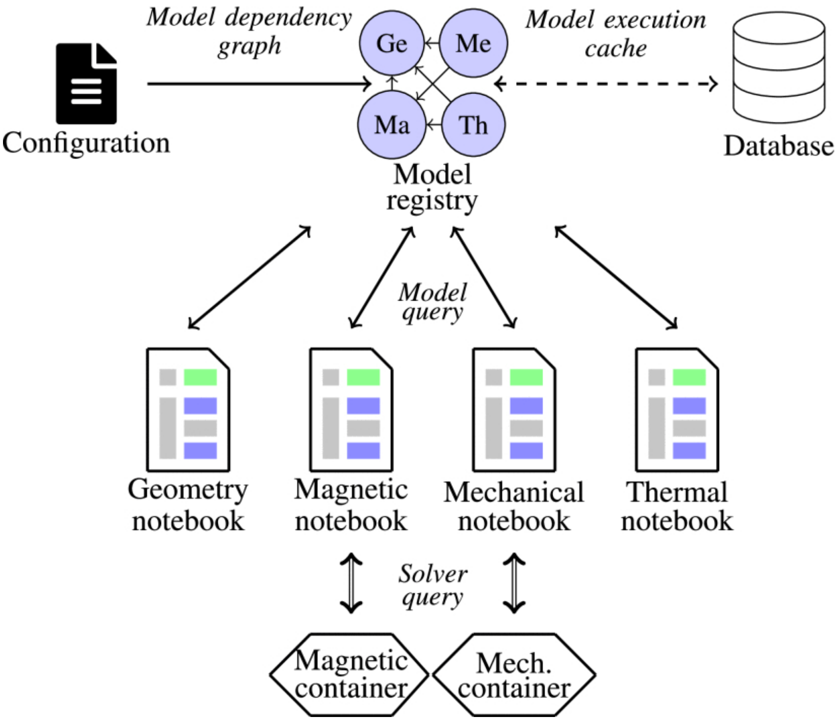

Figure 2.6: Multi-phsysics simulation workflow using PyMBSE. The workflow shows the glue logic in the form of a model dependency graph and the subsequent temporary caching of the simulation results. The notebooks show the simulation scripts of the different modeling domains. From “Model-Based System Engineering Framework for Superconducting Accelerator Magnet Design” by Maciejewski et al. (2023).

2.2.4 Design Process Models

The state-gate model, VDI guideline 2221, or the well-known V-model, published in VDI guideline 2206, are common process models in the industry. Apart from these models, special modeling frameworks, such as the integrated Product engineering Model (iPeM), can be used to create tailored solutions for different development domains. These well-known models will be introduced here briefly:

- **Stage-Gate Model**
  The Stage-Gate approach is a management-oriented model for product development processes. It utilizes a phase model to represent activities along a timeline. The model defines stages that are separated by milestones, known as gates. At each gate, project reviews are conducted to assess progress and make decisions about moving forward. The process model describes the expected deliverables and criteria that should be met at each milestone to proceed to the next stage. This structured approach helps to ensure that product development projects are well-defined, efficiently executed, and aligned with business objectives (Cooper, 1990).
- **VDI Guideline 2221**
  VDI 2221 is a guideline providing a systematic approach to the development and design of technical products and systems across various engineering disciplines. Recently updated, VDI 2221 Sheet 1 now focuses on the fundamentals of methodical development, describing adaptable process models for different development situations (VDI-Gesellschaft Produkt- und Prozessgestaltung et al., 2019). The guideline emphasizes an iterative and agile approach. It stresses the importance of considering technical, economic, and ecological factors throughout the development process. VDI 2221 has expanded its scope beyond traditional hardware to include software, services, business models, and their combinations. The guideline provides a list of modeling frameworks used to describe the unique development processes. In this list the iPeM is referred to as a description model with a high degree of detail through usage of macro- and micro-activities for the process description (Gericke et al., 2021; Jänsch & Birkhofer, 2006; VDI-Gesellschaft Produkt- und Prozessgestaltung et al., 2019).
- **VDI guideline 2206 (V-model)**
  The V-model is defined as the macrocycle in the VDI guideline 2206. This macrocycle starts by defining product requirements and deriving test cases for validation. In the ”system design” phase, the overall system function is divided

into sub-functions and assigned working principles. The ”domain-specific design” step further concretizes the solution concepts in the domains of mechanical engineering, electrical engineering, and information technology. Subsequently, the ”system integration” phase integrates the results of the subsystems into the overall system. As product maturity increases, the properties of the overall system can be verified against the requirements. It is emphasized that multiple iterations of the macrocycle are usually necessary to develop complex mechatronic products (Gausemeier & Moehringer, 2002).

The integrated Product engineering Model (iPeM)

To model the individual character of product development cycles, the iPeM can be used. The iPeM can be understood as a meta-model for deriving individual process models, which we learned before are needed for successful product design. The iPeM, in contrast to other models, considers the interactions between activities, methods, requirements, and results. A major difference to other popular models, such as the V-model, is the iterative character and description capabilities of the iPeM to model and visualize these development iterations. With this approach, the iPeM aims to connect the domains of process management and engineering design (Albers, Reiss, et al., 2016). The second key difference is the incorporation of various product engineering approaches and product generation engineering into the model. Each approach or individual product generation is represented as a separate layer within the model. These layers are named product, strategy, production system, and validation system and are shown in Figure 2.7. The system triple of product engineering serves as the foundation for the iPeM. This triple, according to Albers et al. (2011), defines product engineering as a dynamic interaction among three core systems: the system of objectives, the system of objects, and the operation system. It utilizes system theory to outline the transformation of objectives (all types of goals and conditions for a product to be developed) into tangible objects (the final product and all intermediary development artifacts) facilitated by the operation system. This operation system is a socio-technical framework involving structured activities, methodologies, and processes, alongside necessary resources like employees or budget, to carry out this transformation. Albers et al. (2011) further extend the system triple of product engineering, placing the developer at the center of an iterative product development process characterized by uncertainty. The model portrays the developer as a thinking and acting individual who navigates this complex landscape. To facilitate this, the state of knowledge and the solution space are defined as subsystems within the operation system. Lohmeyer (2013) explains the state of knowledge to represent the totality of case-specific knowledge in a product development process. The solution space describes the set of permissible solutions to a problem situation, which is constrained by the degrees of freedom based on goals and boundary conditions. The system of objectives, system of objects, and operation system continuously evolve. Knowledge is generated through the analysis of existing products, which can be used to synthesize an initial reference system. Based on the reference system, the solution space is defined, and an initial synthesis of results can emerge. These results can then be analyzed to expand the state of knowledge and further detail the target system (Lohmeyer, 2013).

Within the operation system, the iPeM distinguishes between micro and macro activities; micro activities involve iterative problem-solving in technical areas, while macro activities focus on broader product engineering domains.
The macro activities are divided into *basic activities* and *core activities*. The basic activities are used recurringly in parallel to the core activities for project planning and control. These basic activities are called: *manage projects*, *validate and verify*, *manage knowledge*, and *manage changes*. The core activities are carried out to develop and create the desired system within the system engineering lifecycle. The activities are called: *detect profiles*, *detect ideas*, *model principle and embodiment*, *build up prototype*, *produce*, *analyze and design market launch*, *analyze and design utilization*, and *analyze and design decomission*. An in-depth explanation of all activities is published by Albers et al. (2017) and Albers, Reiss, et al. (2016).
The micro activities within the iPeM are specified using the SPALTEN problem-solving process. The SPALTEN acronym originates from the German word ”to split” (Albers, Reiß, Bursac, & Breitschuh, 2016). Each letter in the acronym describes an activity within the SPALTEN problem-solving cycle. The problem-solving activities are situation analysis (S), problem containment (P), detection of alternative solutions (A), selection of solutions (L), analysis of consequences (T), deciding and implementing (E), and recapitulation and learning (N). This universal process is defined to overcome any generic problem. According to Dörner (1987), such a general problem consists of an undesirable initial state, a desired final state, and a barrier that currently impedes the transition from the initial to the final state. The recapitulation and learning step (N) differentiates SPALTEN from the majority of other problem-solving processes, which mostly do not focus on process reflection (Albers, Reiß, Bursac, & Breitschuh, 2016).
The central acting force in SPALTEN is the so-called problem-solving team (PST), which is defined before the process starts and is redefined after each step in this process. During the systematic execution of the problem-solving steps, a continuous idea pool is built, maintained, and checked after each step by the problem-solving team (Albers, Reiß, Bursac, & Breitschuh, 2016). The problem-solving method has a

fractal character; the individual activities can, in turn, be subdivided and methodically solved with the help of SPALTEN (Albers et al., 2010).

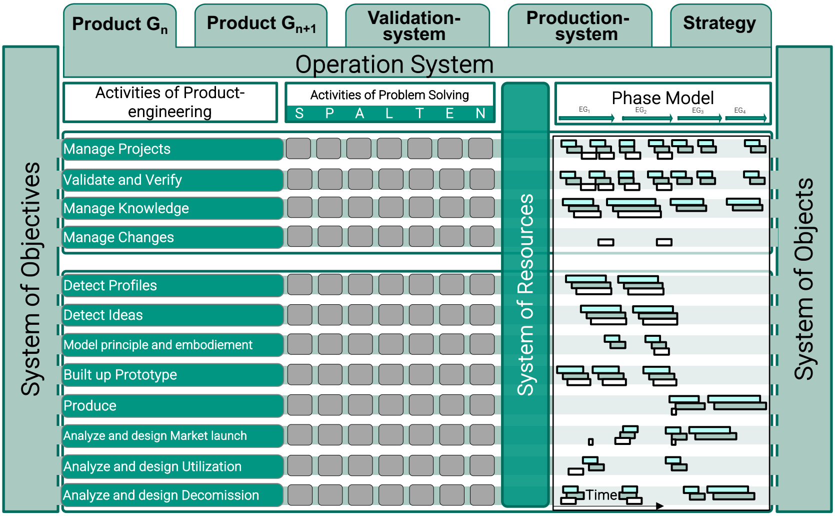

Figure 2.7: The meta model of the iPeM. In this figure, the current product development generation G_n is visualized. The iPeM is made up of the core components: a system of objectives, an operation system, a system of resources, and a system of objectives. Product engineering activities are defined, together with a method catalog for each SPALTEN problem-solving step within the operation system. The actual execution times of these steps are tracked in the phase model and are visualized alongside its reference process and the planned project process times. From "iPeM – Integrated Product Engineering Model in Context of Product Generation Engineering" by Albers, Reiss, et al. (2016).

The execution of all activities within the development process is tracked in the dynamic part of the iPeM, the so-called phase model. In the phase model, three different kinds of activity timelines can be tracked: the reference timeline, which includes the conducted activities from the reference system development, the planned activities for the system in development, and the actual activities that have been carried out during the current system development process. The planned and actual timeline can and mostly will have discrepancies. These discrepancies can be used to define the reference timeline for the next system generations and give insights into critical path planning difficulties. The iPeM meta-model with all explained elements is shown in Figure 2.7.

Organization-Specific Prozess Models

The iPeM meta-model without any customizations is often too generic and broad to be directly applied to a specific domain or product.

Through the process of individualization, the iPeM meta-model can be adapted to three different abstraction levels to create tailored iPeM models for a specific use case and environment. The **general** level contains the iPeM meta-model without any further concretizations. The patterns in a general model are technically valid for any domain and project. The abstraction at this level is high, and thus, general models can mostly only be used to investigate theoretical model element relationships and not directly be used in practical applications since most operative processes are not generalizable to such an extent. The **domain-specific** level tailors the meta-model to a certain domain and serves as a foundation to derive domain-specific reference models. The last abstraction level contains **product-specific** models and contains patterns and activities tailored to a specific product type, such as an accelerator magnet. The individualization step involves formalizing the design activities and specifying the system of objectives and the system of objects according to the environment and use case (Muschik, 2011).

Apart from the individualization of the iPeM across the three abstraction levels, the model provides a way to instantiate the previously specified models during a development project. This deduction process from a meta-model within an abstraction level can result in three model types: reference models, implementation models, or application models. The deduction from reference model patterns to concrete application models in monitored projects can be understood as a form of model-order reduction and results in a model that is exact in terms of formal abstraction but not necessarily complete in terms of model elements and relationships. The insights gained by an application model can then, through an induction step, be carried over to the reference model and, therefore, interactively improve the individualized model (Muschik, 2011). The abstraction levels of the iPeM, together with the instantiation and individualization directions for industry application[4], are shown in Figure 2.8.

[4] The equivalent to the company-specific level for a research application is called ”domain-specific”.

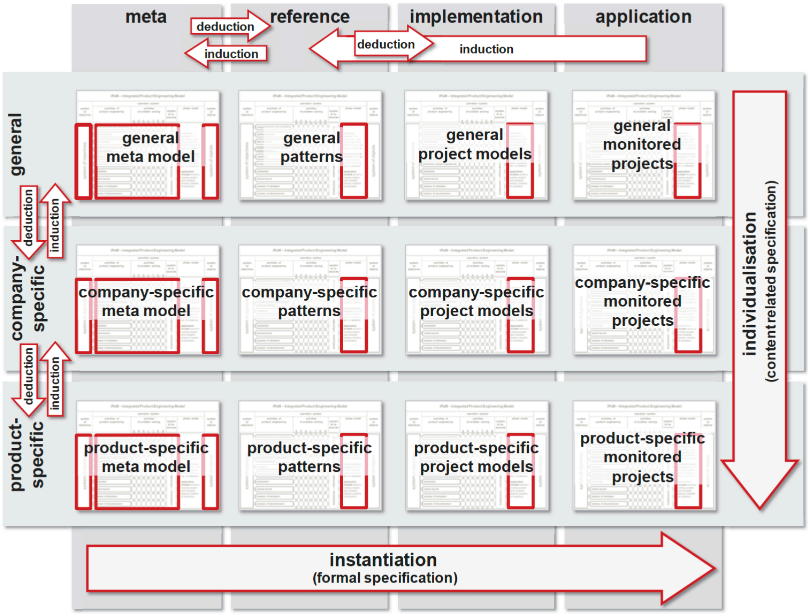

Figure 2.8: The iPeM abstraction levels for an industry application. The three distinct abstraction levels are shown in the vertical direction. The horizontal direction shows the deduction and induction process that can be performed to adapt the model to changing constraints during and in between project applications. From "Development of Systems of Objectives in Early Product Engineering. Doctoral dissertation" by Muschik (2011).

While the theoretical foundation behind the iPeM can perform these tailoring steps and remain valid, there are limited publications, aside from the Integrated Design Support Development Model (IDSDM), that explicitly demonstrate iPeM instances being utilized in a research setting. Many current applications of the iPeM leverage its underlying concepts as implicit guidance throughout the development process rather than directly interacting with the model itself through dedicated iPeM tool support. This gap in the literature should be filled with this thesis.

2.2.5 References in Systems Engineering

Enhancing efficiency and minimizing the risks associated with developing new, successful products and systems are vital for companies and scientific facilities alike. This becomes clear by the fact that out of the components initially believed to necessitate new designs, only one-fifth actually require them. Two-fifths of the parts can be constructed using existing designs, while the remaining two-fifths can be developed by altering current designs (Iyer et al., 2005). Thus, successful system development is only possible by building on and reusing existing knowledge elements. These knowledge elements are often referred to as reference system elements and describe references to existing systems and the respective development artifacts. Reusing and improving these reference system elements across multiple system generations paves the way for successful development projects (Kempf et al., 2023).

Several description models exist to describe such system references across generations, each addressing different aspects of system complexity and maturity. Here, we want to list some examples.
The ISO/IEC 81346 Standard series presents a Reference Designation System (RDS) that assigns unique identifiers to system elements and their interconnections. The RDS's focus is on establishing a standardized method for identifying and referring to system components and their relationships (Balslev & Barré, 2022). More holistic description approaches like the one established by Ascher et al. (2022) encompass requirements, services, components, and processes, ensuring end-to-end traceability. The concept of a ”reference system” is introduced in the model of PGE - Product Generation Engineering according to Albers et al. (2019) to encompass artifacts from former development processes, which are crucial for subsequent projects (Albers et al., 2019). While the Product Generation Engineering (PGE) highlights the variation of reference system elements from the previous projects, the model is also applicable for green-field development without a direct predecessor product, in which case references to related products or systems can be established.
The creation of the PGE has been motivated by prior field studies to model real-life development projects. In recent years, the PGE model has extended its scope to general systems, not only products. It distinguishes itself from other description approaches by focusing on the description and understanding of variation types of reference system elements across system generations (Albers & Rapp, 2022). Because of this level of detail and the inherent traceability of reference system elements, the model of SGE - System Generation Engineering should be used for this thesis, which will be described below.

Model of SGE - System Generation Engineering

According to Albers and Rapp (2022) no system is ever developed into a blank space without any reference system elements. This principle was already introduced as part of the reference process timeline in the iPeM phase model in the previous section. The concept of system development in generations with the ubiquitous existence of a reference system containing various internal and external system reference elements is concretized in the model of SGE - System Generation Engineering. The second core hypothesis of the model of SGE states that ”based on the reference system, a new system is developed by a composition of three different types of variation of subsystems: carryover variation, attribute variation, and principle variation” (Albers & Rapp, 2022, p. 30). This variation composition stresses the importance of system generation thinking in the model of SGE.

The model of SGE describes in detail the development of a new system generation using reference system elements and applying these three types of variations to them.Albers et al. (2020) and Albers, Bursac, and Wintergerst (2015a) describe these variation types like so:

- **Carryover variation (CV)** involves adapting a subsystem from a previous system with minimal adjustments. At the most, interfaces for integration into a new system generation will be adapted.
- **Attribute variation (AV)** involves altering the attributes of the subsystem elements and connections while maintaining the overall structure.
- **Principle variation (PV)** involves adding or removing elements and connections within a subsystem, resulting in a revised component for the new system generation.

The development of a new system generation can be described as an imaging operation, illustrating the transition from a reference system R_n to the system generation G_n (Albers & Rapp, 2022). The imaging operation encapsulates all methods of developing a new system generation and its subsystems through carryover, attribute, and principle variations. The ratio of subsystems developed by each variation type to the total number of subsystems in the new product generation determines the proportion of these three variation types. Therefore, the sum of variation ratios for any system will always be 100% (Albers, Bursac, & Rapp, 2016; Albers, Bursac, & Wintergerst, 2015b). Following this logic, G_n represents the nearest market-ready generation, G_{n-1} is the generation currently in the market, and G_{n+1} is the following generation after G_n, which is possibly already in development. Higher indices may exist in both directions depending on the system and development environment (Albers et al., 2022). Interesting here is the case of G_1 where the system does not

have a direct predecessor. These so-called green-field developments can also be described using the SGE by identifying internal and external reference system elements of systems related to the one to be developed. The core hypothesis by Albers and Rapp (2022) holds even for these G_1 generations because references can always be found for example in other domains or as parts of unrelated products.
The model of SGE is universally applicable to any kind of system. This is shown in the current literature using SGE to model systems such as mechanical tower clocks (Pfaff et al., 2024), digital platform business models (Albers et al., 2023), and even company strategies (Stammnitz et al., 2023).

In the current literature, access to historical data and, thus, to reference system elements has been identified as a challenge in the domain of accelerator magnet development. Iteratively enhancing the performance of magnet designs based on past learning is seen as a crucial element for future accelerator projects. Current modeling efforts in the domain are struggling with non-standardized data formats and the exclusive storage of models in non-usable ways, such as in figures or texts in scientific publications (Biedron et al., 2022; Maciejewski et al., 2023). The current situation in the magnet domain contrasts with the principle of the model of SGE. This needs to be addressed by establishing best practices for knowledge management and transfer to make reference system elements accessible for future development generations.

2.2.6 Systems Engineering Management

Product development projects require the involvement of both systems engineers and project managers, who have distinct yet crucial roles. While systems engineers focus on product requirements, project managers aim to deliver the project on time, within budget, and with the expected quality. However, the lack of cohesion between these roles, often due to organizational silos, has resulted in suboptimal project success rates. To address this issue, INCOSE and PMI, alongside MIT, have emphasized the importance of better collaboration and understanding between systems engineering and project management. They advocate for a more integrated approach to improve project outcomes by addressing the challenges and tensions arising from poor integration and coordination between the two domains (Boswell et al., 2017; Conforto et al., 2013; Langley et al., 2011; Rebentisch et al., 2015).

The approach of combining Product Management (PM) and SE into combined frameworks and approaches is called Systems Engineering Management (SEM). A systematic literature review according to the method published by Xiao and Watson (2019) was conducted to investigate the current SE-PM frameworks and their implementation in actual projects. The literature review ended up with 16 included scientific papers. The review is currently under review (Kaeske, Wagner, et al., 2024a). Kaeske, Wagner, et al. (2024a) found that these reviewed frameworks address various aspects of SE and PM integration, consistently emphasizing the need for tool support. Enterprise architecture frameworks, such as the one published by Halvorson et al. (2022) and single-source-of-truth toolchains, show the most promise in driving integration efforts. However, clear organizational governance and management strategies for methodology changes are crucial, especially when aiming for comprehensive, tailored tool support for magnet design at CERN.

The openSE Framework

CERN, together with other universities and physics research institutes around the world, implemented a custom SEM framework based on the learnings from the design and construction of the LHC. Arguing that common industry best practices are often unsuitable for particle accelerators, the openSE framework was specifically tailored for accelerator studies and development projects (Bonnal et al., 2016). Even though openSE is specified to handle CERN specific challenges, such as the high number and complexity of involved technologies or lead times that can last over a decade, the framework is, at its core, still based on other industry standard lifecycle models. To establish an easy-to-use approach to SE and PM, openSE is deliberately kept simple and is based on six phases:

1. The **Initialize** phase is the initial stage of the project. It focuses on analyzing the current situation to define the problem, proposing possible solutions, and formalizing the decision to initiate the project. This stage results in the creation of the Project Proposal, which may evolve into the Project Roadmap upon approval by the Project Board.

2. The **Study** phase involves gathering and converting user or stakeholder needs into requirements, identifying all potential solutions, and proposing a preferred solution explained via a Conceptual Design Report. This phase aims to align project goals with stakeholder expectations.

3. The **Design** phase finalizes the needs and requirements, undertakes the engineering design, plans subsequent phases, and may develop prototypes. The Technical Design Report, as the deliverable of this phase, aims to solidify the project's foundation through detailed planning and design.

4. The **Build** phase involves detailed design, procurement, manufacturing, assembly, and verification of meeting project requirements. This phase transitions the project from design to tangible outputs.

5. The **Commission** phase ensures project outcomes meet all requirements, adapt to evolving contexts, train operational and maintenance teams, and release documentation for full operational deployment.

6. The **Finalize** phase captures and leverages lessons learned to prevent recurring issues. It emphasizes the importance of reflection and learning for continuous improvement.

Two critical roles within openSE are the *Project Board* and the *Project Manager*. The *Project Board* is responsible for ensuring strategic management, resource availability, validating phase transitions, and resolving conflicts. The *Project Manager* coordinates and organizes the project in accordance with the Board's direction. The development lifecycle of openSE with its phases is shown in Figure 2.9 (Bonnal et al., 2016).

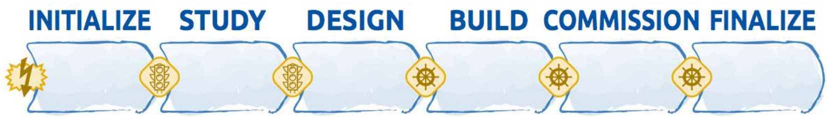

Figure 2.9: The development lifecycle of the openSE framework. From "openSE: a systems engineering framework particularly suited to particle accelerator studies and development projects" by Bonnal et al. (2016).

While openSE sounds like a promising vision, parts of the guidelines and training handouts have never been finished. The additional missing practical implementation steps and tool support make adopting the framework difficult. This claim was confirmed during interviews (chapter 4.2.3) in the CERN TE-MSC group in which openSE was largely unknown to the magnet engineers. Template documents accompany all phases of the development lifecycle. The results of every stage are once again recorded as document artifacts. This contrasts the proposed paradigm shift to model-based processes introduced in Chapter 2.2.3.

2.3 Conclusion

This chapter gave a broad insight into the state of research of superconducting magnet development at CERN and the domain of design science. During this chapter, the following research gaps and challenges have been identified in these two fields:

- The need for higher magnet dipole fields comes with a rising system model complexity and the need for multi-physics simulation. This rising complexity motivates the use of MBSE. Still, current approaches for this are limited in scope, and the concept itself is not as widespread as in other fields, such as automotive or aerospace.
- Missing knowledge management and transfer best practices for magnets make complex multi-physics simulations even more difficult. This results in the non-accessibility and non-conformity of reference system elements and makes system generation engineering often impossible. Current MBSE approaches in the domain focus on the modeling complexity but disregard the knowledge management aspect.
- The iPeM is well-developed and the theories and principles behind it are implicitly applied in industry. Apart from the non-technical IDSDM, there is a lack of documentation of explicit applications that also carry out the individualization steps to create domain- or product-specific reference models.
- The historical drifting apart of PM and SE has been identified in literature. Current specialized SE-PM frameworks lack dedicated tool support and implementation steps and are thus difficult to implement into the development process. The openSE framework at CERN as well tries to combine these two domains but is not widely used within the organization and is, in parts, unfinished. The openSE is based on a document-centric approach, which contrasts with the switch to more modern, model-based concepts.

To summarise, there is currently no explicit design support for developing superconducting accelerator magnets in general and only first prototypical approaches to cope with the rising magnet modeling complexity in particular. The missing knowledge management and transfer best practices have been identified in all areas and are not tackled by existing MBSE approaches. With the rising demand for complex multi-domain magnet modeling, this thesis's aim to develop such support in the form of a methodology is backed by an existing gap in the literature combined with an actual need in industry and research. With the findings in Chapter 3, the scientific approach with the thesis objectives and leading research questions can be derived.

3 Research Design

This chapter introduces CERN as the research environment in which the author has obtained the results as a full-time doctoral student in the technology department. The research objectives are defined, and the scientific methods used to achieve these objectives and answer the underlying research questions are explained in detail.

3.1 Research Environment

The thesis project was carried out in the group for Magnets, Superconductors, and Cryostats (MSC) within the Technology Department (TE) at CERN[5]. This group within CERN was used as the validation and research environment for all results in this thesis. The research project has been carried out in the scope of a dedicated doctoral student program at CERN with Univ.-Prof. Dr.-Ing. Dr. h. c. Albert Albers at the Institute of Product Engineering (IPEK) at Karlsruhe Institute of Technology (KIT) being the supervising professor. This section should introduce the system models, software, and physical objects being developed and tested within the MSC group. Figure 3.1 shows a schematic overview of how these fundamental parts are interconnected as an abstract house.

[5] CERN as a research institute has been introduced in Chapter

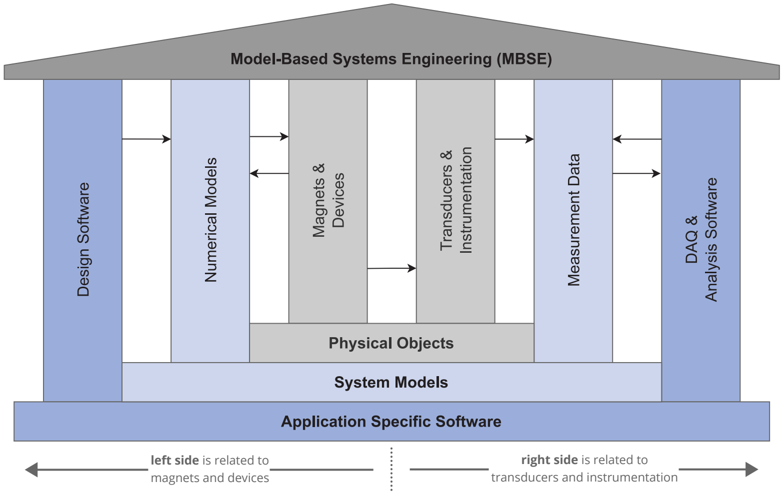

Figure 3.1: Stucture of models, objects, and software within the CERN TE-MSC-TM section. Adapted from "Field Simulation for Accelerator Magnets" by Russenschuck (2025).

Figure 3.1 can be divided vertically into two parts. The left part shows the objects, models, and software related to the general design, simulation, and operation of magnets and devices. The right part corresponds to the instrumentation and transducer systems to measure and characterize these magnets. Three layers of foundations connect both sides:

- **Physical Objects**: magnets and the transducers themselves as physical assets
- **System Models**: measurement data obtained with the transducer systems and numerical simulation models of the magnets which are improved using the measurement data
- **Application Specific Software**: data acquisition and analysis software for magnetic measurements and their post-processing and the design software to create simulation models of current and future magnets

The left magnet side and right measurement side are connected by the need to validate and update numerical magnet models against actual magnetic measurements to adjust for influences like manufacturing defects or material parameters. This connection is shown in Figure 3.2.

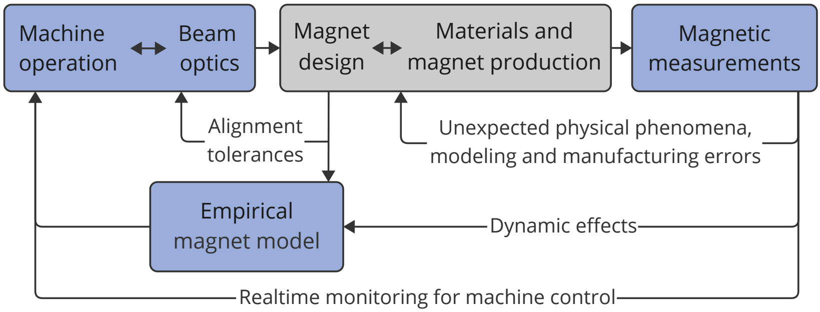

Figure 3.2: Feedback loops to validate and improve empirical magnet models and the operation of the accelerator complex based on magnetic measurements. This coherence between the three domains is called *C3 Coherence*. The arrows between the different systems and models show the interconnected feedback between each other. Adapted from "Field Simulation for Accelerator Magnets" by Russenschuck (2025).

The house's roof schematic shows MBSE as the encompassing concept used throughout all aspects of the TE-MSC section. MBSE has been initially used for multi-physics simulation approaches for the magnet design process by (Maciejewski et al., 2023) but stayed in a prototypical state. Integrating MBSE for all aspects of the CERN development process and superconducting accelerator magnet design, in general, is the establishment of the so-called C3 Coherence. This term stands for the coherence between beam physics, magnet technology, and magnetic measurements and aims to validate magnet design and its assumptions using field measurements. Field measurements can replace and improve numerical simulations in the form of a feedback loop in domains of magnet materials: the magnet design itself, the production process, and the operation of the accelerator complex (Russenschuck, 2025). These feedback loops over the listed domains are shown in Figure 3.2.

3.2 Research Objective

To define the research objectives of this thesis project, the research needs are clarified first. The overall research goal is broken down and operationalized by three research questions.

3.2.1 Research Needs

The connections between physical objects, system models, and application-specific software within the measurement side (right side) of Figure 3.1 are well-established and supported by a variety of dedicated tools, such as FFMM or MTF (Fiscarelli et al., 2018; Mallón Amérigo et al., 2009). In this area, knowledge management deficits can be mainly observed within the development of the transducers themselves, making it difficult to refer to reference system elements of previous system generations. The left magnet side of Figure 3.1, on the other hand, shows improvement potential in terms of linking models to the physical magnets, storing simulation models, and dealing with an ever-growing suite of simulation software. This thesis project should, therefore, mainly focus on the more challenging and complex magnet side of the CERN TE-MSC group activities.

Beginning with the need to understand the magnet design process, the initial situation within the domain, CERN as an organization, and TE-MSC group on a practical level need to be investigated. While various scientific papers address the technical challenges of the development process, prior to this project, publications did not focus on quantifying the more general, organizational, and structural development challenges. This gap shall be filled throughout the project.

The method landscape at CERN is diverse and relies mainly on the individual development approaches of each engineer. While this can be helpful in achieving creative and novel results, it makes knowledge transfer and storage difficult due to the heterogeneous data structures being generated. These individual approaches can negatively impact the results, especially for multi-physics simulations where simulation results need to be parsed between multiple design software combined with a research environment with frequently changing personnel members. This thesis project will address these domain-specific challenges that hinder the magnet modeling process by implementing a methodology for the electromagnetic design of superconducting accelerator magnets. This methodology should follow the concept of MBSE to organize simulation models as dynamic models in comparison to the current, static document-based approach. The first steps for using MBSE for multi-physics magnet simulations have been made, but a structured, widespread approach and adoption are still missing. This work aims to contribute to the integration by formalizing the design steps and designing prototypical tool support to teach and use this methodology throughout the magnet design community.

Research Goal

The present thesis aims to identify the challenges in the domain of superconducting accelerator magnets and develop design support in the form of a methodology to formalize the electromagnetic design and development process. This methodology should follow the concept of Model-Based Systems Engineering and should be integrated into the current development workflow with adequate tool support.

The methodology that will be developed in this work for the electromagnetic design of superconducting accelerator magnets can potentially be transferred to various other domains.

At the system level, the approach of designing and optimizing complex magnet systems, keeping in mind the necessary interfaces and workflows for multi-physics simulations, can be applied to the development of other high-performance (magnet) systems, such as in thermonuclear fusion or maglev technology.

In the domain of particle accelerators, the methodology can be expanded to design other accelerator components, such as magnetic transducers, as well as thermal and mechanical simulations.

For design research, this work demonstrates a systematic design methodology in the context of a challenging physical-technical problem. It shows how a contribution to knowledge gain in the design process is made through appropriate modeling approaches, simulation tools, and the link to past system generations. These methodological aspects can, in principle, be transferred to many other areas of engineering where a MBSE approach is pursued. Especially for the iPeM, the methodology can provide a proof of principle for its direct application and motivate future validation studies and the transfer to other domains.

It is however important to note that separate validation studies and customizations are necessary for application in other areas and domains and that the present results should not be applied without careful consideration of differentiating boundary conditions, especially in foreign domains such as the automotive development.

3.2.2 Research Questions

The research needs, and the operationalization of the research objectives have led to the creation of the following research questions.

1. **What are the challenges in developing superconducting accelerator magnets?**

The first research question is formulated under the assumption that identifying the challenges during the development of superconducting accelerator magnets can give meaningful insights for future design support integration. This question will be answered by conducting two case studies to initially identify the development challenges of the transducer design at CERN. A challenge quantification will be carried out following these case studies. Chapter 4 presents the results answering the first research question.

2. **How can a methodology for the electromagnetic design of superconducting accelerator magnets be formulated, and how can it be taught to its users?**

The second research question is formulated under the assumption that developing a dedicated magnet design methodology and investigating a teaching method for it can structure and improve the development workflow. Existing approaches and tools at CERN will be identified to define possible boundary conditions for the methodology. Based on these boundary conditions, possible modeling frameworks will be introduced. The methodology itself and an adequate teaching tool will be analyzed and explained. Chapter 5 presents the results answering the second research question.

3. **How can the methodology for the electromagnetic design of superconducting accelerator magnets be integrated into the development process, and what does a suitable tool support look like?**

The third research question is formulated under the assumption that dedicated tool support is essential to integrate and apply a methodology for the electromagnetic design process of accelerator magnets. A MBSE database and data management tool will be developed and implemented based on the findings from the previous chapters. The connection between the methodology and the described software tool will be clarified. Chapter 6 presents the results answering the third research question.

The following section will outline the approach used to answer these research questions in greater detail.

3.3 Research Practice

This section introduces the scientific practices used in this thesis project. It gives an overview of the Integrated Design Support Development Model (IDSDM) as the research methodology and explains in detail the empirical methods facilitated throughout the project.

3.3.1 Research Methodology

Design research projects like the one presented in this thesis are highly multidisciplinary and combine practical and theoretical aspects to make practical contributions while understanding and advancing the underlying theories. The need for a framework to plan and carry out such a research project is well-known in the research community, and a well-adopted methodology is the Design Research Methodology (DRM) by Blessing and Chakrabarti (2009).

Specifically designed for empirical studies, DRM stresses the importance of completing research projects as a whole and assessing their outcomes afterward using previously defined success criteria. While implementation and validation are essential steps during an applied research project, contributions within large organizations require more work than is achievable by a single thesis project and require the project to be categorized as a part of a bigger initiative. Frameworks such as the *spiral of applied research* recognize this fact and aim for well-rounded practical and theoretical results of a single doctoral thesis in the context of longer-term projects (Eckert et al., 2003). To find and apply a framework suitable for the research environment at CERN, we will look towards a proven concept in design research, the so-called *action research*.

Action Research

Action Research is a concept that involves both practical action and reflective observation, along with the integration of theory and practice, all with the participation of those involved in the research process. Action research is widely used in various fields and aims to solve practical problems while contributing to academic knowledge.

The term was first introduced by Kurt Lewin in the context of social science, discussing the challenges faced by individuals and organizations trying to improve group relations. Lewin identified uncertainty about the effectiveness and sustainability of intergroup relations research methods, causing confusion and inefficiency for the researchers. He mentions difficulties in measuring research progress and the improvement upon past insights due to unclear situations and a lack of objective standards (Lewin, 1946).

Action research is introduced as a solution to these identified problems, bridging the gap between theory and practice by focusing simultaneously on the practical implementation (*action*) and the theoretical knowledge gain (*research*). This twofold approach is implemented by following an iterative approach of planning, acting, observing, and reflecting (Burns, 2007). In design science, action research is also mentioned as an integral part of applied research in more recent standard literature. During design research projects, action research should be used to build successful tools and supports by integrating and testing them in practical use cases (Eckert et al., 2003).

Carrying out the thesis project with a practical focus in the international research institute CERN, action research should be used as guidance to implement useful technical solutions while gaining theoretical knowledge to complete an academic thesis. A designated implementation model is needed to structure the project and bring the action research concept to a more actionable level. The IDSDM provides such a model.

Integrated Design Support Development Model

The IDSDM is a framework based on the iPeM and is intended to support the design of heuristic design support. It has a general character and can be used for any design support development project (Marxen, 2014). The IDSDM was selected for this research project because it focuses on individual doctoral projects rather than large-scale programs. It takes an activity-based approach instead of a consecutive one and is therefore in line with the action research concept. The formalized activities of the IDSDM, to be used throughout the thesis project, shall be explained here:

- The *Project Planning and Controlling* activity happens during the entire project alongside other activities. Typical questions that are answered during this step are the who, what, when, where, why, and how of the thesis project. The continuous controlling part validates the alignment of the project with the predefined goals and corrects the course.

- To understand the state of the art and research and to identify difficulties and good practices in the respective research environment, the *Empirical Research, Analysis of Real-World Observations* activity is carried out. This step always includes or is based on literature research to ensure the novelty of future design support.
- The observations and findings from the previous steps are used to create design support in the *Embodiment of Design Support* activity. This design support is not limited to physical objects but can be everything from software tools to graphical representations or worksheets. The main goal of this design support is to help overcome the previously identified difficulties.
- To analyze if the design support is achieving the desired outcome, an evaluation in a controlled environment needs to be performed. The *Experimental Studies* activity comprises the identification of isolated design tasks against which the design support functionality is tested.
- Apart from controlled tests, the design support has to perform well in a real-world scenario. The advantages and flaws of using the design software can be identified in this real-world implementation, and changes can be suggested. This activity is called *Implementation Studies*.
- ”If it cannot be taught, it is not a design support as it will not help anyone.”[6] is the motivating principle during the *Transfer Studies* activity. Here, the way of educating new people about the respective design support is figured out. The activity might include steps like generating lecture material or e-learning courses.
- During the *Analysis of Utilization*, the researcher is often not and does not have to be part of the project anymore. The feedback from users of the design support and identified improvement potential during this step can serve as a starting point for a new research project or design support development. (Marxen, 2014)

Figure 3.3 shows the IDSDM together with indicators showing the thesis chapters corresponding to the activities and a customized phase model with the duration of the dates of each activity over the founding period at CERN.

[6] Frequently recited statement by Prof. Albert Albers during his lectures on product engineering.

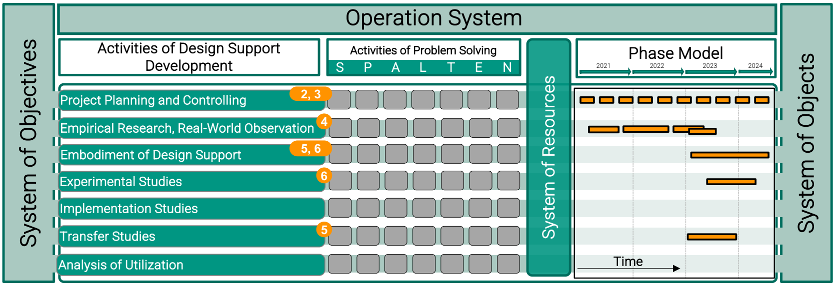

Figure 3.3: Integrated Design Support Development Model (IDSDM) in the context of this research project. The chapters corresponding to the activities of design support development are indicated using the numbered orange annotations. The time each activity took is shown in the phase model. The controlling activity was executed continuously throughout the project and is thus shown throughout the entire timeline. Adapted from "A Framework for Design Support Development based on the integrated Product Engineering Model iPeM. Doctoral dissertation" by Marxen (2014).

In the following section, all individual research methods, as part of the IDSDM activity matrix, that are used in the context of this thesis are presented in more detail.

3.3.2 Research Methods

This section outlines the research methods employed throughout the thesis project, along with the specific stages in which they were utilized. The methods detailed herein are widely recognized and commonly applied across a diverse range of design research projects. Given the significance of the integration component in the later stages of the thesis, software testing has also been incorporated as a research and validation method.

Literature Review

Literature reviews have been used at multiple stages of the thesis project. Starting with the fundamental research to identify the current state of research in Chapter 2 and to derive the research objective from it in Chapter 3.2. At two stages of the project, a more directed and systematic literature study was necessary:

1. To quantify the development challenges in the domain of superconducting accelerator magnets in Chapter 4.2.1

2. To analyze the existing frameworks and description models that are integrated to describe SE and PM in a combined way in Chapter 5

To document the process of carrying out the review process and selecting the relevant literature, the structured review process published in (Xiao & Watson, 2019) was used. The review process is structured in three parts: planning, conducting, and reporting the review. The need for a review is identified in the planning phase, research questions are specified, and a review protocol is developed. The conducting phase involves identifying and selecting primary studies and then extracting, analyzing, and synthesizing the data from these studies. Finally, in the reporting phase, findings from the literature review are written and disseminated. According to Xiao and Watson (2019), all types of literature reviews follow eight common steps: (1) formulating the research problem, (2) developing and validating the review protocol, (3) searching the literature, (4) screening for inclusion, (5) assessing quality, (6) extracting data, (7) analyzing and synthesizing data, and (8) reporting findings. The whole review process is iterative, allowing for adjustments to the research question and review protocol as necessary, often due to issues like overly broad research questions (Xiao & Watson, 2019). The process part of conducting the review within the described process is shown in Figure 3.4.

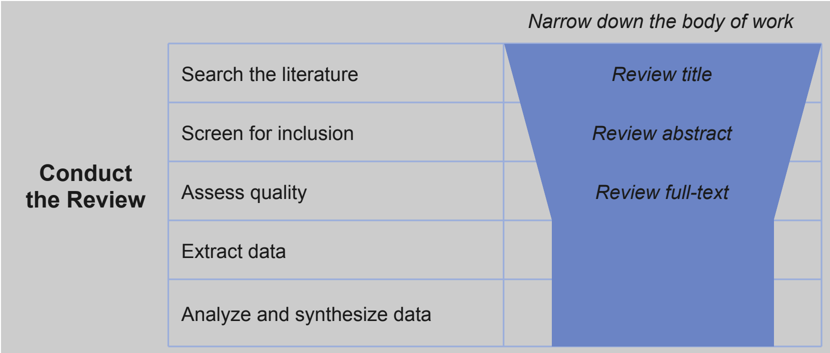

Figure 3.4: Process to conduct a systematic literature review and narrow down the initially identified sources. Adapted from “Guidance on Conducting a Systematic Literature Review” by Xiao and Watson (2019).

All empirical research projects can and should go alongside a thorough literature review, and there are practically no downsides or alternatives to using this method (Yin, 2017).

Interview Study

Interviews are a qualitative research method to gather detailed insights into an individual’s thoughts, beliefs, and experiences through direct interactions (Blessing & Chakrabarti, 2009). Unlike questionnaire surveys, interviews allow respondents to express themselves in their own words, leading to deeper and more detailed insights into their thoughts and opinions (Jain, 2021). According to Blessing and Chakrabarti (2009), the success of an interview relies heavily on the interviewer’s skills in crafting clear questions, avoiding common conversational traps, maintaining a focused dialogue, and staying objective throughout the conversation. When conducted correctly, interviews can deliver valuable qualitative insights during the exploratory study phase. However, overcoming the challenges and conducting effective interviews requires careful preparation and adherence to best practices in question formulation and interview conduct (Blessing & Chakrabarti, 2009; Jain, 2021). According to Blessing and Chakrabarti (2009), multiple types of interviews and no clear naming convention for them exist. For this thesis project, a form of semi-structured interviews with open-ended answers were used on two occasions:

1. To identify the magnet development challenges on a practical level within the CERN TE-MSC group. This is part of an analysis of a real-world design process and is explained in Chapter 4.2.3

2. To get user feedback on the tool support to explain the magnet design methodology. This is part of an experimental study in the parlance of IDSDM and is explained in Chapter 5.

A profile of the Interview Study method with its applicability in this project and its advantages and disadvantages are given in Table 3.1.

Table 3.1: Profile of the Interview Study method. Adapted from "A Framework for Design Support Development based on the integrated Product Engineering Model iPeM. Doctoral dissertation" by Marxen (2014). The areas where this method was applicable in this thesis project are colored in blue.

Interview Study	
Applicability	• Empirical research, analysis of real-world design processes • Experimental studies, evaluation in controlled environment • Implementation studies, real-world deployment of design support • All fields of design science where people's perception of a situation or a process is of interest.
Advantages	• Direct insights into people's thoughts and beliefs
Disadvantages	• High effort for preparation, conduction, transcription, interpretation, and documentation • Possible influence of the interviewer on the results

Survey

Surveys are another research method that gathers opinions through predefined questions. The difference to an interview is the absence of an interviewer during the answering process. This prevents possible influences of the interviewer on the participants and enables a larger number of sample sizes, especially with online survey tools (Jain, 2021). However, disadvantages include the risk of response biases affecting data accuracy, low response rates that challenge the representativeness of findings, the sensitivity of data quality to question design requiring meticulous crafting and pilot testing, and the complexity of data analysis and post-processing (Blessing & Chakrabarti, 2009; Marxen, 2014). According to Jain (2021), surveys can be particularly useful following an initial interview study. With the initial knowledge obtained in the interviews, researchers can better define the rigid questions of the study and are able to obtain helpful quantitative insights.

In Chapter 4.2.2, results of a conducted online survey were post-processed to quantify organizational and structural challenges at CERN. The survey and results are focused on the knowledge management and data transfer process as a core activity of CERN's development workflow. Based on these existing results and being in contact with the research group conducting the survey, the disadvantages of this method could be disregarded. The required minimum sample size for this quantification makes a survey the ideal method for this step. A profile of the Survey method with its applicability in this project and its advantages and disadvantages are given in Table 3.2.

Table 3.2: Profile of the Survey method. Adapted from "A Framework for Design Support Development based on the integrated Product Engineering Model iPeM. Doctoral dissertation" by Marxen (2014). The areas where this method was applicable in this thesis project are colored in blue.

Survey	
Applicability	• Empirical research, analysis of real-world design processes • Experimental studies, evaluation in a controlled environment • Implementation studies, real-world deployment of design support • All fields of design science where people's perception of a situation or a process is of interest.
Advantages	• Direct data acquisition of people's opinions • Access to large sample groups • Statistical post-processing
Disadvantages	• No possibility to intervene during the study • Essential formulation of precise questions • Misunderstandings and misinterpretation can ruin the study

Case Study

Case study research is a qualitative method involving the detailed examination of real-world settings. It is often used for exploratory research, pre-testing hypotheses, or when a deep, comprehensive understanding of a complex issue is required. Despite being a powerful tool for gaining in-depth insights, case study research has been subject to debate and criticism (Blessing & Chakrabarti, 2009). Yin (2017) argues that case studies have limited generalizability, may be influenced by researcher bias, and require significant time and resources to conduct, which can pose challenges in some research contexts. On the other hand, Yin (2017) also states that case studies offer a comprehensive understanding of complex topics and facilitate an explorative research approach, providing context-specific insights that inform theory-building and practical applications However, despite being context-dependent, case studies provide valuable practical knowledge and contribute to scientific development by offering insights that can guide theory and practice (Blessing & Chakrabarti, 2009; Marxen, 2014).

Two case studies are carried out in Chapter 4.1 to understand the initial situation and challenges of the CERN development process. Two magnetic transducers are developed for these two pre-studies, and the insights are gathered from the perspective of a design engineer in the domain. This method is ideal at that stage, and the findings can be investigated later with more quantitative methods. The method is a key step in identifying the direction and overall of the thesis project. A profile of the Case Study method with its applicability in this project and its advantages and disadvantages are given in Table 3.3.

Table 3.3: Profile of the Case Study method. Adapted from "A Framework for Design Support Development based on the integrated Product Engineering Model iPeM. Doctoral dissertation" by Marxen (2014). The areas in which this method was applicable in this thesis project are colored in blue.

Case Study	
Applicability	• Exploratory research aiming to identify research questions • Empirical research analysis of real-world design processes • Implementation studies, real-world deployment of design support • Investigation of complex situations when the goal is a holistic picture • Identification of hypothesis
Advantages	• Holistic approach • Works even with very complex situations
Disadvantages	• Findings from a single case or a few cases may not be widely applicable • Effort, due to the necessary application of several research methods • May confirm preconceived notions due to the lack of control and verification bias

Software Testing

To carry out the experimental studies activity of the IDSDM, a continuous testing suite should be generated for the software implementation of the MBSE database tool. The test cases shall be defined based on predefined, necessary functionality that the tool must fulfill to be usable in the later real-world design workflow. Two types of software testing shall be used: unit testing and integration testing. The International Software Testing Qualifications Board (ISTQB®) defines the two terms as follows:

- **Unit testing**: "A test level that focuses on individual hardware or software components." (International Software Testing Qualifications Board, 2023)
- **Integration testing**: "A test level that focuses on individual hardware or software components." (International Software Testing Qualifications Board, 2023)

For example, a possible unit test for saving an electromagnetic model to a database could be to test a successful saving action in the database. An integration test for that scenario would be a test that tests the entire function chain from the user clicking on ”save”, the model is saved in the database, and the user getting back a successful response from the tool. This difference is shown in Figure 3.5.

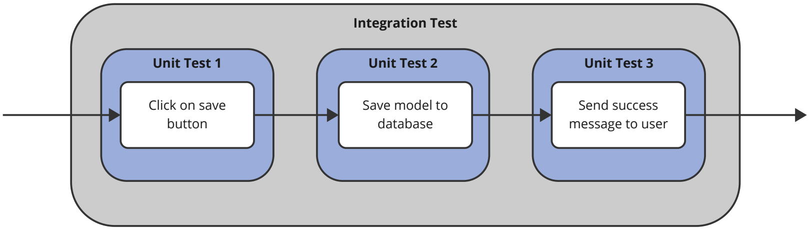

Figure 3.5: Relation between software unit and integration testing. A test that tests a single function, such as a successful send of a message, is called a unit test. A test that tests the execution of multiple units and the entire function chain, including these units.

Software testing should be an essential step of every software development project; thus, no separate profile was created. A common measurement of the scope of the testing suite is the so-called ”test coverage”. The coverage is a percentage metric and states how many lines of code are covered by some test. A high number is desirable to be sure to cover as many functions as possible and realize errors before releasing the software. The developed testing suite and respective test coverage metric are described in Chapter 6.

4 Identification of Magnet Development Challenges

To identify and quantify the superconducting accelerator magnet design challenges using pre-studies, interviews, surveys, and a concluding reference model, the first research question derived in Chapter 3.2.2 will be answered. The question is initially divided into additional sub-questions:

1. **What are the challenges in developing superconducting accelerator magnets?**
   1.1. What initial challenges can be derived during pre-studies, and how does this shape the understanding of the domain?
   1.2. Which challenges can be quantified on domain, organization, and group? How can this quantification be carried out?
   1.3. Which success criteria can be derived from these quantified challenges to measure the success of this thesis project?

4.1 Pre Studies

Two pre-studies will be carried out to get hands-on insight into the development processes and challenges at CERN. Two transducers have been chosen for these studies: the *Translating Fluxmeter* and the *Quench Antenna*. The insights from these pre-studies give a starting point for the second part of this chapter, where the development challenges will be researched and quantified in detail. This approach is in line with the iterative *plan*, *act*, *observe* and *reflect* approach of action research. It is important to note that the transducer must be described in the context of the magnet system, with the magnet being the main cost driver. The transducer and superconducting magnets as part of the accelerator SoS are shown in Figure 2.2.

4.1.1 Translating Fluxmeter

A translating fluxmeter is a measurement system designed to measure static magnetic fields in magnetic regions with high, rectangular aspect ratios. Such aspect ratios are typical for fragment separators or mass spectrometers and make traditional measurements with rotating coils impossible. Utilizing induction coils crafted with printed circuit board (PCB) technology, this device moves longitudinally through a magnetic field to measure field profiles. The fluxmeter integrates voltage from the coil to determine magnetic flux, followed by a deconvolution process to recover the flux density from the measured signals (Liebsch et al., 2023).

The old fluxmeter base was used to build the next generation of the translating fluxmeter, and selected parts with improvement potential were exchanged or modified. This project's carryover variation (CV[7]) was exceptionally high, so documentation and test results of the current system elements were crucial.

As an alternative to the fluxmeter sled encoder, an existing spectrometer system was to be tested. A support for the spectrometer was prototyped, and tests were carried out. After realizing the lower accuracy and alignment difficulties of the spectrometer during these tests, we found an old test protocol in an unrelated network folder, coming to the same conclusion.

During the measurement test of an improved cable chain roller part, the signals of the fluxmeter did not match the positions of the coils inside the measurement head. After investigating this effect, we realized that the internal cabling scheme of the measurement device had changed due to a design error in the measurement head. This cabling workaround needed to be considered in the post-processing scripts but was not documented anywhere at the time.

The project was a success, and multiple fluxmeter subsystems have been significantly improved. The missing documentation and knowledge management practices still led to difficulties during development and caused the duplication of past work. The resulting improvements to the measurement head of the translating fluxmeter were published as a peer-reviewed journal article as a team effort in the research group at CERN (Liebsch et al., 2023).

7 In the parlance of System Generation Engineering (SGE).

4.1.2 Quench Antenna

Quench antennas are specialized sensors used in superconducting magnets. They are designed to detect the early stages of a quench, which is a sudden loss of superconductivity in the magnet. Quench antennas typically consist of a series of pickup coils positioned around or along the magnet. These coils can detect small changes in the magnetic field that occur during the initial phases of a quench. These magnetic field changes are caused by the redistribution of current in the superconducting strands (Ogitsu et al., 1994; Ogitsu et al., 1996; Troitino et al., 2021).

The development of the new quench antenna system involved a fundamental principle variation of the antenna's sensing element and the data processing method. The switch from the previous rigid printed circuit board to the new, flexible ones included multiple iterations and prototype generations. This principle variation was inspired by early scientific results from another research institute dealing with accelerator science (Ogitsu et al., 1994; Ogitsu et al., 1996). While these sources gave valuable insights into the theory and preliminary results, it remained unclear if and in which way early prototypes of the antenna have been implemented. Other sources, like presentations, instructions, or conference submissions, could not be found.

While the design engineer of the previous quench antenna was not working at CERN anymore while the principle variation was carried out, obtaining original design files was difficult. Certain dimensions needed to be measured at the physical predecessor antenna since the rollers and links between the measurement shafts of the device should be reused for the new generation. While trying to find and restore old documentation from the previous system generation and the generation before that, we had to rely on long-term employees having locally stored instances of quench antenna files and artifacts on their computers.

The current post-processing code at the time was not stored in a code versioning system, and it was unclear which version in which network folder the current one was. Post-processed results could not be traced back to the original version of the script they were obtained with.

While this development project was successful, and the accuracy of the state-of-the-art quench antennas could be surpassed by a magnitude, it still remains unclear if similar approaches have been made in the past and if prototypes could have prevented mistakes and efforts along the way.

The initially identified problems during both pre-studies were mainly related to the knowledge management process and knowledge transfer. Internal reference system elements from past system generations were hard to find and identify, and documentation was missing or outdated. A challenge quantification will be carried out to see if these observations are in line with the general situation in the domain and at CERN in general.

4.2 Challenge Quantification

This section shall quantify the initial challenges and insights to define success criteria and improvement areas for the future integration of design support. This quantification shall be done top-down, starting with the most general challenges and becoming more specific along the way. To create distinct levels for the quantification process, the iPeM abstraction levels can be used. Muschik (2011) describe the abstraction for a specific *domain*, *organization*, and *product* (or *system*). Thus, the quantification should be made on these three different levels:

- **Domain**
  The domain challenge quantification is done based on a systematic literature review and also includes top-level management and funding problems.
- **Organization**
  These challenges are focusing on CERN as a research institute, and the findings are based on an organization-wide survey about the scientific information landscape.
- **System**
  The system level quantifies the practical system design challenges faced by domain experts in the TE-MSC group who develop magnets and their subsystems.

4.2.1 Domain Challenges

The systematic literature to identify the challenges on the domain level has been published in a peer-reviewed journal article by Kaeske, Fiscarelli, et al. (2024). After following the systematic literature review method published by Xiao and Watson

(2019), they were left with 20 useful sources. The 13 general domain challenges extracted from these sources are summed up below.

1. **Change of Technology**
   The LHC at CERN uses superconducting magnets made of Nb-Ti, which are reaching their theoretical magnetic field limit (Barzi & Zlobin, 2019; Bottura, Auchmann, et al., 2022; Izquierdo Bermudez et al., 2022; Shen et al., 2022). The transition to new materials, such as HTS and Nb3Sn, could achieve higher magnetic fields but pose significant design and fabrication challenges that need to be overcome to make them usable in series production.

2. **Long Lead Times**
   Developing new superconductors for accelerators is a time-consuming process that usually takes more than a decade of research and development (Bottura, Auchmann, et al., 2022; Bottura, Prestemon, et al., 2022; the FCC Collaboration et al., 2019; Védrine et al., 2022; Wang et al., 2022). Due to this extended timeline, it is essential to conduct parallel R&D and plan for future projects to ensure readiness when construction starts. Major projects, such as the FCC-hh, anticipate decades to complete from the beginning to operation.

3. **Large Scale Infrastructure and Investment**
   Superconducting magnet development for accelerators is costly and requires significant investment in technical fields, facility maintenance, and other materials (Ambrosio, Apollinari, et al., 2022; Bottura, Auchmann, et al., 2022; Bottura, Prestemon, et al., 2022; CERN, 2022; Izquierdo Bermudez et al., 2022; Shiltsev & Zimmermann, 2021; Védrine et al., 2022; Wang et al., 2022). To reduce costs, research focuses on efficient methods, such as modular design and simplified maintenance. Sustained research is crucial to optimize resource use and improve project sustainability.

4. **Maturity of Technology**
   Novel superconductor technologies are still in the developmental stage and are majorly confined to lab settings (Barzi & Zlobin, 2019; Bottura, Auchmann, et al., 2022; Shiltsev & Zimmermann, 2021; Wang et al., 2022). For the next-generation colliders, magnets that can generate up to 16 T fields are necessary. The current technologies, such as HTS, Nb3Sn, or REBCO, are not ready for large-scale use at such field levels yet. This indicates that there is a significant technology gap, which poses a challenge to ongoing research and development efforts.

5. **Continuous, Cross-Domain Teams**
   Developing new magnet technologies requires a collaborative approach between academia and industry. Special R&D programs help retain expertise and attract new talent (Ambrosio, Amm, et al., 2022; Bottura, Auchmann, et al., 2022; Bottura, Prestemon, et al., 2022; CERN, 2022; Gourlay et al., 2022). Budget cuts present significant challenges when it comes to retaining a skilled workforce. Stable teams are essential to advance new technologies for future accelerator projects.

6. **International Collaboration**
   International cooperation among research, universities, and businesses is crucial for developing superconductor technologies for accelerators (Ambrosio, Amm, et al., 2022; Ambrosio, Apollinari, et al., 2022; Bordini et al., 2019; Bottura, Auchmann, et al., 2022; Bottura, Prestemon, et al., 2022; CERN, 2022; Shiltsev & Zimmermann, 2021; Védrine et al., 2022; Wang et al., 2022). Such collaboration helps overcome technical challenges, integrate new infrastructures and mature technologies for mass production, and manage large-scale project costs and complexities through cost-effective strategies and modular designs.

7. **Parallelized R&D Efforts**
   Future High-Energy Physics (HEP) applications require integrating R&D with global collaborations to advance superconducting technologies for accelerator magnets (Ambrosio, Amm, et al., 2022; Bottura, Auchmann, et al., 2022; Izquierdo Bermudez et al., 2022; Védrine et al., 2022). Adequate planning, financial investment, and expanding research scope are necessary to meet emerging needs. Sustainability and inclusiveness are critical for long-term success.

8. **Cross-Cutting Activities**
   High-field magnet development requires a multidisciplinary approach that integrates material science, cryogenics, and numerical modeling (Gourlay et al., 2022; the FCC Collaboration et al., 2019; Védrine et al., 2022). This is crucial for addressing complex design challenges in high-energy physics, which encompass diverse research fields from beam physics to magnet design.

9. **Production Scale**
   Magnets for accelerator projects require strategic decisions based on the required number of units between lab production and industry involvement (Ambrosio, Apollinari, et al., 2022; Lebrun & Taylor, 2015). Small-scale lab production works for a few high-field magnets, while industrial involvement is needed for cost efficiency and uniformity in larger quantities. Challenges include technology transfer and careful procurement management by CERN to balance costs against benefits to member states.

10. **Multi-Physics Modeling**
    High magnetic fields in superconducting magnets require advanced multi-domain simulations to protect them from quenches and push the boundaries of reachable field strength (Brouwer et al., 2019; Garcia, 2021; Maciejewski, 2019; Troitino et al., 2021). Combined and coupled simulation infrastructures and specialized software are needed to help model interactions within magnet systems and prevent operational failures.

11. **Standardization of Simulations**
    To improve multi-physics simulations in superconducting magnets modeling, integrated simulation domains and standardized queries across various sources are needed (Biedron et al., 2022; Maciejewski et al., 2023). Effective information sharing can only be achieved through standardized software interfaces and a transition to a unified simulation workflow.

12. **Usability of Tools**
    Accelerator magnets require evolving software tools and consistently maintained code (Biedron et al., 2022). Sustainable code maintenance practices are crucial to ensure the tools remain functional and up-to-date by managing discrepancies between the system's logic and user interfaces.

13. **Knowledge Management**
    Collaboration across multiple disciplines and global efforts are required to develop superconducting accelerator magnets. To ensure traceability and repeatability, model-based system engineering with versioning and detailed documentation of models is vital (Ambrosio, Apollinari, et al., 2022; Biedron et al., 2022; Maciejewski et al., 2023). Access to historical data and effective knowledge transfer is crucial for managing complexities and enhancing model quality over multiple system generations.

4.2.2 Organization Challenges

To analyze the challenges of CERN as an organization, the data of the *CERN Scientific Information Landscape Project* should be used and interpreted in the context of this thesis project. The project focuses on the knowledge management of scientific information within the organization. With this information being the core outcome of CERN's development activities, the study is representative of the difficulties within the whole organization and its projects (Baranowska et al., 2023). For all survey questions relevant to this chapter the answers of over 200 participants have been collected.

The first metric that should be analyzed is the effort needed to find project-related information in general across the organization. The survey participants could rate this on a scale from 1 (difficult) to 5 (easy). The average effort score of a total of 232 participants turned out to be 3.22. This score is only slightly better than the medium score of 3. To interpret this result, the entire organization's personnel must make a moderate effort to find the relevant scientific data. For an organization whose key outputs this scientific information, this score desires to be improved. The histogram with the effort scores is shown in Figure 4.1.

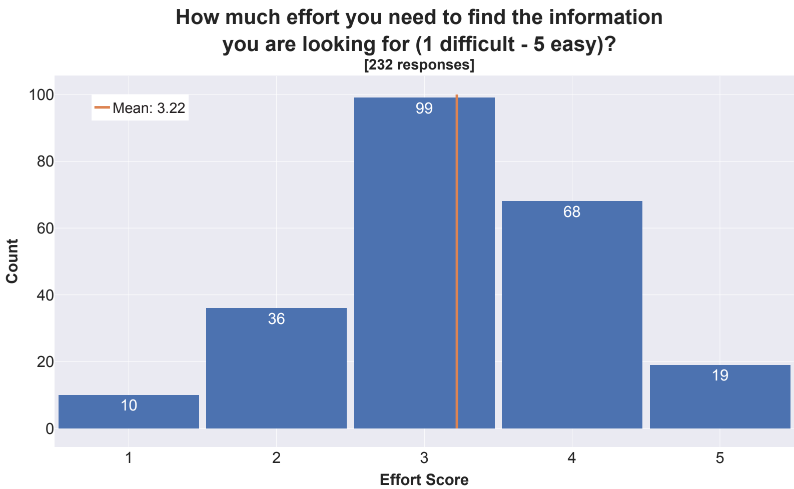

Figure 4.1: Histogram showing the perceived effort of personnel at CERN associated with the finding of project-related scientific information. A score of 1 stands for difficult information finding, and a score of 5 for easy information finding. 232 responses have been collected.

Before being able to find relevant data, this data needs to be stored by people responsible for past projects. To investigate the knowledge management workflow of the general personnel, the survey participants had to answer whether they actively store documents to preserve them for later projects or to expose them to colleagues. These answers were recorded for different, distinct data types. Almost 40% of the participants do not actively store software source code. Engineering documents and research data are generally not stored by 33.5% and 37.9%, respectively. To follow up on the previous question, difficulties in finding relevant data are not surprising if over one-third of the survey participants do not actively use data storage and knowledge management practices. The percentages of the active data storage question are shown in Figure 4.2.

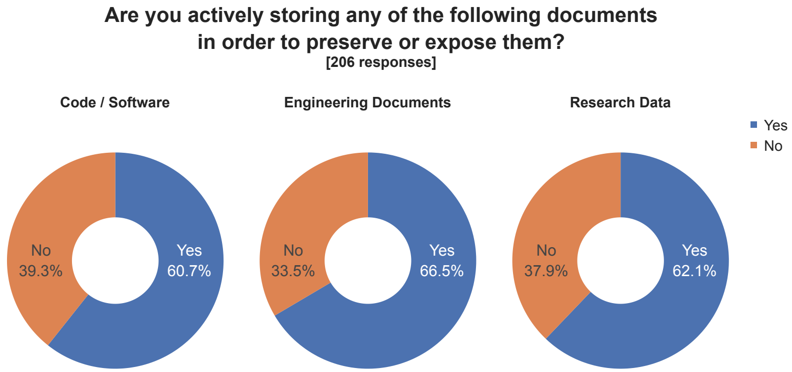

Figure 4.2: Yes or no question whether the survey participants are actively storing documents for the purpose of preservation or the exposure of the data to colleagues. This question was answered for the distinct data types: software source code, engineering documents, and general research data. 206 responses have been collected.

To understand the data search and retrieval workflows, the survey participants had to answer which tools they were using to search for project-relevant software and research data. Over half of the participants stated that they use Google or other general search engines to find this kind of data. The CERN internal engineering document management tool EDMS was only used during this stage by 7% of the participants. One-third of the survey participants rely on their colleagues as a source of information. With the high staff turnover, in relative terms to the long development project times, this is prone to lead to difficulties. The results also show that the survey participants used a wide variety of tools. In the survey report Baranowska et al. (2023) published a list of 23 individual tools that are part of the scientific information landscape at CERN of which 16 are managed and hosted in-house. The variety of tools that grew over the years led to individual approaches and best practices in the different parts of the organizations. These differences now hinder a streamlined organization-wide knowledge management process.

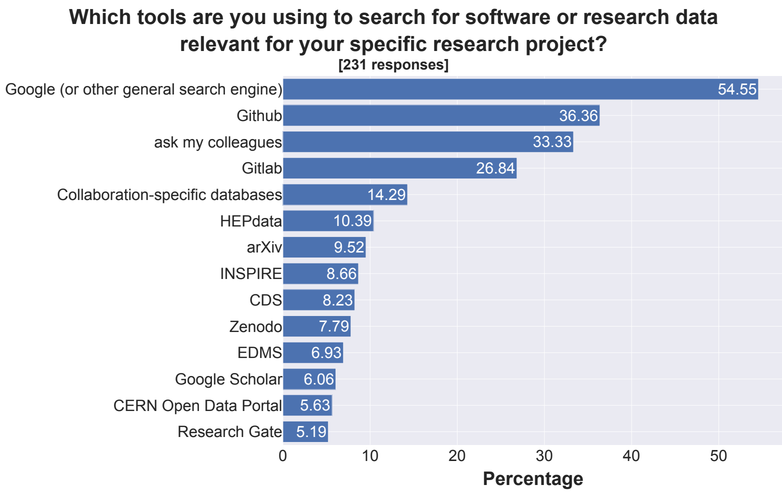

Figure 4.3: Percentages of tools used by the participants to search for project-relevant software and research data. 231 responses have been collected.

The authors of the scientific landscape project report agree on the points regarding the challenges in knowledge management. They go so far as to say that the fragmented tool landscape at CERN makes it impossible to manage the scientific information without significant manual effort. As a possible solution, they propose a streamlined information management workflow in combination with a centralized institutional repository for scientific information and a special Current Research Information System (CRIS) (Baranowska et al., 2023).

4.2.3 System Challenges

The practical challenges during the system development process at CERN were identified during an interview study in the TE-MSC group. The results of these explorative interviews have been initially published by Kaeske, Fiscarelli, et al. (2024) and are elaborated here in greater detail. 14 experts in the group were posed with a set of questions in a semi-structured interview setting. The following four questions of these interviews are relevant to understanding the system development challenges in the group:

1. Did you/do you follow any methodic approach during a development project?

2. What problems/challenges occur to you during a typical project at CERN?

3. Which problems/questions are important to you to solve?

4. What benefits do you see by solving/answering these problems/questions?

The answers to the first questions have been summarized and grouped into three relevant aspects:

- **Methodology & methods**
  There was a conses among the participants that no holistic, CERN wide methodology for magnet development projects exists. Apart from the missing methodology, nine participants could not identify a general structured or methodical approach during development. Seven participants are utilizing domain-specific or individualized approaches to structure projects and solve engineering problems.
- **Tools**
  The majority of participants (10) use existing, specialized tools during a typical development project. Five participants could recall frequently using project management tools, while two participants were using integrated simulation design tools.
- **Processes & workflows**
  Only seven participants could identify any existing procedure during their development workflow. A clear data storage procedure using the CERN internal tools like EDMS could be only identified by four participants. Thus, the category is in line with the non-existing methodology results from above.

The counted answers within these categories are shown in Figure 4.4.

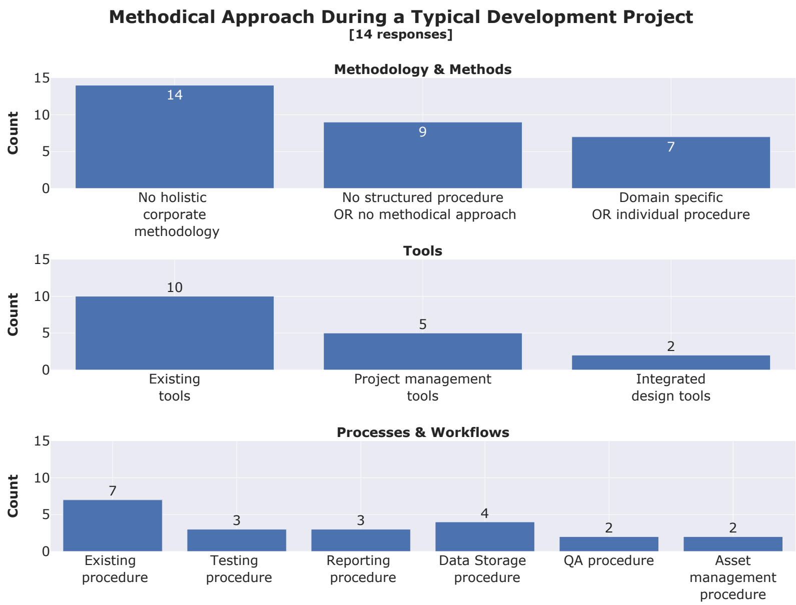

Figure 4.4: Results of the first interview question. The question was meant to identify current methodic approaches during the magnet development process. 14 responses have been collected.

Questions number two and three are analyzed together since they refer to the same challenges and challenge categories. Question two focuses on the frequency with which these problems occur (Occurrence), and question three on their significance (Importance). For our analysis, only the problems that were occurring and/or were important to more than half of the participants. The challenges above this defined threshold are shown in Figure 4.5. Of these seven remaining challenges, four are related to the knowledge management process: Problems with historical data/documents, process quality of the knowledge management, missing and/or low documentation, and knowledge/data transfer. The other three problems are general communication problems, insufficient tool support for the development process, and problems related to standards and best practices. These results are in line with our experiences during the pre-studies and show similar problem situations in a variety of magnet development projects at CERN.

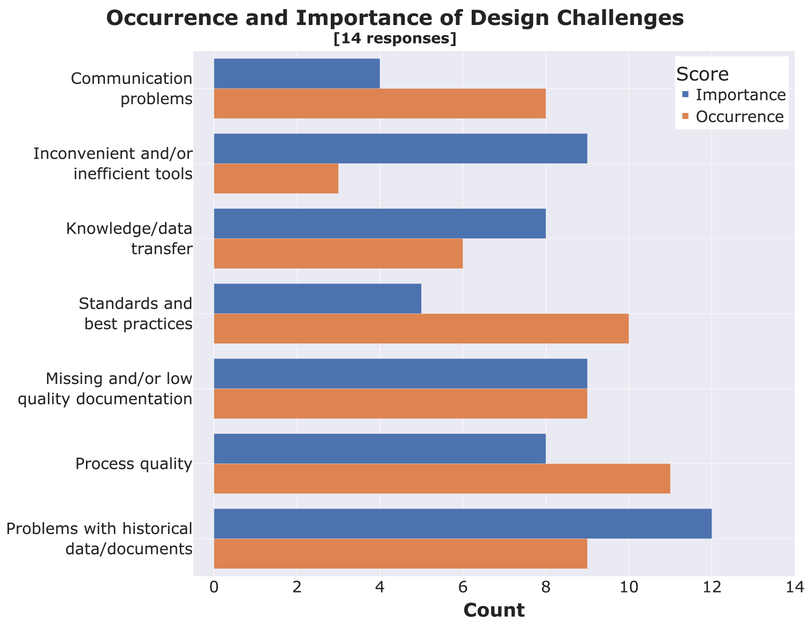

Figure 4.5: Combined results of the second and third interview questions. The questions were meant to identify the occurrence and importance of magnet development challenges. The challenges are ordered in ascending order to their combined score of occurrence and importance. 14 responses have been collected.

The results of the fourth interview question show the expected benefits of solving the above-identified practical development challenges. The participants (9) were expecting improved data, information, and knowledge management. Ten participants were expecting an improved design process in general. This is in line with the strong emphasis on knowledge management challenges in the previous questions. Six participants mentioned expected improved decision-making and better onboarding for new personnel. The counted answers to the fourth question are shown in Figure 4.6.

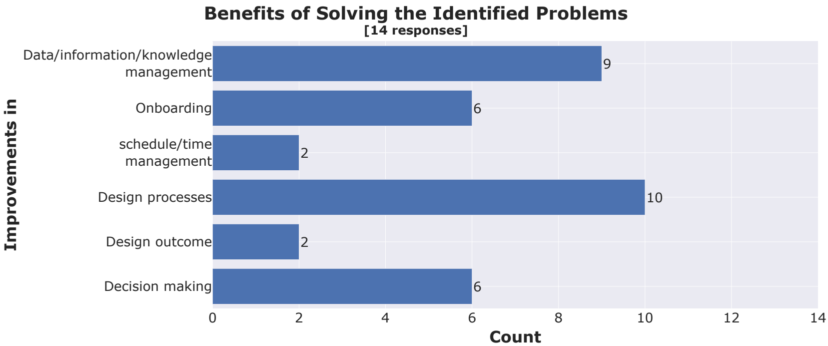

Figure 4.6: Results of the fourth interview question. The question was meant to identify the concrete benefits solving the practical challenges would have on the magnet development process. 14 responses have been collected.

4.3 Reference Model

The challenges identified in this chapter will be grouped using a reference model. The reference model diagram is introduced by Blessing and Chakrabarti (2009) and helps to represent the current situation of a project or environment. The challenges are illustrated as individual nodes (factors in reference model terms) and are linked by the relationships and influences they have on each other. Nodes at the bottom of the diagram are called key factors and describe the root causes. The node at the very top is called the success factor and motivates the research project.

The current literature has identified the root causes of the challenges in the domain of superconducting accelerator magnets. The main causes are the collaboration of cross-domain teams distributed to different countries in industry and academia, the constant search and need for new technologies, the long lead times of up to multiple decades, and the required scale of the need for infrastructure and investment. The frequency of staff turnover, in combination with the required global coordination of R&D projects and the rising complexity of these research projects, put the need for standard and best practices and effective knowledge transfer and management into focus. To improve and build on learning from past development projects, we identified the need for knowledge about past magnet reference system elements as the main success criteria. This reference model with all links and factors is shown in Figure 4.7.

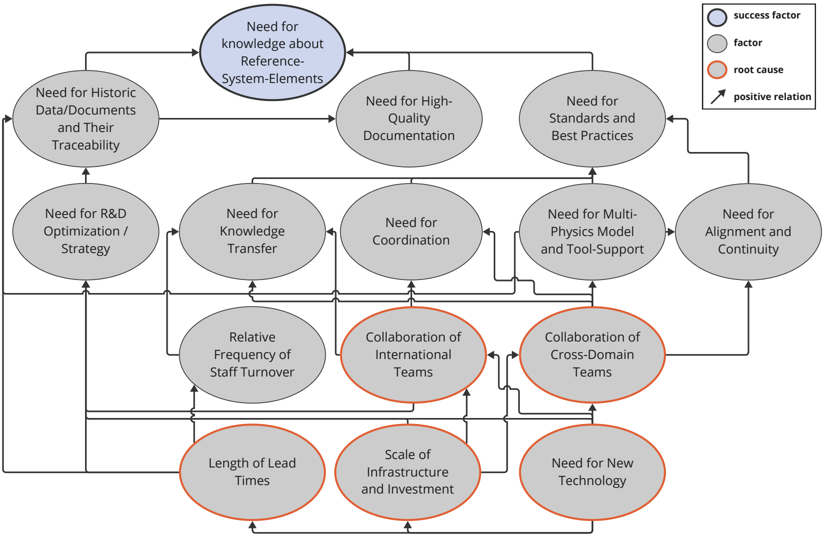

Figure 4.7: Reference model listing all quantified challenges in the development of superconducting accelerator magnets. The links between the challenges are all positively related[8]. The root causes are shown at the bottom of the diagram, and the success factor (knowledge about reference system elements is shown at the top.

From the factors and their relationships between each, the system of objectives for this thesis project could be further specified. These objectives are grouped into three categories, which are listed below.

- **Modeling Process**
  With the simulation requirements becoming more complex and requiring multi-physics modeling workflows, process descriptions have become increasingly important. In relation to critical knowledge management, the description of

[8] Challenge A becomes more significant, leading to related challenge B becoming more significant as well.

these processes and the *formalization of the modeling activities* is a key objective. This formalization will be carried out in Chapter 5.

- **Interfaces**
  Closely related to this is the compatibility of results and artifacts with the different simulation software required to perform multi-physics simulations. Future design support should consider this and needs to implement *generically compatible software interfaces* and APIs. This objective should be adhered to in Chapter 6.
- **Traceability**
  Knowledge about system reference elements can only be achieved by establishing and ensuring traceability of files, documentation, and artifacts across multiple system development generations. To measure this traceability, the *existence of links and references* to past generations within the system models and the *description of the models* itself can be tracked. The objective of making system reference elements accessible will be focused on in Chapter 6.

These objectives should be used beyond this thesis to support future design developments in the domain.

4.4 Summary

A summary of this chapter is given by answering the subquestions of the first research question.

1.1. What initial challenges can be derived during pre-studies, and how does this shape the understanding of the domain?

The initial challenges during the pre-studies primarily revolved around knowledge management, documentation, and legacy system integration. These challenges led to difficulties in development, including issues with component compatibility, undocumented design changes, and lack of version control for code. Despite these obstacles, successful improvements were achieved in both the translating fluxmeter and quench antenna systems. A quantification process is proposed to evaluate the transferability of the initial challenges in the superconducting accelerator magnet domain and to identify further improvement potential.

1.2. Which challenges can be quantified on domain, organization, and group? How can this quantification be carried out?

Quantification of the development challenges was carried out on domain, organization, and system levels. A systematic literature review has been conducted for the domain challenges. The main organization challenges have been derived from an analysis of a CERN survey about the scientific information landscape. Conducting semi-structured interviews has resulted in practical system design challenges for the experts in the group for magnets and superconductors. Apart from key domain challenges, like the long lead times and the difficulties of switching to new superconductor technologies, the knowledge management problems from the pre-studies have been a ubiquitous theme throughout the quantitative process. Missing documentation, lack of data traceability, and lack of knowledge management standards have been critical factors on all three analyzed levels.

1.3. Which success criteria can be derived from these quantified challenges to measure the success of this thesis project?

The initially identified and afterward quantified challenges have been consolidated in a so-called reference model. Apart from the main root causes, the success criteria for this thesis project have been identified in that way. Knowledge about system reference elements of past magnet system development projects and research artifacts, in general, turned out to be the main success criteria. The success factor is directly related to the magnet simulation process, the simulation software interfaces, and the traceability of simulation artifacts. The system of objectives could be concretized by adding the formalization of simulation activities and processed descriptions, the general compatibility of available software interfaces and APIs, the existence of links to past models and external references, and the quality of the system model description.

5 Concept of an Electromagnetic Design Methodology

In the following, based on the quantified challenges from Chapter 4, a methodology for the electromagnetic design of superconducting accelerator magnets will be created together with adequate tool support to teach the new methodology to its users. The second research question derived in Chapter 3.2.2 will be answered for this purpose. The research question is initially divided into additional sub-questions:

2. **How can a methodology for the electromagnetic design of superconducting accelerator magnets be formulated, and how can it be taught to its users?**

   2.1. To which extent do current CERN standards, frameworks, and challenges influence the implementation of the methodology and the choice of modeling approach?

   2.2. How can a tool support to carry out transfer studies and teach the methodology to its users look like?

   2.3. How can the iPeM be used to model the electromagnetic design of superconducting accelerator magnets while being in line with existing CERN frameworks?

5.1 Modelling Approach

The organization-wide challenges and findings from the interviews in the CERN TE-MSC group have led to the conclusion of general missing methodical guidance and adequate tool support during the development process. In contrast to these practical viewpoints from magnet designers and experts in the organization, a dedicated SE and PM framework, the openSE[9], was specifically developed for CERN and is supported through active in-person courses to teach its concepts to the CERN personnel. While this framework exists, it lacks widespread acceptance and adoption throughout

9 The openSE framework was introduced in Chapter 2.2.6.

the organization. Examining the openSE further, it becomes apparent that practical implementation steps are missing and that the later project stages in the framework have never been developed, and that various guidelines and resources are of the status ”Not available yet” (Bonnal, 2024). The templates that the document-based approach of openSE is based upon are in parts missing or are not made public to the eternal CERN personnel.
While openSE may not be fully developed at this stage and no tool support is in place, this framework is the only existing SE and PM standard at CERN. Thus, the magnet methodology introduced in this thesis project should be based on a modeling framework that is capable of regarding both domains (SE and PM) and including the phases of the openSE framework. As shown in Chapter 2.2.6, existing frameworks and implementation fall short in scope and tool support. While enterprise architecture frameworks seem promising for integration, no clear steps for an organization-wide governance process exist. Taking back a step, more general modeling frameworks shall be examined to serve as the methodology foundation at CERN. To choose a fitting framework, selection criteria customized to the CERN research environment shall be defined.

According to Albers et al. (2012), integrated modeling of Product Development processes should equally emphasize management and design aspects to comprehensively cover all relevant factors (**SC1**). With the openSE as a boundary condition and the focus of the work on the electromagnetic modeling process, the model must help maintain consistency and coherence across product and process models for seamless SE-PM integration (**SC2**). To select modeling frameworks that effectively guide both product and process models within the engineering design context, the four validated criteria proposed by Eckert et al. (2017) will be added ((**SC3 - SC6**)). Adequate focus on the human individuals involved will increase acceptance of this formal support, enhance methodological adherence (Albers & Lohmeyer, 2012; Badke-Schaub et al., 2011), and avoid failure similar to other process and organizational modeling methods due to the insufficient emphasis on human behavior (Haque et al., 2003) (**SC7**).
These seven derived selection criteria are listed below in a more concise way:

- **SC1:** Effectively guide both PM and SE modeling
- **SC2:** Balance focus between management and design domains
- **SC3:** Prioritize engineering design context
- **SC4:** Emphasize multi-participant processes
- **SC5:** Provide situation-specific modeling guidance
- **SC6:** Offer an integrated product and process approach
- **SC7:** Position humans at the center of Product Development

The seven selection criteria have been applied to eight conceptual ”macro-level” frameworks resulting from a comprehensive literature review performed by Wynn and Clarkson (2024). After the evaluation, two suitable options could be identified: the Integrated Product engineering Model (iPeM) and the Problem, Social, and Institutional spaces (PSI) modeling framework. The result of how each framework fits the criteria is given in Table 5.1.

The PSI framework achieves a balance by taking a moderate approach, providing flexibility and a fair level of detail in integration processes. The iPeM requires substantial stakeholder involvement and excels in offering comprehensive guidance, making it ideal for situations where detailed guidance is crucial. This detailed guidance is needed specifically for the magnet development domain since the magnet modeling process includes complex and detailed steps, and even more complexity will be introduced by adding more modeling domains to the methodology in the future. Thus, the iPeM was chosen as the modeling framework of choice for this thesis project.

Table 5.1: Ranking of the eight conceptual ”macro-level” frameworks presented by Wynn and Clarkson (2023) to investigate their suitability for general SE-PM integration. The ranking is based on previous results and the author’s expertise in system development at CERN. The circles represent high (●), medium (◑), and low (○) fit to the selection criteria.

	Selection Criteria						
Modeling Frameworks	**SC1**	**SC2**	**SC3**	**SC4**	**SC5**	**SC6**	**SC7**
Ziel–/Objekt–/Prozess–/Handlungssystem (ZOPH) model (Negele et al., 1997)	explicit SE	○	●	●	◑	●	●
Integrated Product engineering Model (iPeM) framework (Albers, Reiss, et al., 2016)	explicit SE & PM	●	●	●	●	●	●
Design Activity Management (DAM) model (O’Donnell & Duffy, 2002)	explicit SE & PM	●	●	●	◑	○	◑
Groupe de Recherche en Automatisation Intégrée (GRAI) reference model (Doumeingts et al., 1996)	explicit SE & PM	●	●	◑	●	●	○
Problem, Social and Institutional spaces (PSI) modeling framework (Reich & Subrahmanian, 2022)	implicit SE & PM	●	●	●	●	●	●
Viable Systems Model (VSM) for dynamically changing environments (Beer, 1995)	implicit SE & PM	◑	◑	◑	●	○	○
Frameworks for adaptive systems (e.g. Chiva-Gomez, 2004; Naumann & Vajna, 2004)	limited to adaption	◑	●	◑	◑	◑	◑
Feedback System Function Structure (FS^2) model (Wynn & Maier, 2022)	limited to feedback	◑	●	◑	●	◑	●

5.2 iPeM Tool Support

After selecting the iPeM as the model of choice to derive the electromagnetic magnet design methodology, a transfer study in the parlance of the IDSDM is carried out. The goal of such a transfer study is to find a way to teach the methodology to its users. In this thesis, we prioritize and conduct the transfer study before introducing the methodology itself. This is in line with the statement credited to Professor Albert Albers: ”If it cannot be taught, it is not a design support as it will not help anyone” (Marxen, 2014).

Various software tools have been developed to facilitate the direct application and education of the iPeM in practical environments. The InnoFox stands out as one of the most recent and best documented of these tools (Albers, Reiß, Bursac, Walter, et al., 2015). However, user feedback has highlighted areas for improvement in the InnoFox tool, such as the lack of features to individualize the iPeM meta-model itself and challenges in accessing the software. To validate the tailoring process using the iPeM at CERN, to provide an alternative to the InnoFox tool, and to be able to explain the derived methodology interactively, a new iPeM tool has been implemented. The functionality and effectiveness of this tool should be initially validated using the openSE activities since standard management methods can be used, and the prototypical integration does not involve custom software development.

5.2.1 Webinterface

The iPeM tool has been developed as a web application to avoid the manual updating procedure on local devices of the InnoFox and to extend the compatibility beyond Android tablets. The unique feature of the new iPeM tool is the possibility to create tailored methodologies based on the iPeM meta-model.

In the iPeM, system thinking is extended to seeing activities during the system development as components of the operation system. This explicitly states that development activities can be modeled as subsystems of the operation systems and thus have a fractal character, like any system. Every activity has inputs and outputs and can have associated activities and subactivities. To create a CERN specific, organization-wide methodology[10], a distinct set of activities needs to be derived in the

[10] This concept was introduced in Chapter 2.2.3.

form of a reference process model. The resulting activity patterns can be inductively adapted after the application of the model from the learnings in real-world project instances. This instantiation of the organization-specific methodology happens and is documented in the dynamic part of the model, the so-called phase model. This phase model can be simplified to resemble a project plan or Gantt chart during the project development lifecycle.

The matrix of buttons spanned by the problem-solving activities and openSE macro activities contains the respective method collection fitting to each of the activity combinations. During a project scenario, users can search for and select assisting methods for the current state from this catalog. The catalog is presented in the form of a method list. Each method in this list is linked to a detailed profile of the method, including a description and actionable steps, among other information and metadata. The iPeM tool contains the layout of the iPeM meta-model[11], but implements them as interactive, clickable HTML elements. The glsipem tool, filled with a generic methodology as an example, is shown in Figure 5.1. A screenshot of an example method profile view is shown in the Appendix in Figure A.1.

[11] This is shown in Figure 2.7 and explained in the respective chapter.

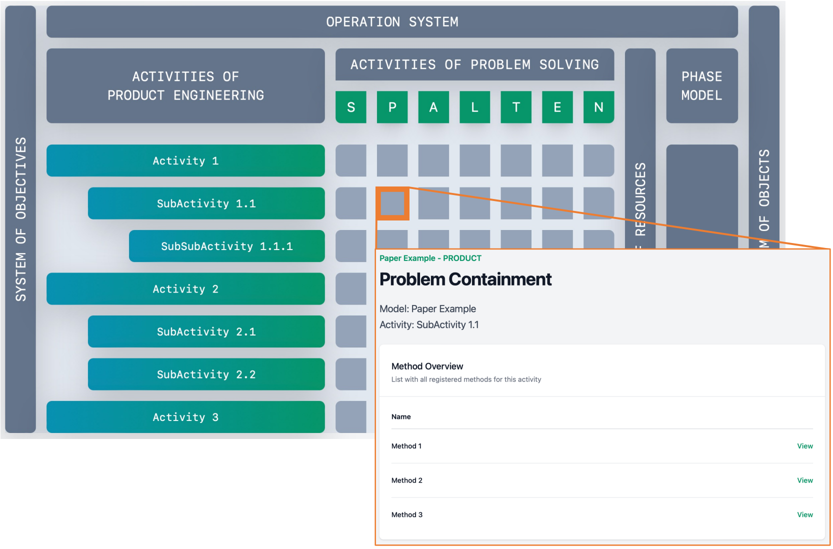

Figure 5.1: The iPeM tool, showing the interactive elements of a generic, example methodology. The product engineering activities show the tool's ability to create custom activities and multiple levels of sub-activities. The activity matrix is spanned by these product engineering activities and the SPALTEN problem-solving activities. Each element in this matrix contains a catalog of custom methods according to the problem-solving and product engineering activity. The dynamic part of the iPeM, the so-called phase model, is used to link the project plan and keep track of the duration of the executed methods and activities. From "Tool support for implementing a methodology in magnet development projects at CERN" by Kaeske, Wagner, et al. (2024b).

5.2.2 Tool Workflow

To validate the iPeM tool, an example case needs to be created, and the tool needs to be implemented in the CERN processes. A dedicated workflow has been prototyped to carry out the implementation. The workflow describes the way starting from existing standards and best practices in the organization, operationalizing them using the iPeM tool, and finally making them available and usable through the export into existing software tools, such as a project management tool. The entire workflow consists of four steps, which are linked below.

1. Identifying standards and best practices and transferring them into the iPeM tool.

2. Formalizing activities and associating them with the (SPALTEN) problem-solving activities. Filling the activity matrix with fitting methods.

3. Exporting the resulting up-to-date activities and method catalog to the project management software (e.g., Merlin Projects).

4. Dragging and dropping relevant activities and methods into the project plan.

This workflow and the following results of the validation study have been additionally published in greater detail in a peer-reviewed paper (Kaeske, Wagner, et al., 2024b). The described workflow is shown in Figure 5.2.

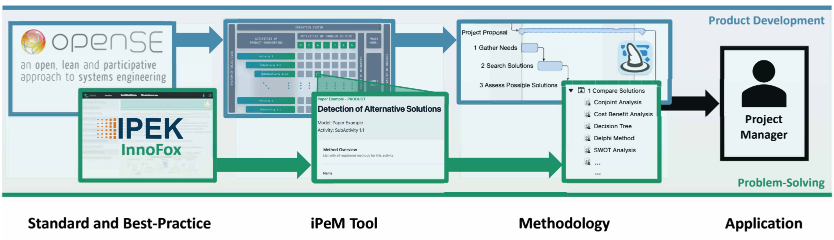

Figure 5.2: Workflow of operationalizing existing standards and best practices by formalizing their activities using the iPeM tool. From the iPeM tool as the single source of truth for the activities and associated methods, an export of the tailored methodology into commonly used project management software such as Merlin Projects can be performed. In this way, any standard or best practice can be operationalized. In this figure, the openSE is used as an example of a best practice on the left side. From "Tool support for implementing a methodology in magnet development projects at CERN" by Kaeske, Wagner, et al. (2024b).

5.2.3 Transfer Study

The openSE was selected as the standard that shall be operationalized during this transfer study to validate the iPeM tool. The well-documented *initialize* phase of the openSE will first be translated into activities that can be used later to carry out interviews to validate the learning tool among users of the organization-specific methodology. The list below explains the phases of the openSE and derives the sub-activities for the initial phase.

1. **Initialize**[12]
   Assessing the current situation to identify the problem, proposing several potential solutions, and formally deciding to initiate the project's front-end phase. The key deliverables of this phase are created by executing these subactivities:
   - Create Project Mandate
   - Create Project Proposal
   - Verify Project Proposal
   - Create Project Roadmap
   - Kick Off Project9

2. **Study**
   Collecting user or stakeholder needs, transforming them into requirements, exploring all potential solutions to the problem, and recommending the preferred solution while demonstrating its feasibility.

3. **Design**
   Finalizing the needs and corresponding requirements, designing the solution through engineering or systems-level design, planning the Build and Commission phases, and developing prototypes or proofs-of-concept as necessary.

4. **Build**
   Conducting a detailed design, creating the equipment and facility through procurement, manufacturing, and installation, and verifying that all requirements have been correctly implemented.

5. **Commission**
   Validating the project's outcomes to meet all requirements, refining unresolved issues, ramping up operations, adapting to emerging needs and technologies, training teams, and releasing documentation.

[12] This phase is documented in detail in the openSE documentation, and the guidelines for creating the required documents such as the project proposal are available online to the general public under https://opense.web.cern.ch/.

6. **Finalize**
   Documenting the project's lessons learned in the close-out report.

Similar to the problem-solving activities of the iPeM, these six phases have a fractal character, and each phase can have sub-phases of each own (openSE Editorial Project, 2016).

To integrate the activities and methods into current project management workflows, an export to the template library of the project management software Merlin Project has been performed. The Merlin software is being commonly used at CERN. If changes to the openSE activities are being made in the iPeM tool, a re-export can be performed to keep the Merlin template library up-to-date.

Subject Matter Expert Interviews

To get feedback on the iPeM tool and its impact on the everyday workflow of its users, five semi-structured interviews with subject matter experts have been carried out at CERN. The participants were asked the following four questions:

1. Could the proposed tool support and improve your personal project management workflow?
2. How could this kind of tool be implemented in your daily routine?
3. Could this tool help the new personnel onboarding process at CERN?
4. Which aspects of the tool are missing or could be improved?

According to the feedback received from the interviewees, the tool was positively received. They highlighted its potential as a central repository for project knowledge and as a support for personnel who do not have formal project management training. The tool was also seen as a way to make administrative tasks less monotonous, allowing technical workers to concentrate on their primary responsibilities. The interviewees considered the tool a structured educational resource that could enhance project efficiency and management understanding organization-wide. The participants also valued the tool's role in easing the onboarding process for new employees by providing practical, contextual knowledge. Overall, the participants considered the tool a significant aid in project management. They suggested that it could evolve to cover all project lifecycle activities and integrate well with existing systems like CERN's EDMS. Improvement potential was identified in the missing coupling of the prototype to CERN internal tools like EDMS and in the way interactive tips and notifications are displayed as guidance. The following list contains the key feedback points obtained from the interview study.

- **Improvement potential:** interactive tipps and notifications; integration with CERN tools; missing openSE phases
- **Benefits:** smoother learning curve; easier onboarding; higher project efficiency
- **Single source of truth:** training tool; closes knowledge gaps; raises company awareness
- **Consensus:** focus on main tasks while keeping up with admin, immediate & long-term benefit; support for untrained personell

5.3 Electromagnetic Design Methodology

After initially validating the iPeM tool as a form of education support, the tool is used to derive the electromagnetic design methodology. This derivation step is an embodiment of design support in the context of IDSDM. The electromagnetic design methodology is part of the system of objectives as defined in the overall research goal in Chapter 3.2. The web-based tool can be used to make the methodology available CERN-wide and serves as interactive documentation even after the end of this thesis project.

To create an individualized reference model of the iPeM that describes the electromagnetic magnet design, as described above, the development activities of this design process need to be specified. These activities can be derived from the already validated, integrated design approach being presented in ROXIE (Russenschuck, 2025). The magnet design activities are explained here:

1. **Feature-Based Coil Geometry Modeling**
   Optimizing field performance can be done by focusing on a few chosen, impactful design variables derived from key system parameters.

2. **Conceptual Coil Design**
   Using genetic algorithms allows the treatment of discrete and continuous optimization problems, such as varying the number of coil turns and the block

positions. Niching methods provide the designer with local optima that can subsequently be studied in detail for dynamic effects, robustness to manufacturing errors, and quench performance.

3. **Multipole Field Error Optimization**
   Determinist optimization algorithms are applied to fine-tune the coil geometries, taking into account manufacturing constraints and robustness to manufacturing tolerances. All layers of a coil should be optimized individually without field errors compensating each other. Sensitivity analysis, using Lagrange-multiplier estimation and payoff tables, delivers the hidden resources of the coil layouts.

4. **Iron-Induced Multipole Minimization**
   The finite element method with a reduced vector potential formulation or the coupling method between boundary and finite elements (BEM–FEM) is used to minimize the iron-induced multipole field errors A parametric geometry and mesh generator for higher-order quadrangular finite elements can be facilitated. At this stage, 2D field simulations are sufficient for long accelerator magnets compared to their cross-section.

5. **Persistent Current Calculation**
   Subject to a varying magnetic field, persistent currents are generated, screening the interior of the superconducting filaments. The induced field errors, which are the largest at the injection field level, can be partially compensated by geometrical field errors or ferromagnetic shims.

6. **Time Transient Effect Simulation**
   Electrical network models of the Rutherford-type cables are used to calculate ramp-induced losses and field errors due to interfilament and interstrand coupling currents. The simulation of time-transient effects in quenching superconducting magnets uses a combination of thermal networks, electrical networks, and finite-element models.

7. **Coil Head Geometry Generation**
   Methods of differential geometry are applied to generate the coil head geometry both on the asymmetric connection side and the symmetric return end. The integrated 3D field harmonics are minimized while taking the local peak field-enhancement into account.

8. **Fringe Field Computation**
   The 3D BEM–FEM coupling method is used for the field calculation of the iron

yoke in the magnet extremities. The method allows for distinguishing the reduced field of the iron yoke and the excitation field of the coils. The influence of the yoke on the integrated multipoles and tip fields in the coil head can thus be readily identified.

9. **Drawing Production and Head-Spacer Manufacturing**
   Drawings for the coil cross-section and the coil heads are facilitated for rapid prototyping. This iterative step is included in the simulation process and is usually performed using computer-controlled five-axis milling to manufacture the spacers for the coil heads.

10. **Experiment Design and Magnetic Measurement Data Simulation**
    The observation function is established for induction-coil magnetometers and field sensors, and the powering cycles of the magnets are studied to predict the signal level in the field transducers.

11. **Manufacturing Error Tracing**
    Inverse field problems are solved using the Levenberg–Marquard algorithm, which minimizes the least-squares error between measured and predicted multipole field errors.

The methodology with the electromagnetic design steps as subactivities of the iPeM *model principle and embodiment* activity and the openSE phases as subactivities of the iPeM *manage projects* activity visualized with the iPeM tool is shown in Figure 5.3

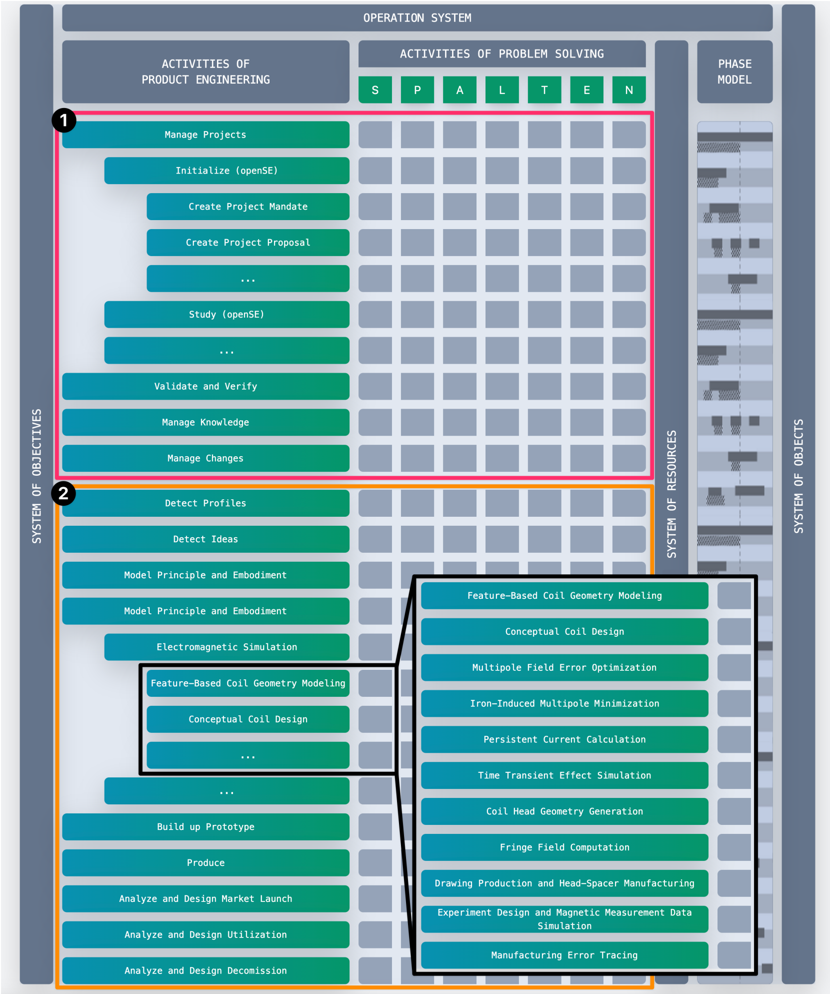

Figure 5.3: The methodology for the electromagnetic design of superconducting accelerator magnets, visualized using the iPeM tool. The red box (1) shows the basic activities of the reference model, including the openSE project management activities. The orange box (2) shows the core activities of the reference model, including the electromagnetic simulation activities. Due to space constraints, the magnet design activities are shown in separate, overlaid detail view.

5.4 Summary

A summary of this chapter is given by answering the subquestions of the second research question.

2.1. To which extent do current CERN standards, frameworks, and challenges influence the implementation of the methodology and the choice of modeling approach?

At CERN, an organization standard framework for SE and PM has been developed. Although this openSE framework is not widely adopted, it is still the only formal description in the design science domain organization-wide. The presence of this framework necessitates a modeling framework for the magnet modeling methodology that can model the domain of PM and SE. After considering various modeling approaches from different fields, the iPeM has been found to be particularly suitable regarding the domain-specific challenges and the given boundary conditions for this thesis project.

2.2. How can a tool support to carry out transfer studies and teach the methodology to its users look like?

An interactive iPeM tool has been created as part of a IDSDM transfer study to make the theory behind the methodology accessible to users and to explain all its activities and methods. This tool implements the iPeM as a clickable HTML web app and can be used to create individualized models and methodologies for different organizations or products. To validate the tool, initial semi-structured interviews were carried out. To be able to get immediate feedback without having to link the tool to other CERN specific software instead of the magnet modeling activities, the openSE project management activities have been used for these interviews. The interviewees have positively received the change management tool in combination with the Merlin Projects management software. The participants have identified future potential and use cases in knowledge management and staff onboarding.

2.3. How can the iPeM be used to model the electromagnetic design of superconducting accelerator magnets while being in line with existing CERN frameworks?

Using the interactive iPeM tool, an individualized reference model for the electromagnetic magnet design process has been created. The induction step to create an organization-specific iPeM model is carried out by formalizing the system development activities and deriving activity patterns. This formalization was done for the existing openSE standard to prove the feasibility of this modeling approach and afterward for the electromagnetic magnet design steps. The design steps have been derived from the integrated design process implemented and validated over many years in the ROXIE software environment.

6 Development of an Integrated Tool for Magnet Model Management

In the following, the practical applicability of the methodology for electromagnetic magnet design introduced in Chapter 5 will be investigated. The third research question derived in Chapter 3.2.2 will be answered for this purpose. The research question is initially divided into additional sub-questions:

3. **How can the methodology for the electromagnetic design of superconducting accelerator magnets be integrated into the development process, and what does a suitable tool support look like?**

    3.1. What are the essential parts of the tool support resulting from the core concepts of the methodology?

    3.2. How must the tool be designed to be able to connect to the current software landscape and to extend current best-practice simulation workflows?

    3.3. To which extent and in which way can the tool facilitate advanced MBSE workflows into the current simulation workflows?

In Chapter 5.3, the openSE activities as part of the iPeM basic activities and the electromagnetic simulation activities as part of the iPeM core activities have been formalized, and a methodology for the electromagnetic magnet design has been created. Chapter 5.3 visualizes this methodology using the developed, interactive iPeM tool, which has been validated in the course of a IDSDM transfer study. In the course of this study, the formalization of the openSE activities was also validated. This chapter will focus on developing a software tool to support the so-called Magnet Model Management Layer (3ML) to integrate the formalized magnet design steps from the derived methodology into the magnet simulation workflows. This software development is another IDSDM embodiment of design support. The two chapters are complementary since the magnet methodology ”cannot be understood and visualized” without the iPeM tool, and it ”cannot be used” in simulation processes without the Magnet Model Management Layer.
An experimental study will be carried out using automated software testing to verify whether the management layer software is achieving the intended results. The intended results for this chapter have been specified in Chapter 4 in the IDSDM

system of objectives and are the availability of generically compatible software interfaces, the possibility to create links and references to past system generations and the traceability of systems and their components.

6.1 Magnet Model Management Layer

In Chapter 4, knowledge management and transfer were identified as the main challenges of the magnet development process. A database and its respective database management tool will be integrated to establish persistent simulation model storage and implement the previously introduced methodology for electromagnetic magnet design. This tool is called the Magnet Model Management Layer (3ML).

To design this model management layer and identify its key components, the core principles from design science and the KaSPro on which the underlying methodology is based should be revisited. These principles are:

- The development of systems in generations with the ubiquity of system reference elements to build on past learnings.
- The usage of the extended ZHO tripel in the form of an individualized iPeM model to track and make use of structured development and problem-solving activities.
- The facilitating of system models to decouple data and views and to establish a single source of truth for development artifacts.

These principles are the foundation of the methodology and thus need to be integrated into and by the tool support.

The top-level building blocks that the tool support needs to cover are magnet system generations. Since not all magnet systems are being built physically, and some are just meant for virtual studies or tests, we need to distinguish between these four system generation types:

1. **Study** cases are used to investigate certain aspects of a magnet design. Common examples are parameter studies and their effects on the magnet design or the review of theories and assumptions. The results of one or multiple studies can then lead to a concrete magnet design case.

2. Magnet **Design** cases contain planned or physically built magnets. These cases are typically part of an official project and can be linked to physical assets in the EDMS database after the magnet production.

3. **Test** cases contain files and queries to verify the functionalities of different software pieces as part of the automated testing procedure. These cases do not necessarily have to make physical sense and can also be used to test fictional edge cases.

4. **Sample** cases showcase important simulation functionalities to the user. These cases can also be used as templates for starting with a certain design step and with certain, common predefined parameters.

Every system generation contains multiple models with some classifying, pre-defined attributes. These attributes are mandatory when creating a new model. The main model attributes are:

- **Type**: The model type specifies either the modeling tool, such as Roxie, Ansys, Steam, or script-based executions. If the model is not executable, other types, like a specification model only containing output parameters for other models as boundary conditions, are possible. This type list is non-exhaustive and will expand with novel use cases in the future.
- **Design step**: The step of the model corresponds to the formalized design activities from the methodology in the previous chapter. Example design steps are *feature-based geometry modeling of the coil* or *Conceptual coil design*.

Multiple models with the same design step and modeling software can exist in the same system generation. This can be needed to create alternative models for the same design step or combine multiple models within the design step. Other parameters, such as the model name and description, can be used to distinguish between these models. While every model can be a reference system element, not every reference system element must be a model. Datatypes, on a more granular level in comparison to a model, need to exist and be usable as references. These data types are, for example, queries from other databases, boundary conditions specified as input parameters, or other external references. These requirements result in a distinct model data structure that is explained in Section 6.1.2.

Referring to the three KaSPro principles form above, the tool must be able to connect models between each other across system generations in the form of system reference elements and within a generation to use the results of previous activities and transform the objective into an object in an iterative process. In other words, model dependencies must be possible across and within the development generation. These two dependency types will be explained here:

- **Intra-generation**
  Within one system generation, the dependencies between the system models are stored in the magnet model management layer. Each model has certain inputs and outputs. In 3ML, a dependency is created when the output of one model is linked to the input of another model. Each of these models in 3ML corresponds to one or more design steps[13]. These design steps implicitly use the model dependencies. When a model output changes, the models that depend on this output as their input will pick up the change and be marked as "outdated." To bring these models and thus the design steps back up-to-date, the design steps need to be re-executed. This concept creates a simulation pipeline with distinct, interconnected models. This simulation pipeline can track changes and execute steps later in the pipeline to keep all models up to date. This pipeline concept is shown in Figure 6.1.

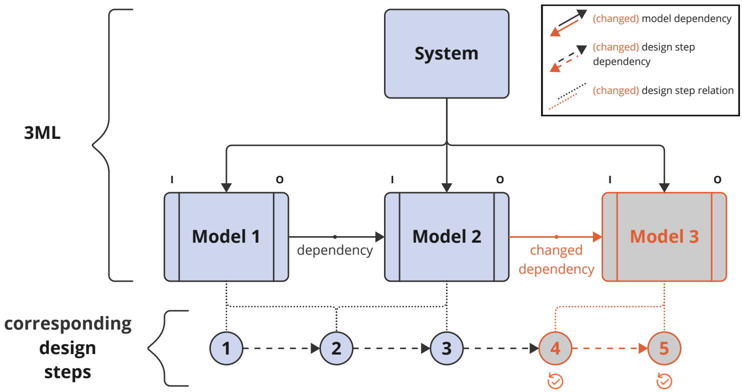

Figure 6.1: Simulation pipeline that shows dependent models within one system generation. If the input dependency of one model changes, the corresponding design steps will be re-executed to keep the simulation pipeline up-to-date.

- **Cross-generation**
  Model dependencies across models of different system generations are also stored in the magnet model management layer and work the same way as

[13] These design steps resemble the formalized design activities introduced in Chapter 5

within the same generation. The multiple types of model outputs, such as artifacts or parameters, can be linked as the inputs of models of another system generation. That way, things such as an always up-to-date model alternative or a new magnet system with a takeover variation of a past subsystem model can be realized. The link between models across two system generations is shown in Figure 6.2[14].

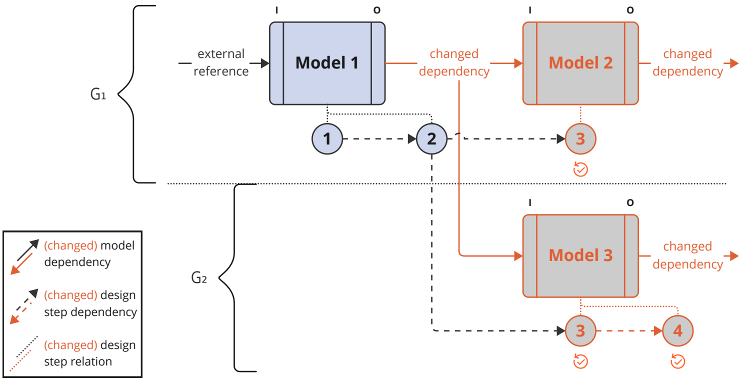

Figure 6.2: Model links across system generations are established by linking output artifacts and parameters as the input of other models. These links are stored in the 3ML database.

6.1.1 User Types and Workflows

The magnet model management layer was developed with the main goal of improving the knowledge management of existing solutions. Thus, the database needed to be integrated into existing simulation workflows without replicating the core functionalities of the already existing simulation suite. The existing MBSE tool explained in Section 2.2.3 is called internally PyMBSE. This PyMBSE environment and its functionality should be expanded by the 3ML database introduced here. For the final MBSE magnet simulation environment, including the PyMBSE glue logic and the 3ML persistent data storage, three integration configurations can be defined. These

[14] For easier understanding, the corresponding design steps and systems containing the models have been committed. These elements are shown in Figure 6.1 and work in the same way across system generations.

configurations are derived from the different magnet developer user types. These user types, together with their typical workflow and the respective integration configurations, are explained below. The explanations are using ROXIE as an example of a magnet simulation environment; commercial tools like ANSYS, or CERN-specific tools like Steam (Bortot et al., 2018), would be equivalent.

1. **ROXIE Magnet Designer**
   A ROXIE magnet designer creates and uses simulation projects in its basic form. A standard project with the magnet model management layer includes only the remote 3ML database and the user's local simulation environment. In this case, the magnet designers download the magnet model, work on it, and execute it on their local machines, for example, in ROXIE. After the model reaches a desired state of completion, they push the models again to the remote database. The database management connection between local and remote handles the loading, saving, and versioning of the models semi-automatically. The workflow of the ROXIE magnet designer is shown in Figure 6.3.

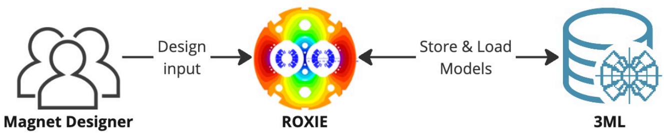

Figure 6.3: Standard workflow of a ROXIE magnet designer. The designer creates the model in the ROXIE simulation environment. The persistent storage and tracking of the magnet models is done in 3ML directly through an interface in ROXIE.

2. **ROXIE Superuser**
   The ROXIE superuser is aware of all the features and limitations of ROXIE. The goal of this user type is to explore more advanced modeling capabilities or to build extensions for the native ROXIE simulation environment. This project type enables the superuser to run multi-physics simulations on their local machine. The PyMBSE tool functions as an orchestrator and connects the model outcomes via an integrated cache. PyMBSE calls and executes different simulation tools as microservices, and the outputs are saved in the cache. Notebooks and other scripts can be integrated into this workflow, as well as model queries and parameters. These locally stored models need to be manually transferred to 3ML to persist the data and synchronize the simulation results. The workflow of the ROXIE Superuser is shown in Figure 6.4.

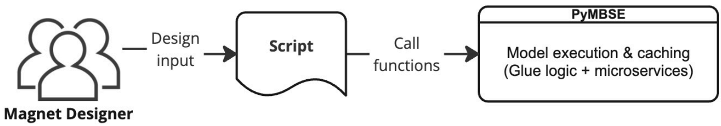

Figure 6.4: Standard workflow of a ROXIE Superuser. This user type utilizes additional script-based functions and local caching of PyMBSE to investigate advanced multi-physics behavior or to write custom extensions extending the native ROXIE capabilities.

3. **Multi-Physics Engineer**
   Multi-physics engineers use a variety of tools and capabilities to be independent from a single simulation environment. A project set up by this user type describes complete integration between the local models, PyMBSE and 3ML. PyMBSE still acts as the orchestration tool but is now also directly connected to the 3ML database. Executed models and results can be stored in the remote database together with their caches to achieve traceability and reduce the effort required to recompute models. This project setup is the end goal and also allows queries to other data sources through the magnet model management layer. Because of its complexity and timescale, this setup will only be partly implemented in this thesis project. This foundational setup can be built upon and extended by future projects. The workflow of the Multi-Physics Engineer is shown in Figure 6.5.

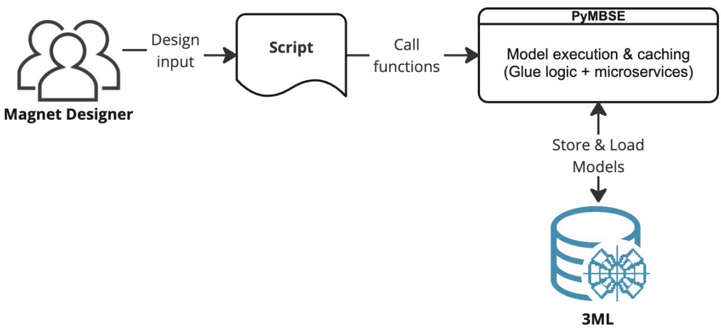

Figure 6.5: Standard workflow of a Multi-Physics Engineer. This workflow utilizes the microservice model execution, glue logic, and catching of PyMBSE and uses 3ML to maintain versioning and persistent model storage.

6.1.2 Data Structure and Database Layout

The database used for the 3ML tool is Oracle SQL. SQL stands for Structured Query Language and relies, as the name implies, on a structured and rigid database table format that needs to be defined in advance. The main database tables are the system, the model, and the data source. All systems and models contain metadata to describe and identify them. Each system can be associated with multiple models. Each model is associated with multiple data sources, and each data source can be associated with multiple models. The data source association uses two many-to-many relationships to classify whether the data source is an input or output dependency. That way, one data source can be the output of one model and, at the same time, the input for another model and design step. The tables of this Oracle database and the relations between the tables are shown in the form of an Entity Relation Diagram (ERD)[15] in Figure 6.6.

[15] An Entity-Relationship Diagram (ERD) is a graphical representation used to model the relationships between entities within a system, primarily in the context of database design of relational databases. They are also referred to as ERDs or ER Models and can be credited to a publication by Pin-Shan (1976).

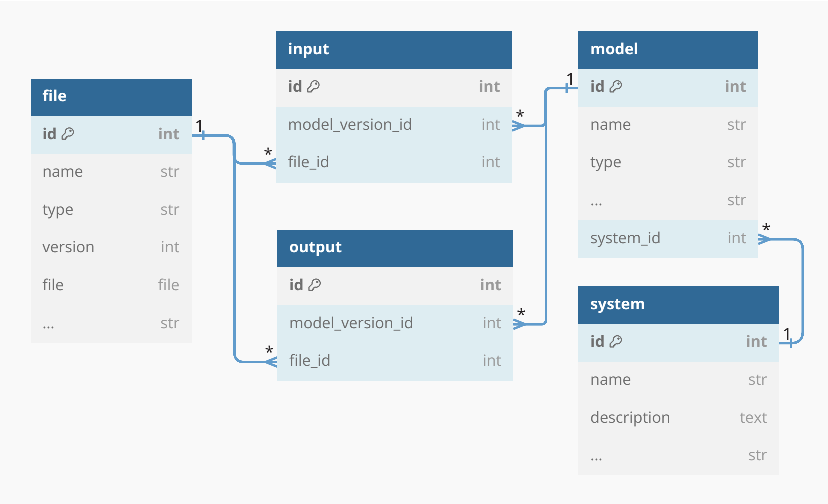

Figure 6.6: Entity-Relationship Diagram (ERD) of the 3ML database. The figure shows the data fields of the database tables and the relationship between the tables. Every system can contain multiple models, and each model can have associations with multiple data sources. These data sources are classified as inputs or outputs for the model.

The returned model by the database is defined as a Python data class. This data class includes four variables to identify the model: the unique *ID* of the model, the *name* of the model and its *description*, and the *system* with which the model is associated. *Artifacts* are the generated results and files during the run of the simulation. This could be, for example, a PDF report with the magnetic field diagrams generated by ROXIE. It could also be an optimization result file that serves as a starting point and *input artifact* for a dependent model. If such an *input dependency* exists for any model, this dependency is specified in the form of an instance of the same model data class. *Queries* can be specified to base the model simulation on external API calls and database values. A call to a material database to retrieve material-specific parameters and run the simulation with these parameters would be defined as a Query. *Output parameters* can be explicitly specified by the user and are either constants or calculated values during the simulation. These parameters can then be used by other models that rely on this model as *input parameters*. One could imagine a model that defines certain boundary conditions like a reference radius and other

```
@dataclass
class 3ML_Model:
    model_id : int
    name: str
    description: str
    system: 3ML_System
    artifacts: List[str]
    queries: Dict[str,type]
    output_parameters: Dict[str,str]
    input_parameters: Dict[str,str]
    input_artifacts: List[str]
    input_dependencies: Dict[str,3ML_Model]
```

Figure 6.7: Python data class of a 3ML model. The class includes metadata to identify the model, build artifacts, and all input and output dependencies.

models that have these parameters as up-to-date inputs. The described model data structure is shown in Figure 6.7.

6.1.3 Integration and Deployment

In addition, the 3ML database management layer should be accessible by a user-friendly web interface. This web interface must allow all actions regarding the knowledge management process for magnet models and systems. Typical operations are the creation, change of metadata, and deletion of the 3ML data. Also, downloading and uploading data sources such as simulation files is necessary. This can achieve a separation of concerns and uncouple the knowledge management process from the specialized simulation software environments. Possible "data curator" roles who are responsible for keeping track of the simulation model without deep knowledge about the simulation suite could be created.

To be able to connect all software parts and user types, the data within the 3ML database needs to be, in addition to the web interface, accessible through an Application Programming Interface (API). This way, different simulation environments such as ROXIE, Ansys, or the PyMBSE notebooks can communicate directly with 3ML through the API connection. These two interface types are shown schematically in Figure 6.8.

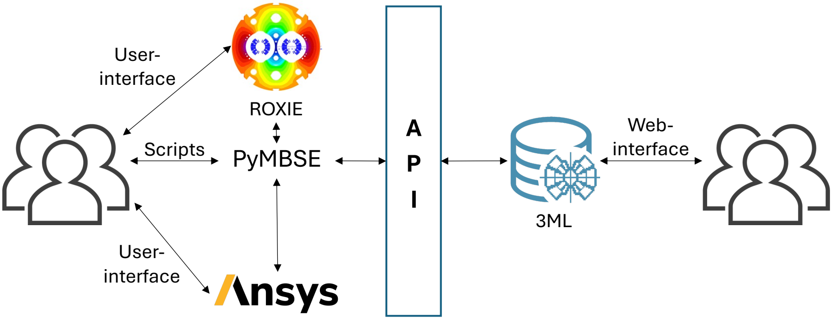

Figure 6.8: The magnet model management layer (3ML) with its two connections. On the right side, the web-based user interface is shown to access system and magnet data directly in a browser without the need for simulation software. On the left side, examples of simulation software are shown. The API, shown in the middle, allows the programmatic communication between software tools and the 3ML database. Examples of these software tools are ROXIE, Ansys, and the PyMBSE notebooks.

The deployment of the magnet model management layer is done through a custom CERN Platform-as-a-Service (PaaS) product. CERN's PaaS[16] allows users to deploy and host applications easily without managing the underlying computing infrastructure. It offers a high degree of automation and integration with CERN's computing environment. The code of 3ML is packaged as a docker container, allowing portability and compatibility on different machines by shipping all dependencies together with an encapsulated running environment. This setup ensures that other users can host 3ML's open-source code on their own on-premise servers. This becomes essential in case users who are not affiliated with CERN do not want to store their magnet models on CERN infrastructure. Built-in authentication that uses the CERN SSO ensures traceability of the model authors and maintains ownership over multiple system generations.

The web interface and the application programming interface shown in Figure 6.8 will be explained in the following two sections.

[16] CERN's PaaS is based on OpenShift OKD4. It leverages Kubernetes for multi-tenancy, which enables the isolated hosting of numerous applications in a shared setting. More information can be found in the PaaS documentation (CERN, 2024b).

6.1.4 Webinterface

The 3ML web interface enables access to the magnet systems and models to everyone at CERN using the central CERN Single-Sign-On (SSO). The web interface's functionality is limited to administrative and organizational tasks and does not aim to perform magnet simulations. When entering the web interface, the user is presented with an overview of all available systems in the database alongside basic metadata for each system. This system list view is shown in Figure 6.9.

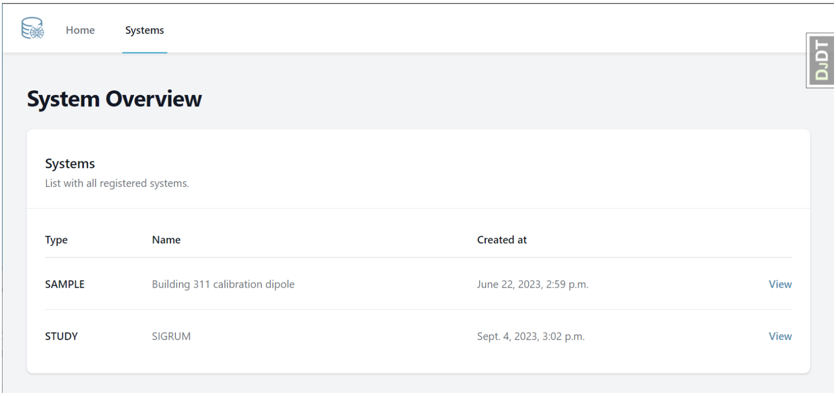

Figure 6.9: Webinterface list view of all available systems in the 3ML database.

After selecting a specific system a detailed view of this system is shown. This detailed view shows a summary of the system with selected simulation pictures, general information, and a list of all associated simulation models. This has the benefit that users do not need to remember the specific system name to find a system. They can browse through a selection and identify the desired system by looking at the pictures and reports that can be attached to the systems. An example of such a system detail view is shown in Figure 6.10.

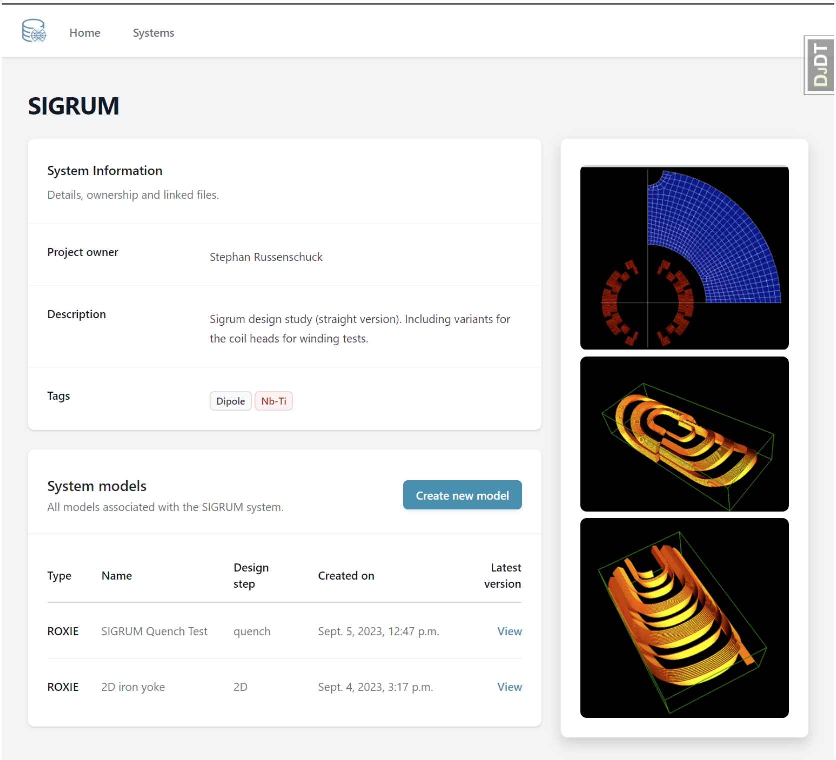

Figure 6.10: Webinterface detail view of the SIGRUM system. Metadata of the system, pictures of the simulation results, and the models associated with the system are shown without having to open a simulation software.

The user can then navigate in the database by choosing a specific design step simulation model. The detail view page of the model shows information about the selected model and gives a historic change log of all changes made to it. These changes can be reverted if needed or referenced in later steps or by later system generations. All input and output artifacts of the model are listed on this detail page as well. An example of this page is shown in Figure 6.11.

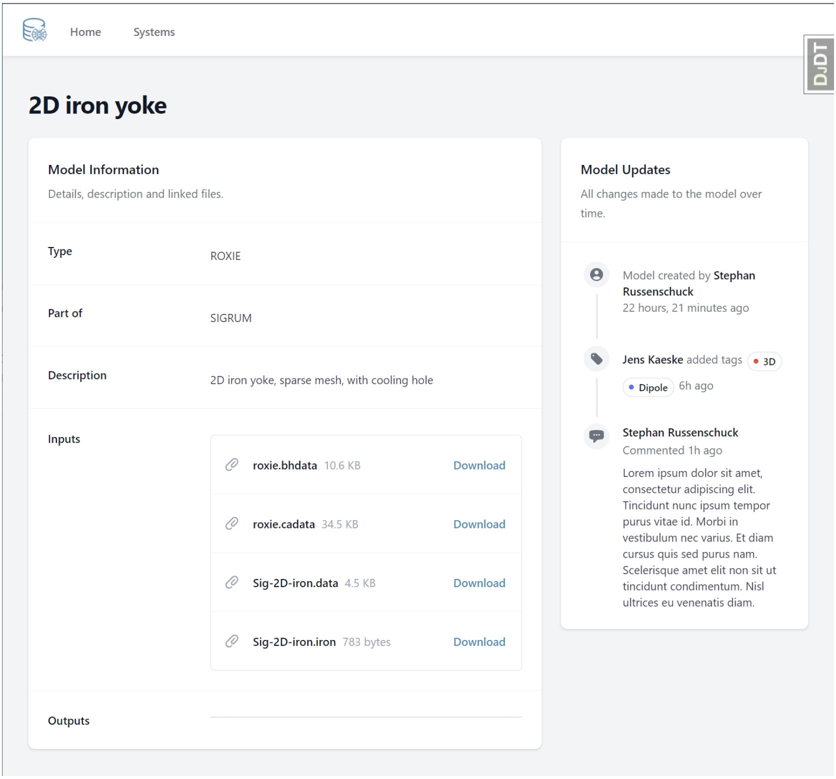

Figure 6.11: Webinterface detail view of the 2D iron yoke model within the SIGRUM system. The detail view shows the metadata of the model, its change history, and associated input and output artifacts.

6.1.5 Application Programming Interface

An API is a way to establish communication between two computers, with one being the client and the other one being the server. REST is a popular format in which such APIs are developed. Also, the 3ML database uses the REST standard. Before getting into the functionalities of the 3ML API, the three main components of REST APIs will be introduced:

1. The **URL endpoint** specifies the link we want to communicate with. This endpoint is linked to an API resource. This could be, for example, magnet metadata or a simulation file. The endpoint to retrieve the magnet model with the ID looks like this: 3ml.app.cern.ch/api/magnets/1

2. The **HTTP verb** specifies the action that should be performed on the specified resource. The verb GET, for example, would retrieve the data for the given resource. There are five commonly used HTTP verbs: GET for reading, POST for creating, PUT and PATCH for updating, and DELETE for deleting resources. The API specifies the verbs that are useable for a given endpoint.

3. The **Body** can contain an optional custom payload with the properties and values to create or modify a resource.

Together with any other optional data inside the body, the server returns a status code. This code indicates if the request was successful or not. In case of an unsuccessful request, the status code specifies the reason, such as unauthorized requests or the non-existence of a queried object. The main REST API components and the relationship between each other to establish client-server communication are shown in Figure 6.12.

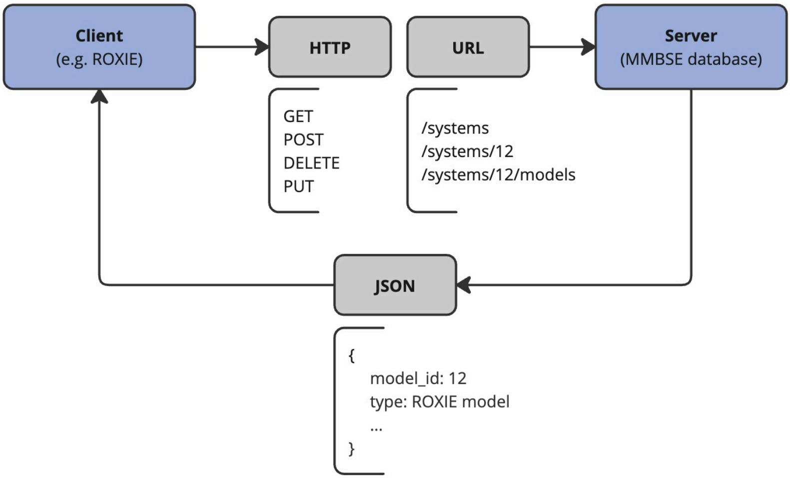

Figure 6.12: Main components of a REST API and its relationships to establish client-server communication. Adapted from “REST APIs Explained - 4 Components. Howie Mann” by Mann (2023).

On UNIX-based systems, a common way to get data from a URL endpoint is to request it using the curl command. An example of such a curl command to retrieve a specific magnet model through the 3ML REST API is shown in Figure 6.13.

```
curl -X 'GET' \
    'https://3ml.app.cern.ch/api/models/12/' \
    -H 'accept: application/json' \
    -H 'X-CSRFToken: <CSRF_Token>'
```

Figure 6.13: Example to get a specific model (ID=12) using curl in a UNIX-based shell.

If the model exists, the API will then return a status code 200 alongside the model in the form of a JSON object. An example of such a response model JSON object is shown in Figure 6.14.

```
{
    model_id: 12,
    model_type: "ROXIE",
    name: "Test",
    description: "This is a test description.",
    design_step: "3D",
    system: 41,
    output_parameters: [
        {
            Rref: {
                model: 61,
                value: "61.00"
            }
        },
    ],
    input_dependencies: [ ... ],
    created_at: "2024-01-30T15:05:42.087061Z",
    input_artifacts: [ ... ],
    output_artifacts: [ ... ],
    ...
}
```

Figure 6.14: Example of the returned model JSON object. When a query for a specific model (ID=12), the 3ML API will return an object like this.

The curl method to make the API request and the brief data transformation to convert the JSON response into a usable variable, for example, is viable but becomes cumbersome when the request and returned data are more complex. On Windows-based systems, the curl command is also not available out of the box, and alternative packages are needed to accomplish the same result. These difficulties call for a client that abstracts the request-response cycle and wraps the workflow into a more convenient interface. To accomplish this, a MMSBE Python client has been developed. This client provides a standardized and easy way to connect all kinds of simulation software to the 3ML database. To immediately see the benefit, the curl command to get a specific magnet model from above can now be directly written in a Python and Jupyter script in a more user-friendly and readable way. The same command as above but using the Python client looks is shown in Figure 6.15.

```python
from 3ML import 3ML

client = 3ML()
model = client.get_model(id=12)
```

Figure 6.15: Example to get a specific model (ID=12) using the Python client get_model function.

The model object is returned in the form of the in Section 6.1.2 specified 3ML_Model data class. Its attributes can be directly accessed, eliminating the need to convert the JSON object from the curl request into a Python variable before accessing its attributes. All available endpoints with usage instructions and their available HTTP verbs are kept up-to-date using an automatically generated webpage[17]. A screenshot of how this documentation looks is shown in Figure 6.16.

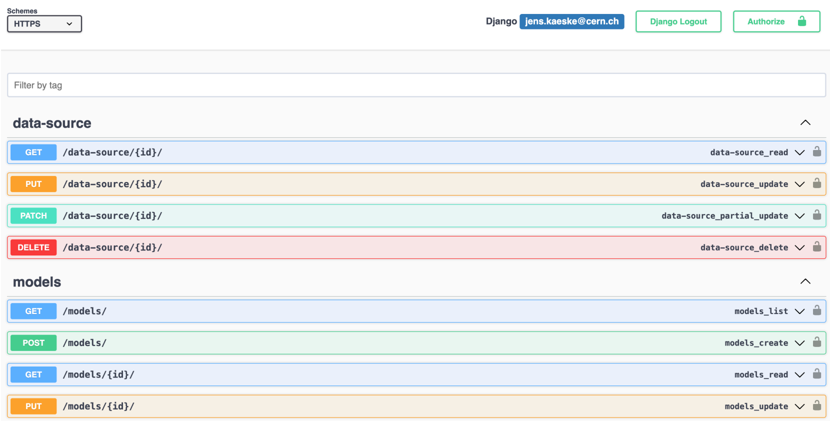

Figure 6.16: Part of the automatically updated, interactive documentation. The documentation lists all available endpoints of the 3ML API together with usage instructions and the schemas of the returned JSON objects.

[17] The automatically created, interactive API documentation is hosted under this URL: 3ml.app.cern.ch/swagger/v1

ROXIE GUI Interface

A user interface was created to connect the ROXIE simulation software to the 3ML database API through the previously described Python client. This interface was created in the popular user interface package PyQt and is integrated as part of the general ROXIE user interface. The choice for the PyQt package was made since advanced features like API calls were needed. These features are technically achievable with the older framework being used for the ROXIE user interface but will require more development time and maintenance effort in the future. Since the Qt GUI is directly integrated into the ROXIE environment, it can be considered a native extension rather than another standalone piece of software.

The home page of this interface can be directly triggered from within ROXIE without closing the program or navigating to another one. After pressing the ”3ML Database” menu button in ROXIE, the user is presented with a welcome window. There, the user can log in with an API authentication token provided by the 3ML web interface. The web interface can be opened directly by clicking the ”Open 3ML Database” button. Authenticated users can then choose to either see a list view with all available systems in the database or to push local model changes to a model of their choice. To push the local changes to the database, the system and the respective model need to be selected. The database requires a comment that explains what changes have been made locally to keep track of a model’s change history over time. This comment is the equivalent of a git commit message for code repositories. The form to specify the model and the change message is also available directly in the GUI.

The welcome window, the system list window, and the window with the model push workflow of the ROXIE GUI are shown in the Appendix in Figure A.2, A.4 and A.3[18].

6.1.6 Implementation Study and Testing

Standard testing of the software code itself is necessary to validate the functionalities of the 3ML database, web interface, and API. As described in Chapter 3.3.2, the concept of unit testing was used to carry out the implementation studies in the scope of the IDSDM. As part of an automated testing pipeline, the unit tests for the

[18] These three user-interface windows, in contrast to the rest of the work presented in this thesis, have been created as part of a team project. Their content only serves as a reference for the reader to be able to understand the bigger picture of the API integration.

Python client are run on every code change in the 3ML repository. Using this pipeline, ”units” of isolated functionalities can be automatically tested, preventing the rollout of changes that break these functionalities. This ensures a continuous validation of the project even after the active time of contribution of this thesis project. The testing suite also serves as the instruction manual for future integration projects with other simulation platforms. Since every function of the Python client needs to be used in the test classes and their results validated, the way to use the functions is documented in the code. The current test coverage of the main Python client class is 100 %. This coverage metric value certifies that the automated unit tests cover all core functionalities and prevent future breaking changes. When the code changes, the metric is automatically calculated and displayed as a badge in the client code repository.
It is important to note that this is not an implementation study in the classical sense, including user-centric validation methods like surveys or interviews. This type of implementation study verifies the functionality of the software support. With the system of objectives and reference model defined in Chapter 4.3, a link between the integration objectives and the knowledge about reference-system-elements as the success factor of this project has been established. According to these relationships, by verifying the functionality, the success factor will be positively influenced (similar to a proxy). Recapitulating the system of objectives for the 3ML implementation, the following objectives were defined:

- **Implementation of generically compatible software interfaces and APIs**
  An API has been implemented, and all endpoints and functionality are continuously tested by the automated testing suite. This API can be used by all types of simulation software. The link to ROXIE has been verified in this chapter.
- **Establish model traceability by enabling links and references to past generations**
  The capability of establishing intra and cross-generation reference links between system models was described in this chapter. Automated testing also covers the creation, deletion, modification, and query of these references.
- **Adding missing descriptions and making them easily accessible**
  Metadata and descriptions can be added to the systems and models and are displayed directly in the web interface. This can help identify reference system elements without having to open a simulation software. 3ML enforces the entry of descriptions, some pictures, and other metadata, which will, in the long term, contribute to higher traceability and the existence of documentation.

The relevant objectives from the system of objectives are reached by the 3ML software components, and their functionality is verified in the long term by automated software components. This concludes a successful integration study and the resulting positive impact on the success factor of increasing the knowledge about reference system elements.

6.2 Advanced Modelling Use Cases

Combining the previously explained functions, interfaces, and simulation software, more advanced and interconnected simulation use cases can be defined and performed. With the growing need for multi-physics simulation in the domain, this is a first step toward combining the modeling capabilities of PyMBSE cache-based modeling with the persistent model storage and knowledge management of 3ML. In the following, two exemplary simulation use cases will be introduced.

6.2.1 Script-Based ROXIE Design

For the ROXIE design based on a Jupyter PyMBSE script, a 2D magnet geometry is generated in Python code. The Jupyter script is stored in the 3ML database in the form of a model, and the geometry is exported in the script as an output artifact of the model. A new ROXIE model is created within the same system. The ROXIE model is linked to the PyMBSE script by linking the geometry as an input artifact. In the ROXIE model, other blocks and settings can be adapted. When the geometry is updated, the 2D block within the ROXIE model will change automatically, but the settings will be kept in ROXIE. This can be used, for example, to define plots and plotting parameters in ROXIE while always having the up-to-date geometry generated in code. The load and save operations are using the get_model and save_model functions of the 3ML Python client. A sequence diagram of this workflow is shown in Figure 6.17.

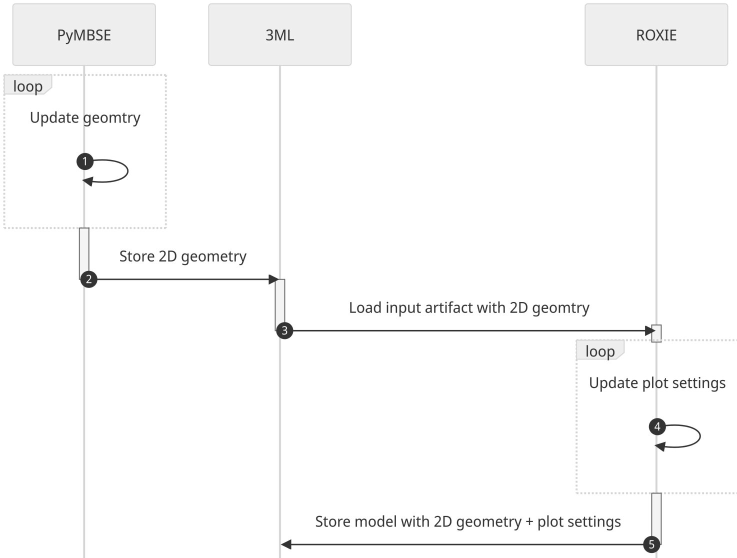

Figure 6.17: Advanced modeling workflow using PyMBSE to create a script-based 2D geometry and using this geometry in a ROXIE model to specify plots and plotting parameters. The link between the models ensures the 2D geometry is up-to-date in the ROXIE model.

6.2.2 Parametrized Script-Based Design

We imagine a system development project that has boundary conditions that change throughout the development lifecycle. To keep up with these changes, the parameterized script-based design workflow can be used. In the beginning, a specification model is created, and the boundary conditions are defined as output parameters of this specification model. The 3ML web interface is used to create and change model parameters. The specification model is saved in the 3ML database and can then be retrieved in a PyMBSE Jupyter script. In the script, the parameters can be directly referenced using Python variables. That way, the magnet design in the script can be parameterized using the boundary conditions from the specification model. When the boundary conditions change, the script can be executed, and the specifications will be applied to the magnet design. The load and save operations are using the get_model and save_model functions of the 3ML Python client. A sequence diagram of this workflow is shown in Figure 6.18.

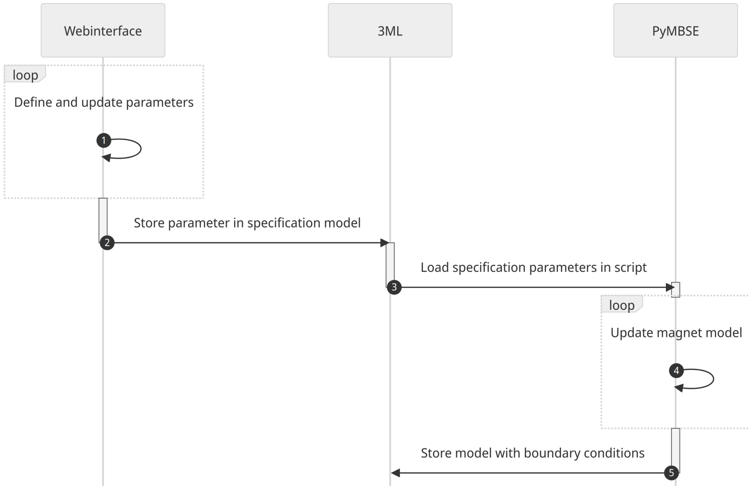

Figure 6.18: Advanced modeling workflow using the 3ML web interface to create parameterized boundary conditions for a magnet development project. These parameters can be referenced in a PyMBSE script and are updated there as soon as the boundary conditions change.

6.3 Summary

A summary of this chapter is given by answering the subquestions of the third research question.

3.1. What are the essential parts of the tool support resulting from the core concepts of the methodology?

A central database was identified as the solution of choice to establish a single source of truth for magnet models and general simulation artifacts. The database layer must be accessible by users directly and through an API using other simulation tools to provide flexibility and the desired data view decoupling in the concept of MBSE. The data in this database needs to be organized into systems and submodels within these systems. The systems describe magnet development projects and, thus, concrete system development generations. The models within the systems can be referenced by other models and later system generations as system reference elements following the concept of SGE. This is intended as a possible solution approach to the ubiquitous knowledge management challenges at CERN. An individualized iPeM model has been implemented into the workflow by associating every magnet model with a formalized design step defined in Chapter 5. This usage of the iPeM follows the extended ZHO tripel and makes it an automated tracking of problem-solving activities within the formalized activities possible.

3.2. How must the tool be designed to be able to connect to the current software landscape and to extend current best-practice simulation workflows?

The developed magnet model management layer must be accessible via a user-friendly web interface to improve the current knowledge management process and decouple the administrative model management part from the technical simulation work. This web interface needs to be available to all users working on a specific project to ensure a consistent workflow. Current simulation workflows and existing software call for an API to communicate with the database. The developed REST API has been extended by a client that simplifies the communication and makes the database responses available as Python variables that can be used within the PyMBSE Jupyter notebooks. Adding a Qt GUI using this client to establish the connection with the ROXIE simulation environment has proven the integration with existing simulation tools. This chapter has identified the essential functions and endpoints, and an automated testing suite was implemented to constantly verify the tool's functionality even after the completion of this thesis project.

3.3. To which extent and in which way can the tool facilitate advanced MBSE workflows into the current simulation workflows?

Two advanced workflows have been defined in this chapter. As advanced, we define workflows as including more than a single simulation environment or script. These initial workflows show the multi-physics simulation capabilities that can be achieved right now and that should be extended in the future. The two examples include the 3ML database, PyMBSE, the 3ML web interface, and ROXIE. The first workflow describes the ROXIE model creation based on the output of a PyMBSE script-based model. The second workflow describes a way to deal with the constantly changing requirements in a development project at CERN. This challenge has been identified by the interview candidates in Chapter 4. Boundary condition parameters that can be defined in the 3ML web interface can be referenced by a PyMBSE model and are automatically updated on the execution of the model if the parameters have been changed.

7 Conclusion

The overall research goal was reached by answering three research questions that have been derived in Chapter 3.2.2. The goal of this thesis project has been defined as:

Research Goal

The present thesis aims to identify the challenges in the domain of superconducting accelerator magnets and develop design support in the form of a methodology to formalize the electromagnetic design and development process. This methodology should follow the concept of Model-Based Systems Engineering and should be integrated into the current development workflow with adequate tool support.

7.1 Summary

The thesis project is summarized by briefly answering the research questions and explaining the research approaches used.

1. **What are the challenges in developing superconducting accelerator magnets?**

Pre-studies, described in Chaper 4, revealed initial challenges related to knowledge management, documentation, and legacy system integration, leading to development issues. A quantification process was carried out at the domain, organization, and group levels using literature reviews, surveys, and interviews. Key challenges identified include long lead times, difficulties in adopting new technologies, and knowledge management problems such as missing documentation, lack of data traceability, and no standardization. The identified challenges were consolidated into a reference model, which helped derive success criteria for the thesis project. These criteria revolve around knowledge of system reference elements from past magnet system development projects and research artifacts, with success factors directly related to the magnet simulation process, simulation software interfaces, and traceability of simulation artifacts. Below is a concise answer to the first research question:

> Domain specifics, such as unusually long lead times, the international collaboration of cross-domain teams in academia and industry, and the constant pursuit of new technologies, are the root causes of the challenges in the development of superconducting accelerator magnets. Following the argumentation in this thesis, knowledge management, especially knowledge about past magnet generations and their system reference elements, can be seen as one of the main influencing levers and success factors for the development process.

2. **How can a methodology for the electromagnetic design of superconducting accelerator magnets be formulated, and how can it be taught to its users?**

Chapter 5 addresses the influence of CERN standards and frameworks on the implementation of the methodology and the choice of modeling approach for the electromagnetic design of superconducting accelerator magnets. CERN has developed an organization standard framework called openSE for SE and PM, which necessitates a modeling framework that can model these domains. The iPeM was found to be particularly suitable given the domain-specific challenges and boundary conditions of the thesis project. By formalizing system development activities and deriving activity patterns, the iPeM can be used to create an individualized reference model for the magnet design process. This was done for the existing openSE standard and the electromagnetic magnet design steps derived from the integrated design process implemented in the ROXIE software environment. To make the methodology accessible to users, an interactive change management tool was created, implementing the iPeM as a clickable HTML web app. Initial semi-structured interviews were conducted to validate the tool using openSE project management activities. The interviewees positively received the change management tool in combination with the Merlin Projects management software, identifying future potential and use cases in knowledge management and staff onboarding. Below is a concise answer to the second research question:

> A methodology or the electromagnetic design of superconducting accelerator magnets has been derived by formalizing the design activities and deriving an individualized organization-specific iPeM reference model. An interactive, web-based learning tool has been developed and validated to facilitate the teaching of the underlying methodology principles.

3. **How can the methodology for the electromagnetic design of superconducting accelerator magnets be integrated into the development process, and what does a suitable tool support look like?**

The chapter focuses on the development of a tool to support the methodology for the electromagnetic design of superconducting accelerator magnets, addressing three subquestions of the third research question. The essential parts of the tool support include a central database that serves as a single source of truth for magnet models and simulation artifacts. The database should be accessible directly by users and through an API, allowing for flexibility and data view decoupling in the context of MBSE. The data is organized into systems (magnet development projects) and submodels, and it can be accessed by referencing models from other systems and generations, following the concept of SGE. An individualized iPeM model is integrated into the workflow by associating each magnet model with a formalized design step. A user-friendly web interface was developed to connect the tool to the current software landscape and extend best-practice simulation workflows. This interface improves the knowledge management process and decouples administrative model management from technical simulation work. A REST API with a client simplifies communication and makes database responses available as Python variables for use in PyMBSE Jupyter notebooks. Adding a Qt GUI to establish a connection with the ROXIE simulation environment demonstrates integration with existing simulation tools. The tool facilitates advanced MBSE workflows by enabling multi-physics simulations that involve more than one simulation environment or script. Two examples are provided, showcasing the integration of the 3ML database, PyMBSE, the 3ML web interface, and ROXIE. The first workflow describes the creation of a ROXIE model based on the output of a PyMBSE script-based model, while the second workflow addresses the challenge of constantly changing requirements in a development project at CERN by allowing boundary condition parameters defined in the 3ML web interface to be referenced and automatically updated in a PyMBSE model. Below is a concise answer to the third research question:

> The magnet design methodology can be integrated into the development lifecycle in the form of a magnet model database. This database must be accessible through a web-based user interface and an API. The database management tooling needs to enable these two connection forms. The web interface connection allows knowledge management and transfer of the magnet models without opening simulation tools. The API enables the essential integration into the current simulation software landscape and established workflows.

7.2 Discussion and Outlook

Upon completion of the project and answering the research questions, potential and open points for future work became apparent. Below, open points in the main parts of the thesis projects will be provided as starting points for future research projects while discussing the obtained results.

1. **Development Challenges**
   The development challenges in the TE-MSC group at CERN have been identified using 14 semi-structured interviews. While this research method provided in-depth insight into the practical challenges and the design process, the results cannot be considered quantitatively significant. Using a literature review and a survey, the challenges at domain and organization levels could be investigated, and critical points like knowledge management could be identified on all three levels. While still not statistically significant, this method combination approach can be helpful, especially during problem-containment steps. It can also help gain a deep understanding of a new domain or topic when quantitative methods are not available or usable. With distinct, short methodic steps, this approach can be especially recommended for future thesis projects.
   Shifting focus from the research methods to the identified challenges, Chapter 4 can be used as the descriptive step and motivation for future work in the domain. Here, we want to list a few examples:

   a) Well-defined project kickoff processes or methodical support during important meetings could address the identified communication problems and resulting frequently changing requirements.

   b) A dedicated project to migrate data to actively maintained documentation platforms could address the outdated documentation in the organization, and management could enforce documentation standards.

   c) The challenge of ”multi-physics simulations” shows improvement potential in the form of new simulation tools, communication between them, stable code maintenance efforts, and tighter coupling of existing software solutions.

2. **iPeM Tool**
   While the application of the iPeM in this project is specific to CERN as an organization, it serves as the first documented, explicit usage of the iPeM modeling

framework for large-scale academia projects. The results serve as a guideline for future individualization projects. The here documented application shows that the iPeM modeling framework is capable of complex applications and results as the winner against other prototypical modeling approaches in other domains when a detailed integration is necessary. This proves real-world modeling capabilities far beyond the university setting.
While the iPeM change management tool is functional, and its usefulness has been initially tested and validated, improvement potential remains. Quantitative feedback on the use of the change management tool needs to be collected and interpreted. The actual change in the activities of the magnet design methodology and the resulting change process that needs to be carried out will be exciting. The iPeM tool can be used outside the CERN research environment, and teaching use-cases in university or the use as part of a methodology workshop in other industries should be examined. This could help to derive various iPeM based methodologies and can then serve as a proxy to collect more quantitative feedback about the glsipem modeling framework itself.

3. **3ML**
While an automated testing suite of the magnet model management layer and the respective Python client is in place, user testing in real-world scenarios is essential. Only then can more complex errors be detected, and more advanced use cases and new features can be defined. User tests require an initial critical mass of curated system models in the 3ML database to see the full platform capabilities and understand the reference setting capabilities between the methodology design steps. These models need to be manually checked under a variety of decentralized, old project files and entered into the database. This requires ongoing data entry and maintenance work.
Initially, ROXIE has been used to validate the API connection and prove communication capabilities with existing software tools. The connection between 3ML and other simulation software needs to be established and validated. This requires dedicated software development projects in the future.
Validating the design steps and continuously improving the simulation pipelines and design methodology are necessary to raise awareness for the tool and to provide the users with sustainable simulation benefits along the way. This includes the investigation of advanced, coupled simulation workflows, including a variety of simulation tools.

Bibliography

Aad, G., Abajyan, T., Abbott, B., Abdallah, J., Abdel Khalek, S., Abdelalim, A. A., Abdinov, O., Aben, R., Abi, B., Abolins, M., AbouZeid, O. S., Abramowicz, H., Abreu, H., Acharya, B. S., Adamczyk, L., Adams, D. L., Addy, T. N., Adelman, J., Adomeit, S., … Zwalinski, L. (2012). Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. *Physics Letters B*, *716*(1), 1–29. https://doi.org/10.1016/j.physletb.2012.08.020

Albers, A., Braun, A., & Muschik, S. (2010). Uniqueness and the multiple fractal character of product engineering processes. In P. Heisig, P. J. Clarkson, & S. Vajna (Eds.), *Modelling and Management of Engineering Processes* (pp. 15–26). Springer. https://doi.org/10.1007/978-1-84996-199-8_2

Albers, A., Bursac, N., & Rapp, S. (2016). PGE - Product generation engineering - Case study of the dual mass flywheel. *DS 84: Proceedings of the DESIGN 2016 14th International Design Conference*, 791–800. https://www.designsociety.org/publication/38889/PGE+-+PRODUCT+GENERATION+ENGINEERING+-+CASE+STUDY+OF+THE+DUAL+MASS+FLYWHEEL

Albers, A., & Lohmeyer, Q. (2012). Advanced systems engineering - Towards a model-based and human-centered methodology. *Tools and methods of competitive engineering: Proceedings of the ninth International Symposium on Tools and Methods of Competitive Engineering (TMCE 2012)*, 407–416. https://www.semanticscholar.org/paper/Advanced-systems-engineering-Towards-a-model-based-Albers-Lohmeyer/3e8797d6cf781f11cd70e5b0eeb990b178b5ab49

Albers, A., Rapp, S., Fahl, J., Hirschter, T., Revfi, S., Schulz, M., Stürmlinger, T., & Spadinger, M. (2020). Proposing a generalized description of variations in different types of systems by the model of PGE – Product generation engineering. *Proceedings of the Design Society: DESIGN Conference*, *1*, 2235–2244. https://doi.org/10.1017/dsd.2020.315

Albers, A., Behrendt, M., Klingler, S., Reiß, N., & Bursac, N. (2017). Agile product engineering through continuous validation in PGE – Product Generation Engineering. *Design Science*, *3*, e5. https://doi.org/10.1017/dsj.2017.5

Albers, A., Braun, A., & Pinner, T. (2012). Integrated Modelling of Information to Support Product Engineering Processes. *DS 72: Modelling and Management of Engineering Processes - Concepts, Tools and Case Studies*, 031–044. https://www.designsociety.org/publication/36006/Integrated+Modelling+of+Information+to+Support+Product+Engineering+Processes

Albers, A., Bursac, N., & Wintergerst, E. (2015a). Product generation development-importance and challenges from a design research perspective. *New developments in mechanics and mechanical engineering : proceedings of the International Conference on Mechanical Engineering (ME 2015)*, *13*, 16–21. https://publikationen.bibliothek.kit.edu/1000047770

Albers, A., Bursac, N., & Wintergerst, E. (2015b). Produktgenerationsentwicklung – Bedeutung und Herausforderungen aus einer entwicklungsmethodischen Perspektive. *Stuttgarter Symposium für Produktentwicklung, SSP 2015*, 1–10. https://publikationen.bibliothek.kit.edu/1000067942

Albers, A., Hahn, C., Brecht, P., Cetinkaya, Ü., Pfaff, F., Schlegel, M., & Fischer, M. (2023). Digital Platform Business Model within the Model of SGE -System Generation Engineering: Definition and Classification in Cyber-Physical Systems. *Proceedings of the Second Australian International Conference on Industrial Engineering and Operations Management, Melbourne, Australia, November 14-16, 2023*. https://doi.org/10.46254/AU02.20230078

Albers, A., Kürten, C., Rapp, S., Birk, C., Hünemeyer, S., & Kempf, C. (2022). SGE – Systemgenerationsentwicklung: Analyse und Zusammenhänge von Entwicklungspfaden in der Produktentstehung. *KIT Scientific Working Paper*, *199*, 15. https://doi.org/10.5445/IR/1000151151

Albers, A., Lohmeyer, Q., & Ebel, B. (2011). Dimensions of objectives in interdisciplinary product development projects. *DS 68-2: Proceedings of the 18th International Conference on Engineering Design (ICED 11), Impacting Society through Engineering Design, Vol. 2: Design Theory and Research Methodology*, 256–265. https : / / www . designsociety . org / publication / 30476 / DIMENSIONS + OF + OBJECTIVES + IN + INTERDISCIPLINARY + PRODUCT+DEVELOPMENT+PROJECTS

Albers, A., Maul, L., & Bursac, N. (2013). Internal Innovation Communities from a User's Perspective: How to Foster Motivation for Participation. In M. Abramovici & R. Stark (Eds.), *Smart Product Engineering* (pp. 525–534). Springer.

Albers, A., & Rapp, S. (2022). Model of SGE: System Generation Engineering as Basis for Structured Planning and Management of Development. In D. Krause & E. Heyden (Eds.), *Design Methodology for Future Products: Data Driven, Agile and Flexible* (pp. 27–46). Springer International Publishing.

Albers, A., Rapp, S., Spadinger, M., Richter, T., Birk, C., Marthaler, F., Heimicke, J., Kurtz, V., & Wessels, H. (2019). The Reference System in the Model of PGE: Proposing a Generalized Description of Reference Products and their Interrelations. *Proceedings of the Design Society: International Conference on Engineering Design*, *1*(1), 1693–1702. https://doi.org/10.1017/dsi.2019.175

Albers, A., Reiß, N., Bursac, N., & Breitschuh, J. (2016). 15 years of SPALTEN problem solving methodology in product development. *DS 85-1: Proceedings of NordDesign 2016, Volume 1, Trondheim, Norway, 10th - 12th August 2016*, 411–420. https://www.designsociety.org/publication/39318/15+Years+of+SPALTEN+Problem+Solving+Methodology+in+Product+Development

Albers, A., Reiß, N., Bursac, N., Walter, B., & Gladysz, B. (2015). Innofox - Situationsspezifische Methodenempfehlung im Produktentstehungsprozess. *Stuttgarter Symposium für Produktentwicklung SSP 2015*. https://www.researchgate.net/publication/279542318

Albers, A., Reiss, N., Bursac, N., & Richter, T. (2016). iPeM – Integrated Product Engineering Model in Context of Product Generation Engineering. *Procedia CIRP*, *50*, 100–105. https://doi.org/10.1016/j.procir.2016.04.168

Amaldi, U. (2000). The importance of particle accelerators. *Europhysics News*, *31*(6), 5–9. https://doi.org/10.1051/epn:2000601

Ambrosio, G., Amm, K., Anerella, M., Apollinari, G., Arbelaez, D., Auchmann, B., Balachandran, S., Baldini, M., Ballarino, A., Barua, S., et al. (2022). A strategic approach to advance magnet technology for next generation colliders. arXiv. https://doi.org/10.48550/arXiv.2203.13985

Ambrosio, G., Apollinari, G., Baldini, M., Carcagno, R., Boffo, C., Claypool, B., Feher, S., Hays, S., Hoang, D., Kashikhin, V., et al. (2022). White paper on leading-edge technology and feasibility-directed (LEAF) program aimed at readiness demonstration for energy frontier circular colliders by the next decade. arXiv. https://doi.org/10.48550/arXiv.2203.07654

Ascher, D., Heiland, E., Schnell, D., Hillmann, P., & Karcher, A. (2022). Methodology for Holistic Reference Modeling in Systems Engineering. arXiv. https://doi.org/10.48550/arXiv.2211.11453

Badke-Schaub, P., Daalhuizen, J., & Roozenburg, N. (2011). Towards a Designer-Centred Methodology: Descriptive Considerations and Prescriptive Reflections. In H. Birkhofer (Ed.), *The Future of Design Methodology* (pp. 181–197). Springer. https://doi.org/10.1007/978-0-85729-615-3_16

Balslev, H., & Barré, T. (2022). Why system models need the RDS 81346 reference model: The key to digital continuity across silos and enterprises. *INCOSE International Symposium*, *32*(1), 1052–1069. https://doi.org/10.1002/iis2.12981

Baranowska, P., Basaglia, T., Kohls, A., Moskovic, M., & Tzovanakis, H. (2023). *CERN Scientific Information Landscape Project: Project Overview and Identified Needs: Summary of findings during Milestones 1 and 2* (tech. rep.). CERN. Geneva. https://doi.org/10.17181/CERN-OPEN-2023-006

Barna, D., Giunchi, G., Novák, M., Brunner, K., Német, A., Petrone, C., Atanasov, M., Bajas, H., & Feuvrier, J. (2019). An MgB2 superconducting shield prototype for the future circular collider septum magnet. *IEEE Transactions on Applied Superconductivity*, *29*(8), 1–10. https://doi.org/10.1109/TASC.2019.2920359

Barzi, E., & Zlobin, A. V. (2019). Nb3Sn wires and cables for high-field accelerator magnets. In D. Schoerling & A. V. Zlobin (Eds.), *Nb3Sn Accelerator Magnets: Designs, Technologies and Performance* (pp. 23–51). Springer, Cham.

Beer, S. (1995). *Brain of the Firm*. John Wiley & Sons.

Benavides, E. M. (2012). The design process. In E. M. Benavides (Ed.), *Advanced Engineering Design* (pp. 1–258). Woodhead Publishing. https://doi.org/10.1533/9780857095046.1

Berschik, M. C., Schumacher, T., Laukotka, F. N., Krause, D., & Inkermann, D. (2023). MBSE within the engineering design community - An exploratory study. *Proceedings of the Design Society*, *3*, 2595–2604. https://doi.org/10.1017/pds.2023.260

Bertalanffy, L. v. (1969). *General system theory: Foundations, development, applications*. George Braziller.

Biedron, S., Brouwer, L., Bruhwiler, D., Cook, N., Edelen, A., Filippetto, D., Huang, C.-K., Huebl, A., Kuklev, N., Lehe, R., et al. (2022). Snowmass21 accelerator modeling community white paper. arXiv. https://doi.org/https://doi.org/10.48550/arXiv.2203.08335

Blessing, L. T., & Chakrabarti, A. (2009). *DRM, a Design Research Methodology*. Springer London. https://doi.org/10.1007/978-1-84882-587-1

Bonnal, P., Feral, B., Kershaw, K., & Nicquevert, B. (2016). openSE: A systems engineering framework particularly suited to particle accelerator studies and development projects. *Proceedings of the 7th International Particle Accelerator Conference (IPAC2016)*, 2398–2401. https://accelconf.web.cern.ch/ipac2016/papers/wepmr055.pdf

Bonnal, P. (2024). About openSE. CERN. Retrieved May 10, 2024, from https://opense.web.cern.ch/about

Bordini, B., Bottura, L., Devred, A., Fiscarelli, L., Karppinen, M., de Rijk, G., Rossi, L., Savary, F., & Willering, G. (2019). Nb3Sn 11 T dipole for the high luminosity LHC (CERN). In D. Schoerling & A. V. Zlobin (Eds.), *Nb3Sn Accelerator Magnets: Designs, Technologies and Performance* (pp. 223–258). Springer.

Bortot, L., Auchmann, B., Garcia, I. C., Navarro, A. M. F., Maciejewski, M., Mentink, M., Prioli, M., Ravaioli, E., Schps, S., & Verweij, A. P. (2018). STEAM: A hierarchical cosimulation framework for superconducting accelerator magnet circuits. *IEEE Transactions on Applied Superconductivity*, *28*(3), 1–6. https://doi.org/10.1109/TASC.2017.2787665

Boswell, J. W., Anbari, F. T., & Via, J. W. (2017). Systems Engineering and Project Management: Points of Intersection, Overlaps, and Tensions. *2017 Portland International Conference on Management of Engineering and Technology (PICMET)*, 1–6. https://doi.org/10.23919/PICMET.2017.8125348

Bottura, L., Auchmann, B., Ballarino, A., Devred, A., Izquierdo-Bermudez, S., De Rijk, G., Rossi, L., Savary, F., Schoerling, D., CEA, H. F., et al. (2022). A high field magnet development for HEP in europe - A proposal. *Proceedings: 2021 US Community Study on the Future of Particle Physics : Snowmass 2021*. https://indico.cern.ch/event/999657/contributions/4207478/attachments/2179743/3681623/Snomass_HFM_LoI_v1.pdf

Bottura, L., Prestemon, S., Rossi, L., & Zlobin, A. V. (2022). Superconducting magnets and technologies for future colliders. *Frontiers in Physics*, 882. https://doi.org/https://doi.org/10.3389/fphy.2022.935196

Boyer, C., Delamare, C., Mallon-Amerigo, S., Manola-Poggioli, E., Martel, P., Mottier, M., Muller, J., Pettersson, T., Rousseau, B., Petit, S., Suwalska, A., & Widegren, D. (2002). The CERN EDMS – Engineering and equipment data management system. *Proceedings of EPAC 2002*, 2697–2699. https://inspirehep.net/literature/610069

Brice, M. (2004). LHC dipole testing facility completed [Photograph]. Retrieved June 4, 2024, from https://cds.cern.ch/record/724733

Brouwer, L., Arbelaez, D., Auchmann, B., Bortot, L., & Stubberud, E. (2019). User defined elements in ANSYS for 2D multiphysics modeling of superconducting magnets. *Superconductor Science and Technology*, *32*(9). https://doi.org/10.1088/1361-6668/ab2e63

Burns, A. (2007). Action Research. In J. Cummins & C. Davison (Eds.), *International Handbook of English Language Teaching* (pp. 987–1002). Springer US. https://doi.org/10.1007/978-0-387-46301-8_66

Carter, R. G. (2011). Acceleration technologies for charged particles: An introduction. *Contemporary Physics*, *52*(1), 15–41. https://doi.org/10.1080/00107514.2010.527706

CERN. (2017). The LHCb experiment is charmed to announce observation of a new particle with two heavy quarks. CERN. Retrieved June 4, 2024, from https://home.cern/news/press-release/cern/lhcb-experiment-charmed-announce-observation-new-particle-two-heavy-quarks

CERN. (2021). ALPHA cools antimatter using laser light for the first time. CERN. Retrieved June 4, 2024, from https://home.cern/news/press-release/experiments/alpha-cools-antimatter-using-laser-light-first-time

CERN. (2022). *European Strategy for Particle Physics - Accelerator R&D Roadmap* (C. Mounet, Ed.; Vol. CERN-2022-001). CERN. https://doi.org/10.23731/CYRM-2022-001

CERN. (2024a). Future Circular Collider [Digital artwork]. Retrieved March 5, 2024, from https://home.cern/science/accelerators/future-circular-collider

CERN. (2024b). PaaS Docs. CERN. Retrieved April 24, 2024, from https://paas.docs.cern.ch/

Chiva-Gomez, R. (2004). Repercussions of complex adaptive systems on product design management. *Technovation*, *24*(9), 707–711. https://doi.org/10.1016/S0166-4972(02)00155-4

Conforto, E., Rossi, M., Rebentisch, E., Oehmen, J., & Pacenza, M. (2013). Survey Report: Improving Integration of Program Management and Systems Engineering. https://dspace.mit.edu/handle/1721.1/79681

Cooper, R. (1990). Stage-gate systems: A new tool for managing new products. *Business Horizons*, *33*, 44–54. https://doi.org/10.1016/0007-6813(90)90040-I

Delligatti, L. (2014). *SysML Distilled: A Brief Guide to the Systems Modeling Language*. Addison-Wesley.

Dörner, D. (1987). *Problemlösen als Informationsverarbeitung* (3. Aufl). Kohlhammer. https://fis.uni-bamberg.de/handle/uniba/32350

Doumeingts, G., Girard, P., & Eynard, B. (1996). Gim: Grai Integrated Methodology for Product Development. In G. Q. Huang (Ed.), *Design for X: Concurrent engineering imperatives* (pp. 153–172). Springer Netherlands. https://doi.org/10.1007/978-94-011-3985-4_8

Dumitrescu, R., Albers, A., Riedel, O., Stark, R., & Gausemeier, J. (2021). *Advanced Systems Engineering. Wertschöpfung im Wandel*. Fraunhofer IEM. https://publica.fraunhofer.de/handle/publica/301252

Eckert, C. M., Clarkson, P. J., & Stacey, M. K. (2003). The spiral of applied research: A methodological view on integrated design research. *Proceedings of ICED 03*, 245–246. https://www.designsociety.org/publication/23944/THE+SPIRAL+OF+APPLIED+RESEARCH%3A+A+METHODOLOGICAL+VIEW+ON+INTEGRATED+DESIGN+RESEARCH

Eckert, C. M., Wynn, D. C., Maier, J. F., Albers, A., Bursac, N., Chen, H. L. X., Clarkson, P. J., Gericke, K., Gladysz, B., & Shapiro, D. (2017). On the integration of product and process models in engineering design. *Design Science*, *3*, e3. https://doi.org/10.1017/dsj.2017.2

Ferchow, J. (2021). *Additive manufacturing towards industrial series production: Post-processing strategies and design* (Doctoral dissertation). ETH Zurich. https://doi.org/10.3929/ethz-b-000514979

Ferracin, P., Ambrosio, G., Anerella, M., Arbelaez, D., Brouwer, L., Barzi, E., Cooley, L. D., Cozzolino, J., Garcia Fajardo, L., Gupta, R., Juchno, M., Kashikhin,

V. V., Kurian, F., Marinozzi, V., Novitski, I., Rochepault, E., Stern, J., Vallone, G., Yahia, B., & Zlobin, A. (2023). Conceptual Design of 20 T Hybrid Accelerator Dipole Magnets. *IEEE Transactions on Applied Superconductivity*, *33*(5), 1–7. https://doi.org/10.1109/TASC.2023.3250382

Ferrentino, V. (2020). *Analysis of thermal transients in a superconducting combined function magnet for hadron therapy gantry* (Master's thesis). Univeristy of Naples Federico II. https://repository.cern/records/3m1bj-nfm12

Fiscarelli, L., Bajas, H., Dunkel, O., Ferracin, P., Bermudez, S. I., Russenschuck, S., Todesco, E., & Ambrosio, G. (2018). Magnetic measurements on the first CERN-built models of the insertion quadrupole MQXF for HL-LHC. *IEEE Transactions on Applied Superconductivity*, *28*(3), 1–5. https://doi.org/10.1109/TASC.2017.2786684

Friedrich, T., Hilbes, C., & Nordt, A. (2017). Systems of systems engineering for particle accelerator based research facilities: A case study on engineering machine protection. *2017 Annual IEEE International Systems Conference (SysCon)*, 1–8. https://doi.org/10.1109/SYSCON.2017.7934806

Fu, C., Liu, J., & Wang, S. (2021). Building SysML Model Graph to Support the System Model Reuse. *IEEE Access*, *9*, 132374–132389. https://doi.org/10.1109/ACCESS.2021.3115165

Garcia, I. C. (2021). *Mathematical analysis and simulation of field models in accelerator circuits*. Springer Nature. https://doi.org/10.1007/978-3-030-63273-1

Gausemeier, J., & Moehringer, S. (2002). VDI 2206- A new guideline for the design of mechatronic systems. *IFAC Proceedings Volumes*, *35*(2), 785–790. https://doi.org/10.1016/S1474-6670(17)34035-1

Gericke, K., Bender, B., Pahl, G., Beitz, W., Feldhusen, J., & Grote, K.-H. (2021). Der Produktentwicklungsprozess. In B. Bender & K. Gericke (Eds.), *Pahl/Beitz Konstruktionslehre: Methoden und Anwendung erfolgreicher Produktentwicklung* (pp. 57–93). Springer. https://doi.org/10.1007/978-3-662-57303-7_4

Gerrike, K., Eckert, C., & Stacey, M. (2017). What do we need to say about a design method? *Proceedings of the 21st International Conference on Engineering Design (ICED17)*. http://oro.open.ac.uk/50445/

Gourlay, S., Raubenheimer, T., Shiltsev, V., Arduini, G., Assmann, R., Barbier, C., Bai, M., Belomestnykh, S., Bermudez, S., Bhat, P., et al. (2022). Snowmass' 21 accelerator frontier report. arXiv. https://doi.org/https://doi.org/10.48550/arXiv.2209.14136

Gregory, S. A. (1966). Design and the design method. In S. A. Gregory (Ed.), *The Design Method* (pp. 3–11). Springer US. https://doi.org/10.1007/978-1-4899-6331-4

Guo, Y., Zhao, H., Qi, K., & Guo, J. (2022). Analysis of the Mainstream MBSE Methodologies from the Modeling Practice View. *Proceedings of CECNet 2022*, 146–154. https://doi.org/10.3233/FAIA220529

Halvorson, M., Fuchs, J., Thomas, L. D., Blair, A., Patel, S., & Moyers, N. (2022). Model-based mission planning: Reducing mission planning costs by generating mission-unique architecture and process frameworks. *Proceedings of the International Astronautical Congress (IAC)*, *2022-September*. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85167571208&partnerID=40&md5=1dab00584ece11bbeac5ea3d2ff052dd

Haque, B., Pawar, K. S., & Barson, R. J. (2003). The application of business process modelling to organisational analysis of concurrent engineering environments. *Technovation*, *23*(2), 147–162. https://doi.org/10.1016/S0166-4972(01)00103-1

Hoell, S. (2022). *Characterization of the thermal contraction of superconducting magnet coils for the High-Luminosity upgrade of the Large Hadron Collider (HL-LHC)* (Master's thesis). Karlsruher Institut für Technologie (KIT). https://cds.cern.ch/record/2845427

Holt, J., Perry, S., Payne, R., Bryans, J., Hallerstede, S., & Hansen, F. O. (2015). A Model-Based Approach for Requirements Engineering for Systems of Systems. *IEEE Systems Journal*, *9*(1), 252–262. https://doi.org/10.1109/JSYST.2014.2312051

INCOSE. (2007). *Systems Engineering Vision 2020* (tech. rep. INCOSE-TP-2004-004-02). International Council on Systems Engineering. Seattle, WA. https://sdincose.org/wp-content/uploads/2011/12/SEVision2020_20071003_v2_03.pdf

International Software Testing Qualifications Board. (2023). ISTQB Glossary. ISTQB. Retrieved February 16, 2024, from https://glossary.istqb.org/en_US/search

Iyer, N., Jayanti, S., Lou, K., Kalyanaraman, Y., & Ramani, K. (2005). Three-dimensional shape searching: State-of-the-art review and future trends. *Computer-Aided Design*, *37*(5), 509–530. https://doi.org/10.1016/j.cad.2004.07.002

Izquierdo Bermudez, S., Sabbi, G., & Zlobin, A. (2022). *Accelerator technology magnets* (tech. rep. FERMILAB-FN-1208-TD). https://doi.org/10.48550/arXiv.2208.13349

Jain, N. (2021). Survey Versus Interviews: Comparing Data Collection Tools for Exploratory Research. *The Qualitative Report*, *26*(2), 541–554. https://doi.org/10.46743/2160-3715/2021.4492

Jänsch, J., & Birkhofer, H. (2006). The development of the guideline VDI 2221 - The change of direction. *DS 36: Proceedings DESIGN 2006, the 9th International Design Conference*, 45–52. https://www.designsociety.org/

publication/18983/THE+DEVELOPMENT+OF+THE+GUIDELINE+VDI+2221+-+THE+CHANGE+OF+DIRECTION

Kaeske, J., Wagner, E., Albers, A., & Russenschuck, S. (2024a). *Governance and Mentoring Strategy for Systems Engineering and Project Management: Towards Integrated Management of Magnet-Design at CERN* (Paper Submitted for Publication).

Kalmus, P. I. P. (1986). Options for Machines and Experiments in the Future. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, *404*(1827), 285–298. https://www.jstor.org/stable/2397954

Kempf, C., Rapp, S., Behdinan, K., & Albers, A. (2023). Reference System Element Identification Atlas -methods and tools to identify references system elements in product engineering. *World Patent Information*, *75*. https://doi.org/10.1016/j.wpi.2023.102239

Kossiakoff, A., Seymour, S., Flanigan, D., & Biemer, S. (2020). Model-based systems engineering (MBSE). In A. Kossiakoff, S. Seymour, D. Flanigan, & S. Biemer (Eds.), *Systems Engineering Principles and Practice* (pp. 253–273). https://doi.org/10.1002/9781119516699.ch10

Langley, M., Robitaille, S., & Thomas, J. (2011). Toward a New Mindset: Bridging the Gap Between Program Management and Systems Engineering. *INSIGHT*, *14*(3), 4–8. https://doi.org/10.1002/inst.20111434

Lebrun, P., & Taylor, T. (2015). Managing the Laboratory and Large Projects. In C. Fabjan, T. Taylor, D. Treille, & H. Wenninger (Eds.), *Technology Meets Research* (pp. 393–422). WORLD SCIENTIFIC. https://doi.org/10.1142/9789814749145_0011

Lewin, K. (1946). Action Research and Minority Problems. *Journal of Social Issues*, *2*(4), 34–46. https://doi.org/10.1111/j.1540-4560.1946.tb02295.x

Lohmeyer, Q. (2013). Menschzentrierte modellierung von produktentstehungssystemen unter besonderer berücksichtigung der synthese und analyse dynamischer zielsysteme. Doctoral dissertation. In A. Albers & S. Matthiesen (Eds.), *Forschungsberichte des IPEK - Institut für Produktentwicklung. Systeme, Methoden, Prozesse (Vol. 59)*. Karlsruher Institut für Technologie (KIT). https://doi.org/10.5445/IR/1000035102

Mabrouk, A., Penas, O., Plateaux, R., Barakallah, M., Choley, J.-Y., & Akrout, A. (2018). Integration of agility in a MBSE methodology for multidisciplinary systems design. *2018 IEEE International Systems Engineering Symposium (ISSE)*, 1–5. https://doi.org/10.1109/SysEng.2018.8544425

Maciejewski, M., Auchmann, B., Araujo, D. M., Vallone, G., Leuthold, J., & Smajic, J. (2023). Model-Based System Engineering Framework for Superconducting Accelerator Magnet Design. *IEEE Transactions on Applied Superconductivity*, 1–5. https://doi.org/10.1109/TASC.2023.3249647

Maciejewski, M. (2019). *Co-simulation of transient effects in superconducting accelerator magnets* (Doctoral dissertation). University of Lodz. https://cds.cern.ch/record/2675039

Madni, A. M., & Sievers, M. (2018). Model-based systems engineering: Motivation, current status, and research opportunities. *Systems Engineering*, *21*(3), 172–190. https://doi.org/10.1002/sys.21438

Mallón Amérigo, S., Martel, P., Petit, S., Widegren, D., & Switzerland, G. (2009). CERN's global equipment data repository. *Proceedings of the ICALEPCS2009*. https://accelconf.web.cern.ch/icalepcs2009/papers/tub004.pdf

Mandel, C., Böning, J., Behrendt, M., & Albers, A. (2021). A model-based systems engineering approach to support continuous validation in PGE - Product generation engineering. *2021 IEEE International Symposium on Systems Engineering (ISSE)*, 1–8. https://doi.org/10.1109/ISSE51541.2021.9582475

Mandel, C., Kaspar, J., Heitmann, R., Horstmeyer, S., Martin, A., & Albers, A. (2023). Implementation and Assessment of a Comprehensive Model-Based Systems Engineering Methodology with Regard to User Acceptance in Practice. *Procedia CIRP*, *119*, 897–902. https://doi.org/10.1016/j.procir.2023.03.135

Mandel, C., Wäschle, M., Lutz, S., & Behrendt, M. (2021). A model-based approach for automation and traceability of validation activities – Clarified for advanced driver assistance systems. *9th International Symposium on Development Methodology, 9.-10- November 2021, Wiesbaden, Germany*. https://publikationen.bibliothek.kit.edu/1000142322

Mann, H. (2023). REST APIs Explained - 4 Components. Howie Mann. Retrieved April 18, 2024, from https://mannhowie.com/rest-api

Marxen, L. (2014). A Framework for Design Support Development based on the integrated Product Engineering Model iPeM. Doctoral dissertation. In A. Albers & S. Matthiesen (Eds.), *Forschungsberichte des IPEK - Institut für Produktentwicklung. Systeme, Methoden, Prozesse (Vol. 74)*. Karlsruher Institut für Technologie (KIT). https://publikationen.bibliothek.kit.edu/1000045823

Masior, J., Schneider, B., Kürümlüoglu, M., & Riedel, O. (2020). Beyond Model-Based Systems Engineering towards Managing Complexity. *Procedia CIRP*, *91*, 325–329. https://doi.org/10.1016/j.procir.2020.02.183

Matthiesen, S., Schmidt, S., Moeser, G., & Munker, F. (2014). The Karlsruhe SysKIT approach – A three-step SysML teaching approach for mechatronic students. *Procedia CIRP*, *21*, 385–390. https://doi.org/10.1016/j.procir.2014.03.136

Mazzitelli, G. (2011). Application of particle accelerators in research. *Radiation Protection Dosimetry*, *146*(4), 372–376. https://doi.org/10.1093/rpd/ncr241

Mierau, A., Fischer, E., Kaether, F., Roux, C., Bleile, A., Marusov, V., Sugita, K., Szwangruber, P., Weiss, H., Khodzhibagiyan, H., & Kostromin, S. (2018). Testing of the Superconducting Magnets for the SIS100 Synchrotron. *IEEE Transactions on Applied Superconductivity*, *28*(3), 1–5. https://doi.org/10.1109/TASC.2017.2777832

Muschik, S. (2011). Development of Systems of Objectives in Early Product Engineering. Doctoral dissertation. In A. Albers & S. Matthiesen (Eds.), *Forschungsberichte des IPEK - Institut für Produktentwicklung. Systeme, Methoden, Prozesse (Vol. 50)*. Karlsruher Institut für Technologie (KIT). https://doi.org/10.5445/IR/1000023768

Naumann, T., & Vajna, S. (2004). Adaptive system management. *DS 32: Proceedings of DESIGN 2004, the 8th International Design Conference, Dubrovnik, Croatia*, 435–440. https://www.designsociety.org/publication/19786/ADAPTIVE+SYSTEM+MANAGEMENT

Negele, H., Fricke, E., & Igenbergs, E. (1997). ZOPH – A Systemic Approach to the Modeling of Product Development Systems. *INCOSE International Symposium*, *7*(1), 266–273. https://doi.org/10.1002/j.2334-5837.1997.tb02181.x

O'Donnell, F., & Duffy, A. (2002). Modelling design development performance. *International Journal of Operations & Production Management*, *22*(11), 1198–1221. https://doi.org/10.1108/01443570210450301

Ogitsu, T., Devred, A., Kim, K., Krzywinski, J., Radusewicz, P., Schermer, R., Kobayashi, T., Tsuchiya, K., Muratore, J., & Wanderer, P. (1994). Quench antenna for superconducting particle accelerator magnets. *IEEE Transactions on Magnetics*, *30*(4), 2273–2276. https://doi.org/10.1109/20.305728

Ogitsu, T., Terashima, A., Tsuchiya, K., Ganetis, G., Muratore, J., & Wanderer, P. (1996). Quench observation using quench antennas on RHIC IR quadrupole magnets. *IEEE Transactions on Magnetics*, *4*, 3098–3101. https://doi.org/10.1109/20.511531

openSE Editorial Project. (2016). *openSE* (tech. rep.). CERN. https://opense.web.cern.ch/sites/default/files/openSE_Framework/openSE_Framework.pdf

Papke, B. L., Wang, G., Kratzke, R., & Schreiber, C. (2020). Implementing MBSE – An Enterprise Approach to an Enterprise Problem. *INCOSE International Symposium*, *30*(1), 1550–1567. https://doi.org/10.1002/j.2334-5837.2020.00803.x

Pfaff, F., Schlegel, M., Völk, T., Reinheckel, K., & Albers, A. (2024). Using product profiles for retrospective case studies in SGE – system generation engineering. *Proceedings of the Design Society*, *4*, 2695–2704. https://doi.org/10.1017/pds.2024.272

Pin-Shan, C. (1976). The entity-relationship model—toward a unified view of data. *ACM Transactions on Database Systems (TODS)*. https://doi.org/10.1145/320434.320440

Pratt, M., & Dabkowski, M. (2022). Analyzing the Integration of MBSE Approaches within the Aerospace Industry according to UTAUT. *Industrial and Systems Engineering Review*, *10*(2), 127–134. https://doi.org/10.37266/ISER.2022v10i2.pp127-134

Prestemon, S., Amm, K., Cooley, L., Gourlay, S., Larbalestier, D., Velev, G., & Zlobin, A. (2020). *The 2020 Updated Roadmaps for the US Magnet Development Program* (tech. rep.). U.S. Magnet Development Program. https://doi.org/10.48550/arXiv.2011.09539

Rebentisch, E. S., Townsend, S., & Conforto, E. (2015). Collaboration Across Linked Disciplines: Skills and Roles for Integrating Systems Engineering and Program Management. *122nd American Society for Engineering Education Annual Conference and Exposition 2015*. https://www.researchgate.net/publication/311846490

Reich, Y., & Subrahmanian, E. (2022). The PSI Framework and Theory of Design. *IEEE Transactions on Engineering Management*, *69*(4), 1037–1049. https://doi.org/10.1109/TEM.2020.2973238

Resta-López, J. (2022). Long-term future particle accelerators. arXiv. https://doi.org/10.48550/arXiv.2206.08834

Robertson, A. H. (1981). European Organisation for Nuclear Research (CERN). In A. H. Robertson (Ed.), *Annuaire Europeen / European Yearbook: Vol. XXVII* (pp. 526–535). Springer Netherlands. https://doi.org/10.1007/978-94-015-1192-6_14

Ropohl, G. (2009). *Allgemeine Technologie : Eine Systemtheorie der Technik*. KIT Scientific Publishing. https://doi.org/10.5445/KSP/1000011529

Russenschuck, S. (1995). A computer program for the design of superconducting accelerator magnets. *Proceedings of ACES'95*, 366–377. https://cds.cern.ch/record/289488

Russenschuck, S. (2025). *Field Simulation for Accelerator Magnets* (1st ed.). Wiley. https://www.wiley.com/en-be/Field+Simulation+for+Accelerator+Magnets%3A+Volume+1%3A+Theory+of+Fields+and+Magnetic+Measurements+%2F+Volume+2%3A+Methods+for+Design+and+Optimization-p-9783527414178#description-section

Shen, T., Fajardo, L. G., Myers, C., Hafalia Jr, A., Fernández, J. L. R., Arbelaez, D., Brouwer, L., Caspi, S., Ferracin, P., Gourlay, S., et al. (2022). Design, fabrication, and characterization of a high-field high-temperature superconducting Bi-2212 accelerator dipole magnet. *Physical Review Accelerators and Beams*, *25*(12), 13. https://doi.org/https://doi.org/10.1103/PhysRevAccelBeams.25.122401

Shiltsev, V., & Zimmermann, F. (2021). Modern and future colliders. *Reviews of Modern Physics*, *93*(1), 015006. https://arxiv.org/pdf/2003.09084.pdf

Sillitto, H., Martin, J., McKinney, D., Griego, R., Dori, D., Krob, D., Godfrey, P., Arnold, E., & Jackson, S. (2019). *Systems Engineering and System Definitions* (tech. rep.). INCOSE. https://www.incose.org/docs/default-source/default-document-library/final_-se-definition.pdf

Stachowiak, H. (1973). *Allgemeine Modelltheorie*. Springer.

Stammnitz, F., Schlegel, M., Pfaff, F., & Albers, A. (2023). *Proposal of a reference-based development of company strategies based on the model of SGE -System Generation Engineering*. https://doi.org/10.46720/FWC2023-AVD-004

the FCC Collaboration, Abada, A., Abbrescia, M., AbdusSalam, S. S., Abdyukhanov, I., Abelleira Fernandez, J., Abramov, A., Aburaia, M., Acar, A. O., Adzic, P. R., Agrawal, P., Aguilar-Saavedra, J. A., Aguilera-Verdugo, J. J., Aiba, M., Aichinger, I., Aielli, G., Akay, A., Akhundov, A., Aksakal, H., … Zurita, J. (2019). FCC-HH: The hadron collider: Future circular collider conceptual design report volume 3. *The European Physical Journal Special Topics*, *228*(4), 755–1107. https://doi.org/10.1140/epjst/e2019-900087-0

Todesco, E., Bajas, H., Bajko, M., Ballarino, A., Bermudez, S. I., Bordini, B., Bottura, L., Rijk, G. D., Devred, A., Ramos, D. D., Duda, M., Ferracin, P., Fessia, P., Fleiter, J., Fiscarelli, L., Foussat, A., Kirby, G., Mangiarotti, F., Mentink, M., … Felice, H. (2021). The high luminosity LHC interaction region magnets towards series production. *Superconductor Science and Technology*, *34*(5), 053001. https://doi.org/10.1088/1361-6668/abdba4

Troitino, J. F., Bajas, H., Bianchi, L., Castaldo, B., Ferracin, P., Guinchard, M., Izquierdo, S., Lorenzo, J., Mangiarotti, F., Perez, J., et al. (2021). A methodology for the analysis of the three-dimensional mechanical behavior of a Nb3Sn superconducting accelerator magnet during a quench. *Superconductor Science and Technology*, *34*(8), 084003. https://doi.org/10.1088/1361-6668/ac0952

Turner, B. (2000). CERN — The European Laboratory for Particle Physics. In B. Turner (Ed.), *The Statesman's Yearbook: The Politics, Cultures and Economies of the World 2001* (pp. 77–78). Palgrave Macmillan UK. https://doi.org/10.1057/9780230271296_19

Van Delft, D., & Kes, P. (2010). The discovery of superconductivity. *Physics Today*, *63*(9), 38–43. https://doi.org/10.1063/1.3490499

VDI-Gesellschaft Produkt- und Prozessgestaltung, VDI Society Product and Process Design, VDI Verein Deutscher Ingenieure e.V., & VDI - The Association of German Engineers. (2019). VDI 2221 blatt 1 entwicklung technischer produkte und systeme - Modell der produktentwicklung. https://wwwdb.dbod.de/login?url=https://www.nautos.de/O9G/search/item-detail/DE88720241

Védrine, P., Rossi, L., Shepherd, B., Rochepault, E., Noe, M., Auchmann, B., Baudouy, B., Fazilleau, P., Senatore, C., Prestemon, S., et al. (2022). CERN: Chapter 2: High-field magnets. *CERN Yellow Reports: Monographs*, *1*, 9–59. https://doi.org/10.23731/CYRM-2022-001.9

Wang, X., Yahia, A. B., Bosque, E., Ferracin, P., Gourlay, S., Gupta, R., Higley, H., Kashikhin, V., Kumar, M., Lombardo, V., et al. (2022). REBCO - A silver bullet for our next high-field magnet and collider budget. arXiv. https://doi.org/arXiv:2203.08736

Wardzinska, A., Petit, S., Bray, R., Delamare, C., Arza, G. G., Krastev, T., Pater, K., Suwalska, A., & Widegren, D. (2015). The Evolution of CERN EDMS. *Journal of Physics: Conference Series*, *664*(3), 032032. https://doi.org/10.1088/1742-6596/664/3/032032

Wynn, D. C., & Clarkson, P. J. (2024). *The Design and Development Process: Perspectives, Approaches and Models*. Springer International Publishing. https://doi.org/10.1007/978-3-031-38168-3

Wynn, D. C., & Maier, A. M. (2022). Feedback systems in the design and development process. *Research in Engineering Design*, *33*(3), 273–306. https://doi.org/10.1007/s00163-022-00386-z

Xiao, Y., & Watson, M. (2019). Guidance on Conducting a Systematic Literature Review. *Journal of Planning Education and Research*, *39*(1), 93–112. https://doi.org/10.1177/0739456X17723971

Yin, R. K. (2017). *Case Study Research and Applications: Design and Methods*. SAGE Publications.

Zlobin, A. V., & Schoerling, D. (2019). Superconducting Magnets for Accelerators. In D. Schoerling & A. V. Zlobin (Eds.), *Nb3Sn Accelerator Magnets: Designs, Technologies and Performance* (pp. 3–22). Springer International Publishing. https://doi.org/10.1007/978-3-030-16118-7_1

Unpublished work co-authored by the author of this dissertation:

Kaeske, J., Wagner, E., Albers, A., & Russenschuck, S. (2024a). *Governance and Mentoring Strategy for Systems Engineering and Project Management: Towards Integrated Management of Magnet-Design at CERN* (Paper Submitted for Publication).

A Appendix

A.1 Magnet Design Methodology

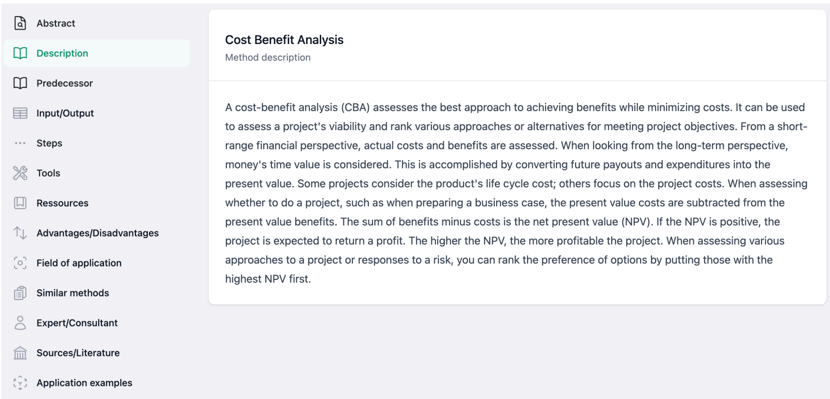

Figure A.1: Example method profile displayed as the detail view when clicking on a method of the method catalog within the change management tool. The profile shows information such as the method description, steps, necessary tools, and resources or sources with further information.

A.2 Magnet Model Management Layer (3ML)

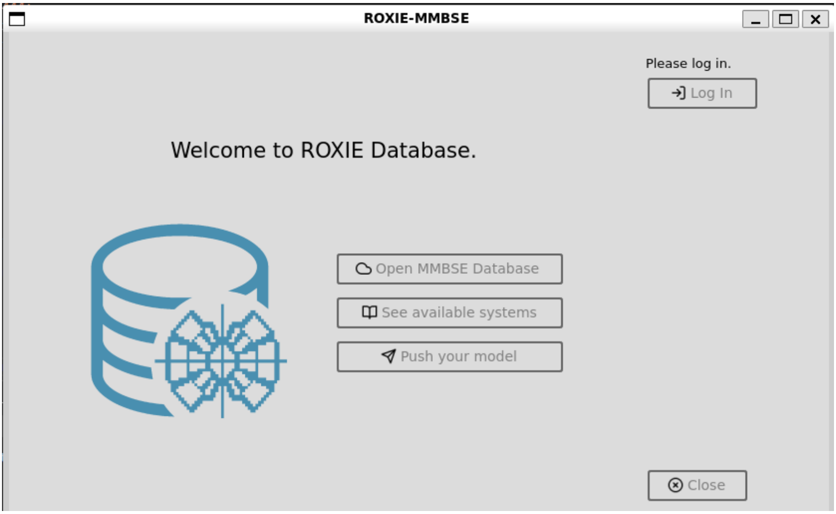

Figure A.2: Welcome window of the ROXIE Qt GUI to interact with the MMBSE API. The window can be opened directly from the ROXIE UI.

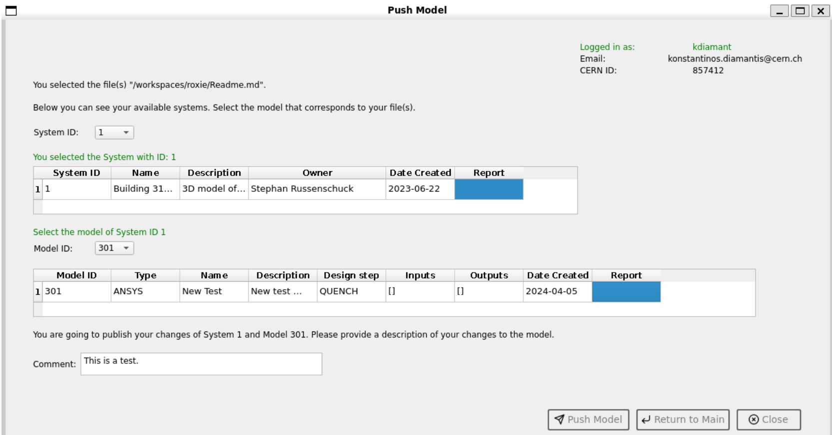

Figure A.3: ROXIE Qt GUI window to push models and local changes to the MMBSE database. The window lets the user select the model to be pushed and an explanation of what kind of changes have been made.

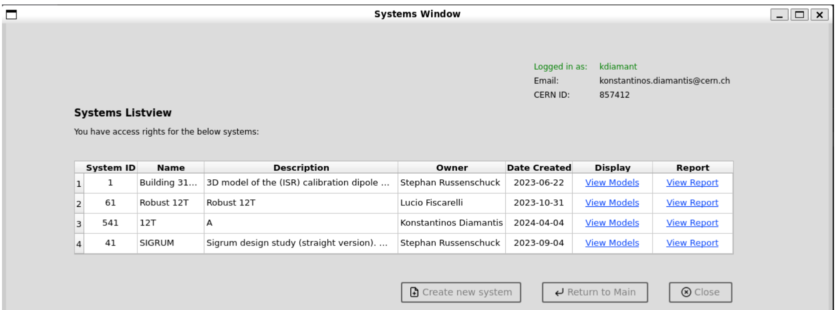

Figure A.4: ROXIE Qt GUI window to see all available systems in the MMBSE database. The systems are clickable, and the associated models will be shown similarly in another window. The models can then be directly loaded into the ROXIE simulation environment.

Publications Co-Authored by the Author of This Dissertation

Kaeske, J., Fiscarelli, L., Albers, A., & Russenschuck, S. (2024). Overview of identified challenges in the development process of superconducting accelerator magnets. *Designs*, *8*(1). https://doi.org/10.3390/designs8010013

Kaeske, J., Wagner, E., Albers, A., & Russenschuck, S. (2024b). Tool support for implementing a methodology in magnet development projects at CERN. *Proceedings of the Design Society*, *4*, 2615–2624. https://doi.org/10.1017/pds.2024.264

Liebsch, M., Russenschuck, S., & Kaeske, J. (2023). An induction-coil magnetometer for mid-plane measurements in spectrometer magnets. *Sensors and Actuators A: Physical*, *355*, 114334. https://doi.org/10.1016/j.sna.2023.114334

Wagenmann, S., Krause, A., Rall, J., Kaeske, J., Schoeck, M., Bursac, N., & Albers, A. (2023). Reference architecture for metadata management - A case study on data mining in the development of cyber-physical systems. *Proceedings of the 2023 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, 1057–1061. https://doi.org/10.1109/IEEM58616.2023.10406413