THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

# Smart Maintenance in Battery Production

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*“A battery will do for the electricity supply chain what refrigeration did to our food supply chain”*

\- Professor Donald Sadowav

Electrochemist, MIT Materials Science

# ABSTRACT

Smart Maintenance has emerged as an important concept for managing maintenance in digitalized manufacturing, yet its implementation remains insufficiently understood, particularly in newly established factories and greenfield manufacturing. Prior research has established its conceptualization and provided its facilitation, but empirical evidence into its implementation – how it is put into effect – remain limited. This is especially evident in greenfield battery production, a rapidly growing European industry characterized by significant challenges, reflected in several recently paused or failed industrialization projects. This creates a need to better understand how battery production is ramped up and the role of Smart Maintenance in enabling its success.

The aim of this thesis is therefore to examine how Smart Maintenance can be understood and developed in battery production. It addresses two research questions: (1) the main challenges associated with maintenance in battery production, and (2) how Smart Maintenance can contribute to its development. The research is based on an industrial doctoral project carried out at a large battery manufacturer in Sweden between 2022 and 2025. It follows an iterative research design aimed at exploring, analyzing, and evaluating prioritized research and development projects during production ramp-up. The thesis is based on five appended papers employing ethnographic, case study, multi-method, and design science research approaches. Together, the studies identify critical challenges, establish important development needs, and outline relevant research avenues across socio-technical components, and begin to address these in relation to the four dimensions of Smart Maintenance.

The results show that the main challenges associated with maintenance in battery production relate to performance, workforce, integration, and design. These are derived from 31 research avenues. The thesis further demonstrates how these are addressed through four prioritized research and development projects, illustrating how the four dimension of Smart Maintenance - internal integration, human capital resource, external integration, and data-driven decision-making - can be developed in battery production. More specifically, they outline a structured set of deployment requirements, worker attributes, integration enablers, and design possibilities across the dimensions of Smart Maintenance. In the end, the thesis concludes that Smart Maintenance should not be understood as a final state, but as a continuous process of development. This provides theoretical and practical contributions by demonstrating how maintenance in battery production can be developed using Smart Maintenance, while also advancing theory through its focus on implementation.

**Keywords**: Asset Management, Battery Production, Digitalization, Greenfield Manufacturing, Human Capabilities, Performance Management, Predictive Maintenance, Smart Maintenance

# PREFACE

Dear reader,

I am pleased that you have chosen to read this licentiate thesis. I would like to take a moment to share a bit of the story behind it.

My first encounter with Smart Maintenance came in 2022 during my master's thesis. While the concept was not entirely new, it was gaining real momentum in industry, driven by a growing demand for the digitalization of maintenance practices. At that time, I explored how to implement Smart Maintenance in the pulp and paper industry, which resulted in the additional paper included in this thesis.

When I later joined a large battery manufacturer in Sweden, these questions naturally followed me. In discussions with the maintenance director, we agreed that Smart Maintenance would be central – yet challenging – for the emerging battery industry in Europe. This was when the idea took shape: to develop maintenance in battery production through an industrial doctoral research project. In that sense, this thesis reflects an ongoing dialogue between theory and practice.

I began my journey in the battery factory as a production engineer, working at the final stages of production. While my role initially focused on commissioning, my focus soon shifted to maintenance. Unlike production, which could be planned and automated, maintenance had to respond to failures in many unpredictable ways. This raised questions about the conditions for new battery manufacturers: the opportunity to build capabilities from the outset, but without the experience and established practices of mature industries.

Working as an industrial doctoral student in a rapidly developing industry meant being surrounded by a constant flow of questions related to best practices. I often faced more relevant questions than time. The factory became a living laboratory, where theories could be explored in practice. This required continuous prioritization and close collaboration with both industry and academia. At the same time, maintaining scientific rigor made it essential to ground the work in research methodology.

Several of the development projects carried out in the battery factory formed the basis for this thesis. From an industrial perspective, they addressed practical challenges in battery production; from an academic perspective, they informed theories in maintenance digitalization. Five of these projects were prioritized and developed into the appended papers. Together, they reflect the main challenges associated with maintenance in battery production and illustrate how Smart Maintenance can contribute to the development of this emerging industry.

# ACKNOWLEDGEMENTS

The work behind this thesis would not have been possible without the encouragement and support of the people surrounding me and those involved in my research. I would like to express my sincere gratitude to those who have contributed to and mentored me throughout my research journey.

First and foremost, I would like to thank my main supervisor, Anders Skoogh, for his continuous guidance and encouragement during my studies.

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Furthermore, I would like to express my appreciation to my examiner, Björn Johansson, for always helping to pave the way forward and for his positive energy.

I would also like to thank Patrik Nilsson for believing in me from the beginning and for supporting the development of my role as an industrial doctoral student.

My thanks also go to Martin Karlsson for his advice and insights in navigating the landscape between industry and academia in times of uncertainty.

Finally, I would like to acknowledge all academic and industrial partners who have shown interest in and contributed to my research. Without your engagement, this thesis would not have been possible.

Last but not least, I would like to thank my partner and my family for always supporting me in pursuing the paths I choose.

*Oscar Larsson*
*Gothenburg, June 2026*

# LIST OF APPENDED PAPERS

The five appended papers in this thesis are listed here, along with the contributions and distribution of work among the authors.

**Paper I** **Research Avenues for Maintenance Operations in Battery Production**

**Oscar Larsson**, Anders Skoogh, and Jon Bokrantz

Presented at the 44th IFIP WG 5.7 Interntaional Conference, *APMS 2025*
Kamakura, August 31 - 4 September, 2025.
Published in *Proceedings*, vol. 2, no. 765, pp. 413-427.

Distribution of work: First author. Designed the research study, conducted the ethnographic immersion, led the writing process with contributions from co-authors, and presented the paper at the conference.

**Paper II** **Addressing Requirements for Maintenance Performance Indicators During the Ramp-Up of Battery Production**

**Oscar Larsson**, Camila Kin Márquez, and Jon Bokrantz

Presented at the 44th IFIP WG 5.7 Interntaional Conference, *APMS 2025*
Kamakura, August 31 - 4 September, 2025.
Published in *Proceedings*, vol. 2, no. 765, pp. 428-442.

Distribution of work: First author. First author. Designed the case study, led the writing process with contributions from co-authors, and presented the paper at the conference.

**Paper III** **Worker Attributes and Training Needs for Maintenance Technicians: Insight from Lithium-Ion Battery Production**

Axel Ramhult, Anton Pettersson, **Oscar Larsson**, Jon Bokrantz

Published in Production and Manufacturing Research (April 2026)

Distribution of work: Third author. Designed the case study, coordinated the data collection work, and supported the writing process as co-author.

**Paper IV** **Integrating Asset Management in Greenfield Manufacturing**

**Oscar Larsson**, Adalberto Polenghi, Anita Notarianni, Anders Skoogh, Jon Bokrantz

Submitted to Journal (May 2026)

Distribution of work: First author. Designed the research study, supported the literature review procedure, conducted the interviews and thematic analysis, and led the writing process with contributions from co-authors.

**Paper V** **Designing Predictive Maintenance as Digital Servitization in Greenfield Manufacturing**

**Oscar Larsson**, Jan Holmström, Anders Skoogh, Jon Bokrantz

To be submitted to Journal

Distribution of work: First author. Designed the research study, conducted the design of experiments, and led the writing process with contributions from co-authors.

# LIST OF ADDITIONAL PAPERS

The additional paper included in this thesis is listed here, along with the contributions and distribution of work among the authors.

**Paper VI** **Implementing Smart Maintenance in the Manufacturing Industry**

**Oscar Larsson**, Robin Ferm, Jon Bokrantz, Anders Skoogh

Published in Journal of Manufacturing Technology Management (March 2026)

Distribution of work: First author. Designed the research study, conducted the action research procedure with contributions from co-authors, and led the writing process.

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| | |
|---|---|
| AM | Asset Management |
| CBM | Condition-based maintenance |
| DDD | Data-driven decision-making |
| EXI | External integration |
| HCR | Human capital resource |
| INI | Internal integration |
| KSAO | Knowledge, skills, abilities and other characteristics |
| PdM | Predictive maintenance |
| PI | Performance indicator |
| RQ | Research question |
| SM | Smart Maintenance |

# 1

# INTRODUCTION

*The introduction presents the background of this licentiate thesis, followed by its vision, aim, and RQs. It further outlines the scope and delimitations and concludes by describing the structure of the thesis.*

## 1.1 BACKGROUND

Industrial maintenance is a crucial part of production systems and a foundational enabler of future industrial digitalization. It directly affects production reliability and operational performance and is therefore indispensable for meeting increasingly demanding production targets in modern manufacturing (Thomas, 2018, Akkermans et al., 2024). As manufacturing systems become more automated and interconnected, maintenance is no longer merely a support function but a central mechanism for operating next-generation factories (Gopalakrishnan et al., 2022).

Despite its strategic importance, maintenance has not developed at the same pace as manufacturing. While manufacturing has rapidly adopted Industry 4.0 technologies – and is now transitioning toward Industry 5.0 – maintenance has evolved more slowly (Akkermans et al., 2024, Roda and Macchi, 2021). This imbalance constrains industrial development and shifts the focus toward maintenance organizations. Digitalized maintenance offers the potential to improve industrial performance, provided it is meaningfully applied across maintenance levels.

In response to this gap, Smart Maintenance (SM) has emerged as a growing trend in both academia and industry (Bokrantz et al., 2020c). SM reflects a broader view of maintenance digitalization by integrating digital technologies (Compare et al., 2019, Silvestri et al., 2020, Ayvaz and Alpay, 2021) with organizational design. Research emphasizes that maintenance digitalization cannot be achieved through technology alone; it requires complementary coordination and human competencies to deliver value in practice (Bokrantz et al., 2020b, Beier et al., 2020, Sgarbossa et al., 2020).

SM is needed not only in existing manufacturing, i.e. brownfield, but also in the establishment and ramp-up of new facilities, i.e. greenfield. A clear example is large-scale battery production in Europe (European Commission, 2022). These production facilities, i.e. gigafactories, are digitalized from the outset, creating a need for SM to maintain production effectively and efficiently (Machado et al., 2020, Soori et al., 2024). Digitalized maintenance thus becomes a central part of greenfield industrialization (Esmaeilian et al., 2016), also referred to as the twin transition (Rehman et al., 2023, Ollagnier et al., 2021).

Battery production has become a strategic instrument for industrial development (European Commission, 2022), particularly in Europe, where domestic supply is essential for electrification (Ngoy et al., 2025). However, it is highly complex and difficult to industrialize, as reflected in several failed attempts (International Energy Agency, 2025). It involves more than 140 tightly coupled processes and thousands of cause–effect relationships (Kornas et al., 2019, Dahmen et al., 2024). These characteristics place exceptional demands on production reliability and maintenance efficiency, requiring the development of SM to support battery production.

Gigafactories generate vast amounts of data, pointing to their potential for implementing SM (Soori et al., 2023, Hu et al., 2024). The battery industry accounts for a significant share of industrial artificial intelligence research (World Economic Forum, 2025), and digital technologies can therefore be used to develop the industrial know-how needed to catch up with competitors (Johansson et al., 2024, Bokrantz et al., 2024). However, many digital transformations remain shallow, with technologies often functioning as add-ons rather than digitalizing maintenance (Roda and Macchi, 2021, Akkermans et al., 2024).

Against this backdrop, this thesis aims to examine maintenance in battery production and how SM can be implemented to contribute to its development. Here, implementation is understood as the process of putting SM into effect. Earlier SM research has primarily focused on its conceptualization and facilitation (Bokrantz et al., 2020b, Lundgren et al., 2021). However, more studies are needed on its implementation (Larsson et al., 2026, Lundgren et al., 2022), not least in the context of greenfield industrialization and the establishment of large-scale battery production in Europe.

## 1.2 VISION, AIM, AND RESEARCH QUESTIONS

Maintenance is central to the establishment and development of large-scale battery production in Europe. In highly digitalized manufacturing environemnts, it directly influences the overall performance and quality of production (Polenghi et al., 2019, Gopalakrishnan et al., 2022). As European gigafactories ramp up under significant time pressure, maintenance and its digitalized capabilities must be developed in parallel with production commissioning to ensure sustained competitiveness.

Maintenance in battery production therefore needs to be digitalized and developed along the four dimensions of SM (Bokrantz et al., 2020c) to enable data-driven decision-making (DDD) during ramp-up and build competitive advantage over brownfield manufacturers. However, focusing solely on digital technologies – such as condition-based maintenance (CBM) or predictive maintenance (PdM) – to become “smart” is insufficient. Instead, organizational, technological, and social elements must be developed together to ensure that SM delivers value in practice.

This thesis envisions a European battery industry that achieves long-term sustainability through SM, where high quality and production capacity are enabled by DDD. This is expected to accelerate the transition toward net-zero while strengthening industrial capabilities and future technological leadership in Europe. From this perspective, the thesis examines SM as a pathway to generating the knowledge required to support new battery manufacturers in ramping up – or preparing to do so – and ultimately achieving global competitiveness.

Hence, the overall aim of this licentiate thesis is to support the development of greenfield battery production by providing both academia and industry with strategic guidance and an actionable blueprint for what maintenance in battery production entails. More specifically, the thesis seeks to examine the challenges associated with maintenance in battery production in order to understand how SM can be developed to, in turn, support the industrialization and digitalization of battery production. To achieve this, the thesis identifies critical challenges, establishes important development needs, outlines relevant research avenues, and begins to address these in relation to the four dimensions of SM. In doing so, it bridges theory and practice, helping future battery manufacturers build on existing knowledge and avoid repeating past mistakes.

Based on this aim, the following research questions (RQs) are addressed:

### RQ1: What are the main challenges associated with maintenance in battery production?

This RQ is posed to develop a holistic understanding of the most critical obstacles hindering the successful industrialization and digitalization of maintenance in battery production. While prior maintenance research has identified several technological, organizational, and social challenges for its development, these are often studied in isolation or within brownfield manufacturing contexts. For this reason, the main challenges of maintenance in battery production, as a greenfield manufacturing context, remain largely underexplored.

### RQ2: How can Smart Maintenance contribute to the development of battery production?

This RQ moves beyond problem identification toward problem solving and value creation. While maintenance is critical for production reliability, its contribution to the broader development of battery production – particularly during gigafactory establishment – remains very limited. Existing literature often treats maintenance as a supporting function rather than an active driver of learning for sustainable and digitalized manufacturing. For this reason, maintenance digitalization in battery production needs to be further exemplified through the implementation of SM.

## 1.3 SCOPE AND DELIMITATIONS

This licentiate thesis examines SM in battery production, using a recently established gigafactory in Sweden as its empirical setting. The scope is limited to the maintenance function during establishment and ramp-up, focusing on early-stage industrialization. Battery production is therefore treated as a greenfield context rather than being directly comparable to brownfield manufacturing.

The thesis adopts a socio-technical perspective and examines selected research and development projects aligned with the dimensions of SM. Rather than providing a comprehensive account, these projects scopes key manifestations of SM in battery production and highlight broader development dynamics.

The selection of projects reflects industrial priorities in collaboration with the battery manufacturer, which ensures practical relevance but also constitutes a delimitation, as not all possible SM initiatives are covered. The findings are analytically rather than statistically generalizable (Flyvbjerg, 2004), offering conceptually grounded insights into maintenance development in greenfield industrialization.

Finally, the thesis draws on empirical material from the ramp-up phase of Swedish battery production between 2022 and 2025. While the studied company filed for bankruptcy in 2025, all empirical work was completed prior to this event, and it does not affect the validity of the results.

## 1.4 OUTLINE OF THE THESIS

After this first chapter introducing the background and purpose of this research, this thesis is structured into the following seven chapters.

**Chapter 2, Frame of Reference** introduces SM, maintenance development, and the characteristics of battery production.

**Chapter 3, Research Approach** describes the research setting, approach, design, and methods applied in the thesis.

**Chapter 4, Results of Appended Papers** recapitulates the five studies and their contributions to the RQs.

**Chapter 5, Smart Maintenance in Battery Production** synthesizes the results in relation to SM and battery production development.

**Chapter 6, Discussion** addresses and answers the RQs and concludes the research quality, contributions, limitations, and future work.

**Chapter 7, Conclusion** summarizes the thesis and outlines its theoretical and practical relevance.

# 2

# FRAME OF REFERENCE

*The frame of reference provides perspectives on maintenance development, with a particular focus on the conceptualization, facilitation, and implementation of SM, as well as the characteristics of maintenance in battery production.*

## 2.1 MAINTENANCE DEVELOPMENT

Maintenance development has become increasingly important as manufacturing systems digitalize. In literature, this development is commonly discussed from both technological and organizational perspectives. These perspectives are reflected in the notions of *evolution*, referring to the technological progression of maintenance tools and technologies, and *revolution*, referring to broader shifts in maintenance practices associated with changes in industrial paradigms.

### Evolution

Maintenance development has historically been driven by both technological advances and organizational change. Early maintenance practices were predominantly reactive, focusing on corrective actions after failures had occurred. Over time, preventive approaches were introduced to reduce unexpected breakdowns and stabilize production performance. As manufacturing systems became increasingly digital, maintenance began to evolve into a strategic function concerned not only with uptime and cost efficiency, but also with quality improvements and long-term asset value (Garg and Deshmukh, 2006, Mobley, 2011).

From a technological perspective, maintenance development is often described as an evolutionary progression of maintenance strategies, ranging from corrective maintenance and preventive maintenance to more data-intensive approaches such as CBM, PdM, and ultimately prescriptive maintenance (Sala et al., 2025). This evolution reflects increasing reliance on high-resolution data (see Figure 1) enabled by its sensing, acquisition, and storage to enhance productivity and sustainability in maintenance. While these advancements improve the ability to monitor equipment conditions and predict maintenance needs, they also introduce increasing demands on data infrastructure, analytical capabilities, and system integration (Nunes et al., 2023).

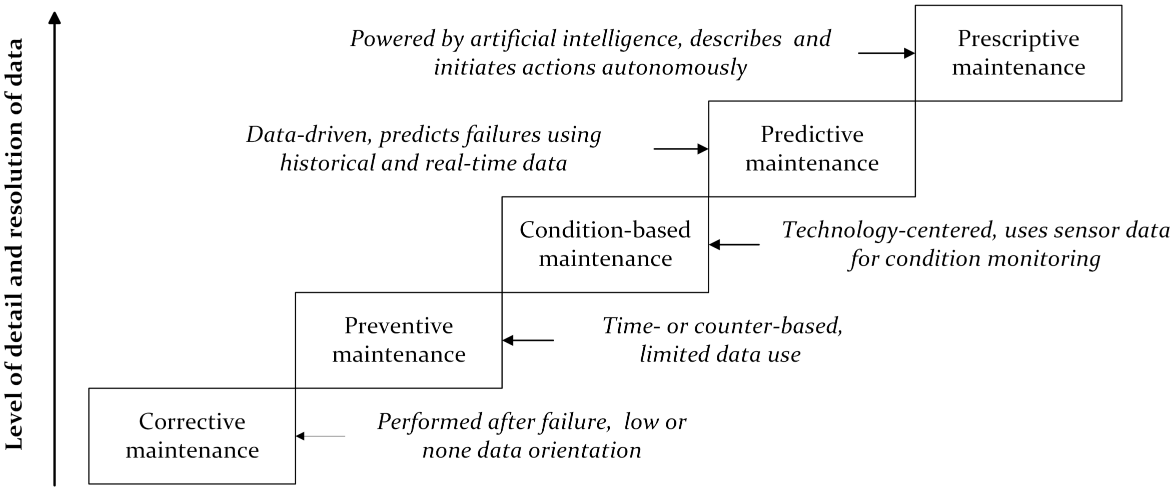


Figure 1. Maintenance evolution in relation to data resolution.

Advances in monitoring and prediction technologies have enabled maintenance decisions to be better informed by both operating conditions and accumulated historical data describing equipment degradation over time (Jardine et al., 2006, Lee et al., 2014). PdM is defined as the use of sensor and historical data, combined with data analytics, to forecast failures and estimate remaining useful life, rather than as a direct evolution from CBM (Zonta et al., 2020). In this context, digital prognostics in maintenance can be understood as cyber-physical systems that link smart sensing and sensor data (physical) to data analytics and remaining useful life estimations (cyber) (Gao et al., 2015), as illustrated in Figure 2. These enable more digitalized maintenance in smart factories and reduce reliance on fixed schedules or purely experience-based judgments.

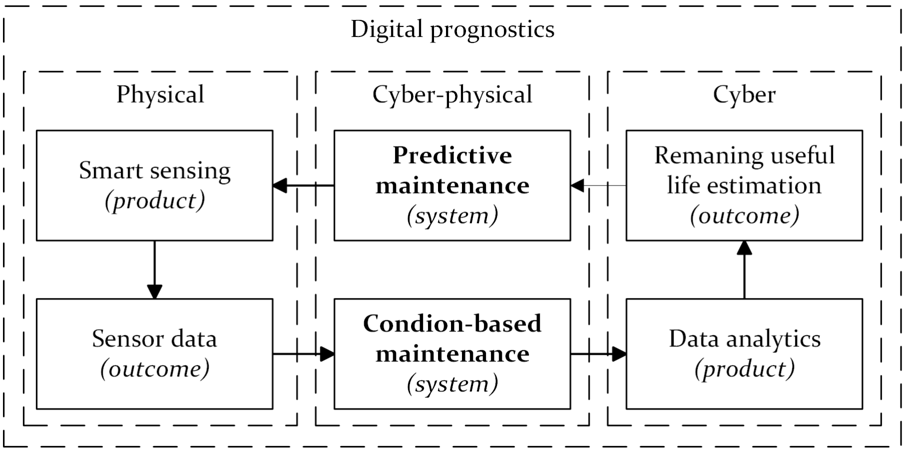


Figure 2. CBM and PdM (Gao et al., 2015).

In parallel with this technological progression, an organizational perspective emphasizes that maintenance digitalization cannot be reduced to technology adoption alone. Instead, maintenance development in digitalized manufacturing is understood as a socio-technical transformation in which organizational structures, competences, and leadership co-evolve with digital technologies (Bokrantz et al., 2020b). Research increasingly highlights that many digital maintenance initiatives fail not due to technological limitations, but rather due to insufficient organizational readiness, unclear strategic alignment, and limited integration between maintenance, production, and engineering functions (Roda and Macchi, 2021, Hein-Pensel et al., 2023).

These two perspectives – technological and organizational – are closely intertwined and become particularly salient when viewed through the lens of maintenance evolution.

### Revolution

Maintenance practices can be situated within successive industrial paradigms. In Industry 1.0 and 2.0, maintenance was largely manual and reactive, embedded within craft-based production systems. The introduction of automation and computer-based control systems during Industry 3.0 marked a fundamental shift, enabling systematic monitoring, planning, and documentation of maintenance activities. However, despite widespread automation, many maintenance organizations today still operate largely within an Industry 3.0 logic, relying on fragmented data infrastructures and lagging performance indicators (PIs) (Akkermans et al., 2024). This is depicted in Figure 3.

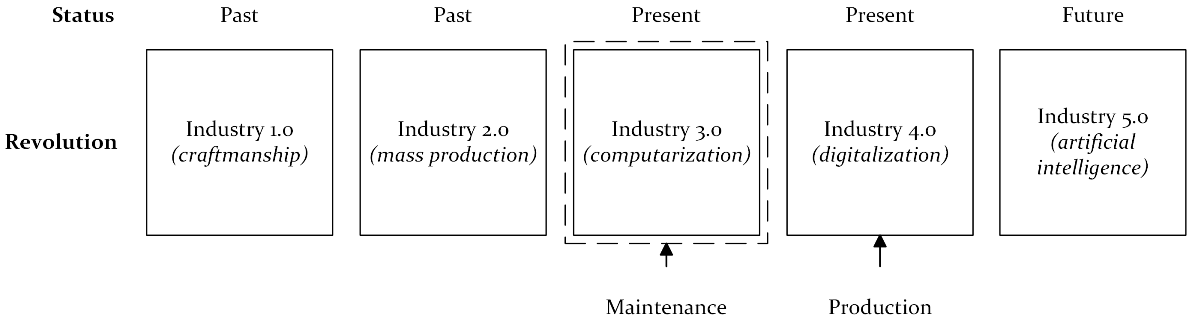


Figure 3. Industrial paradigms and the status of production and maintenance.

Industry 4.0 envisions cyber-physical production and maintenance systems, including pervasive connectivity for DDD (Hermann et al., 2016). While production systems have increasingly adopted these principles due to their higher potential for automation, maintenance systems have often lagged behind, constrained by legacy assets, siloed data, and integration issues. As a result, production and maintenance transformation in manufacturing remains uneven, with significant variation in maturity across industries and firms (Alcácer and Cruz-Machado, 2019, Neumann et al., 2021). Production is more digitalized, which increases the need for maintenance to adapt accordingly, i.e., to become digitalized.

Looking ahead, Industry 5.0 is rapidly becoming a reality, emphasizing human-centricity alongside sustainability and resilience (Murtaza et al., 2024). It calls for maintenance that leverages human capabilities through transparency and collaboration with artificial intelligence. This involves developing functions that support adaptability, fault tolerance, and recovery under uncertainty (Bukowski and Werbinska-Wojciechowska, 2025). For maintenance, this places new demands on cognitive support, physical augmentation, human-in-the-loop design, and ethical alignment (Chen et al., 2025a, Van Oudenhoven et al., 2023). Rather than replacing personnel, future maintenance is expected to augment human capabilities and support DDD in smart factories.

This revolution highlights the need for maintenance to accelerate its digitalization and become "smarter" – SM – which integrates technological and organizational dimensions in digitalized manufacturing.

## 2.2 SMART MAINTENANCE

SM has emerged as a response to the limitations of purely technology-driven approaches to maintenance digitalization. Rather than focusing on individual tools or methods, SM conceptualizes maintenance as an organizational design suited to environments characterized by pervasive digitalization. Although several related concepts exist, such as intelligent maintenance, SM has received particular attention in Europe in recent years (Roda and Macchi, 2021).

### Conceptualization

SM is an organizational design for managing maintenance in digitally pervasive manufacturing environments, comprising four interrelated dimensions that enable effective decision-making in maintenance digitalization (Bokrantz et al., 2020c). It comprises four interrelated dimensions: DDD, human capital resource (HCR), internal integration (INI), and external integration (EXI) (see Figure 4). These dimensions are later operationalized through measurement constructs for use in industrial organizations (Bokrantz et al., 2020a).

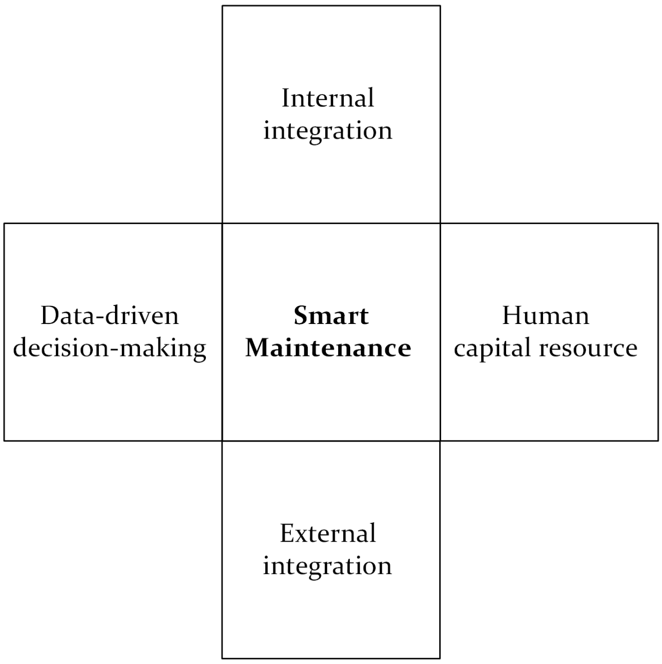


Figure 4. Conceptualization of SM.

DDD refers to the systematic use of high-quality data and analytics to support maintenance planning, execution, and continuous improvement. HCR emphasize the skills, competences, and learning capabilities required for maintenance to operate and develop in digitalized manufacturing. INI captures the alignment and collaboration between maintenance and other organizational functions, particularly production and engineering, while EXI highlights the importance of supplier relationships and ecosystem-level collaboration for maintenance digitalization.

This conceptualization positions SM as a socio-technical system in which technological capabilities and organizational enablers must be jointly developed.

### Facilitation

While the conceptualization of SM provides a normative description of what constitutes a SM organization, it does not specify how such a configuration can be achieved in practice. Addressing this gap, Lundgren et al. (2021) focuses on the facilitation of SM implementation.

Lundgren et al. (2021) propose a six-step strategic development process to guide maintenance organizations in the implementation of SM (see the inner circle in Figure 5). This process is then further refined after testing its implementation in the manufacturing industry (see the outer circle in Figure 5) (Larsson et al., 2026). The process is iterative and emphasizes employee involvement and strategic prioritization across the four SM dimensions. It starts with benchmarking the maintenance organization to identify improvement needs, followed by the setting of aligned goals, prioritization of development needs, and planning and execution of key activities. Continuous follow-up supports learning and sustained organizational development. The process is facilitated by the SM instrument (Bokrantz et al., 2020a) which enables benchmarking, goal-setting, and progress tracking.

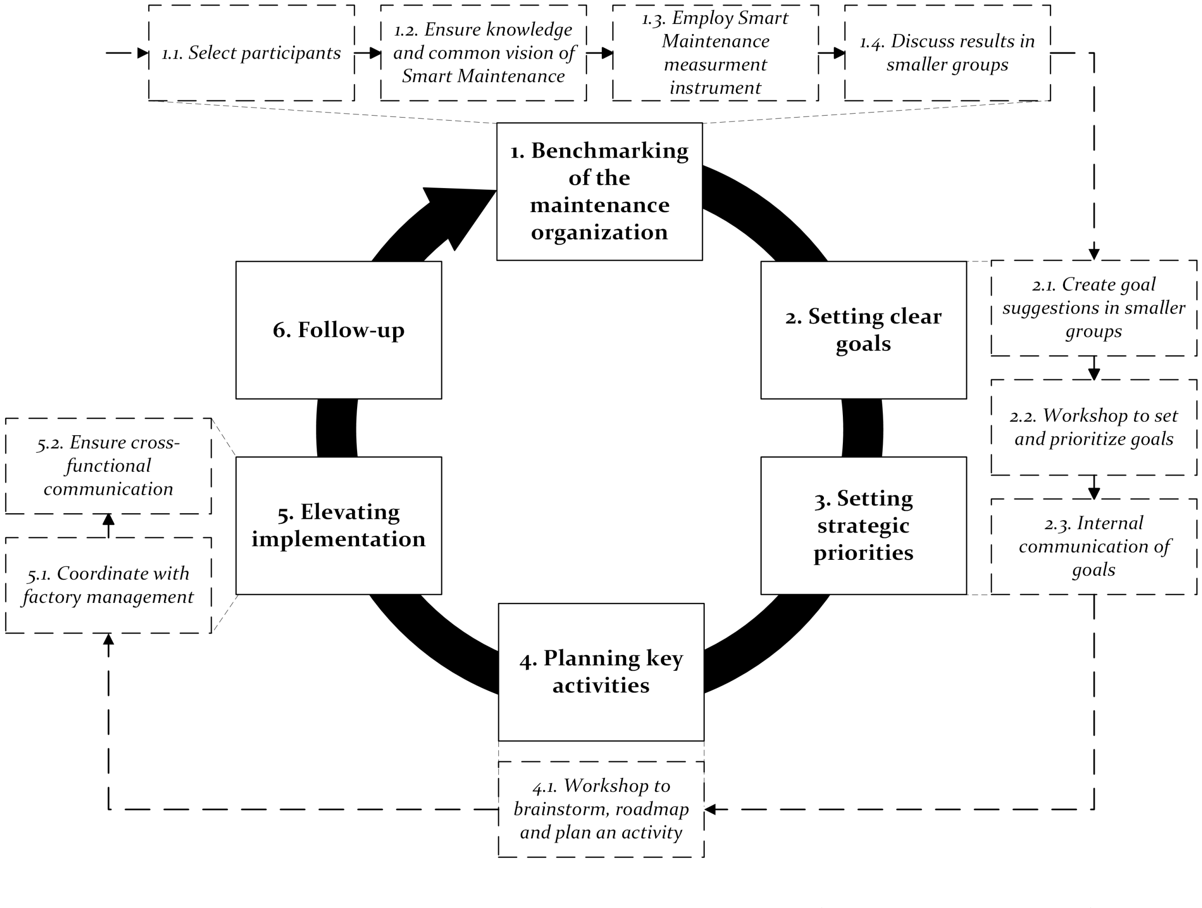


Figure 5. The refined strategy development process (Larsson et al., 2026).

From a facilitation perspective, SM implementation is better understood as an organizational change process rather than a linear technology rollout, requiring leadership commitment, structured learning, and continuous alignment between strategy and operations.

## Implementation

Despite the growing body of SM research, empirical insights into its implementation in digitalized manufacturing remain limited, particularly in emerging contexts such as greenfield battery production. In practice, many industrial organizations struggle to implement SM due to limited resources, low digital maturity, technology-centered initiatives, and insufficient human integration (Hein-Pensel et al., 2023). Addressing these constraints is highly context-specific but generally requires increased attention to and the development of human competencies and collaborative ecosystems, alongside advanced sensing and data infrastructures and digital twin capabilities (Osunsanmi et al., 2025).

Several digitalization studies in manufacturing highlight organizational challenges in implementing SM (Lundgren et al., 2022, Larsson et al., 2026, Kumar and Galar, 2018, Badri et al., 2018), as well as challenges in leveraging digital technologies (James et al., 2023). However, these studies have primarily been conducted in brownfield settings (e.g., digitalization in an existing factory), leaving greenfield manufacturing underexplored. As brownfield digitalization involves upgrading existing systems, it differs significantly from implementing new systems in greenfield contexts, see Table 1 (Deloitte, 2020). Greenfield manufacturing enables more radical digitalization, as technologies can be designed in alignment with industrialization from the outset. Regardless of context, SM implementation is learning-intensive and evolves over time, suggesting that both manufacturing contexts require careful preparation, albeit in different ways.

Table 1. Brownfield versus greenfield digitalization (Deloitte, 2020).

| Aspect | Brownfield | Greenfield |
|---|---|---|
| **Approach** | Conversion of existing systems | Implementation of new systems |
| **Starting point** | Builds on existing processes and data infrastructures | Creates new processes and data infrastructures |
| **Deployment time** | Shorter deployment time | Longer deployment time |
| **Business impact** | Less disruption to existing processes | More disruption as new processes are implemented |
| **Cost structure** | Lower implementation cost | Higher implementation cost |
| **Resource requirements** | Fewer resources required | A greater number of resources required |
| **Standardisation** | Standards already exist to some degree | Standards have to be defined |
| **Problem-solving** | Internal constraints limit problem-solving | Problem-solving has no constraints |
| **Innovation potential** | Fewer opportunities for new functionalities | More opportunities to new functionalities |
| **Change management** | Less change management is required | More change management is required |

## 2.3 MAINTENANCE IN BATTERY PRODUCTION

Battery production is a demanding context for industrial maintenance, characterized by high capital intensity, rapid technological change, and strict quality and safety requirements. In this context, maintenance goes beyond traditional support and becomes a more integrated function focused on ensuring technical availability in battery production.

### Battery Industry

Battery production has become a cornerstone of the global electrification of transport, yet the industry is currently marked by several structural pressures and trade-offs. Demand has increased rapidly over the past decade, driven by the large-scale deployment of electric vehicles and energy storage systems (Amici et al., 2022). While lithium-ion batteries remain the dominant and most industrially mature technology, alternative chemistries such as solid-state and sodium-ion batteries continue to develop without being fully established at scale (Liu et al., 2021, Bai et al., 2025). This ongoing technological change and uncertainty expose new battery manufacturers to investment risks when committing to capital-intensive and highly specific production assets that may require replacement or modification in the future.

Global capacity remains highly concentrated, with Asia – particularly China – accounting for approximately 65–75% of total battery production (International Energy Agency, 2025). Furthermore, the majority of mining, material processing, and cell component manufacturing takes place in China (International Energy Agency, 2023). This concentration also reflects accumulated experience in operational excellence in battery production and maintenance, resulting in pronounced regional asymmetries in industrial know-how (Ragonnaud, 2025). European efforts have therefore been initiated to reduce these dependencies and strengthen recently established gigafactories (European Battery Alliance, 2025). However, many of these programs are developed under significant time pressure, and limited local experience remains a bottleneck for European battery production (Johansson et al., 2024).

Likewise, previous studies have shown that developments in the battery industry are outpacing the maturation of production assets, resulting in persistent misalignments between advances in battery technology and manufacturing capabilities (Kwade et al., 2018). These trade-offs are further amplified by geopolitical dynamics, which restrict technology transfer and complicate global value chains, for example through differing standards (Deloitte, 2025). At the same time, new battery manufacturers face increasing external pressure to improve energy efficiency, sustainability performance, and cost competitiveness (Ghasemi Yeklangi et al., 2024), further complicating factory establishment and ramp-up in new regions.

As a consequence, newly established gigafactories in Europe face substantial financial challenges during the ramp-up of their operations, often described as the “valley of death” (see Figure 6), where revenues fail to offset high capital investments (Attia et al., 2025). Under these conditions, the ability to manage technical availability in battery production becomes of utmost importance, placing maintenance at the forefront. Asset Management (AM) has therefore emerged as a potential approach to address several of these industrial pressures and trade-offs (Dutta et al., 2023). However, to ensure sustained industrial competitiveness in the transition toward Industry 5.0, SM is likewise becoming a key component in the establishment and ramp-up the European battery industry.

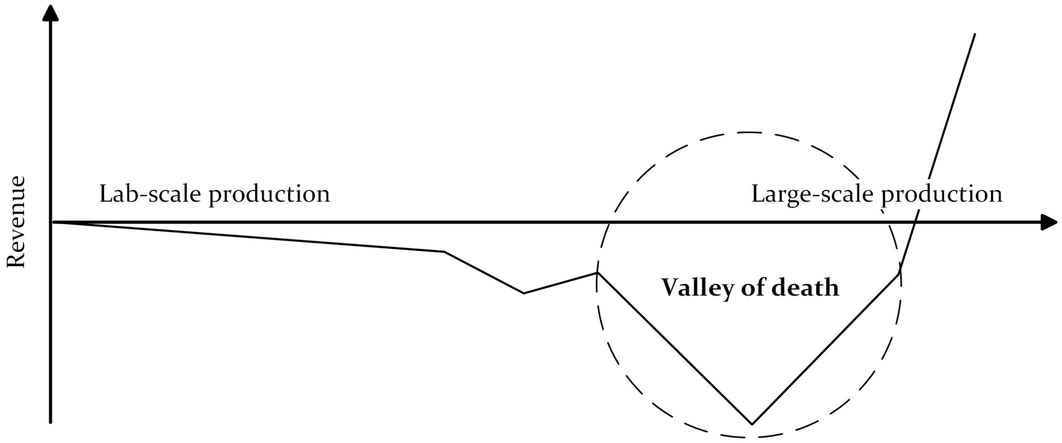


Figure 6. “Valley of death”.

## Production Processes

Battery production is characterized by a high degree of technical complexity and interdependencies between processes, materials, and equipment. The manufacturing process typically consists of four major stages: material conditioning, electrode manufacturing, cell assembly, and cell finishing through formation and aging (see Figure 7) (Liu et al., 2021, Örüm Aydin et al., 2023). Each production stage relies on distinct processes, materials, and equipment, ranging from chemical processing and continuous roll-to-roll systems to discrete assembly systems and time-intensive conditioning equipment (Plumeyer et al., 2023). The stages consist of multiple process steps, which can be described in more detail in Liu et al. (2021). It should be noted that there are several ways to categorize battery production, and this represents one possible way of structuring it.

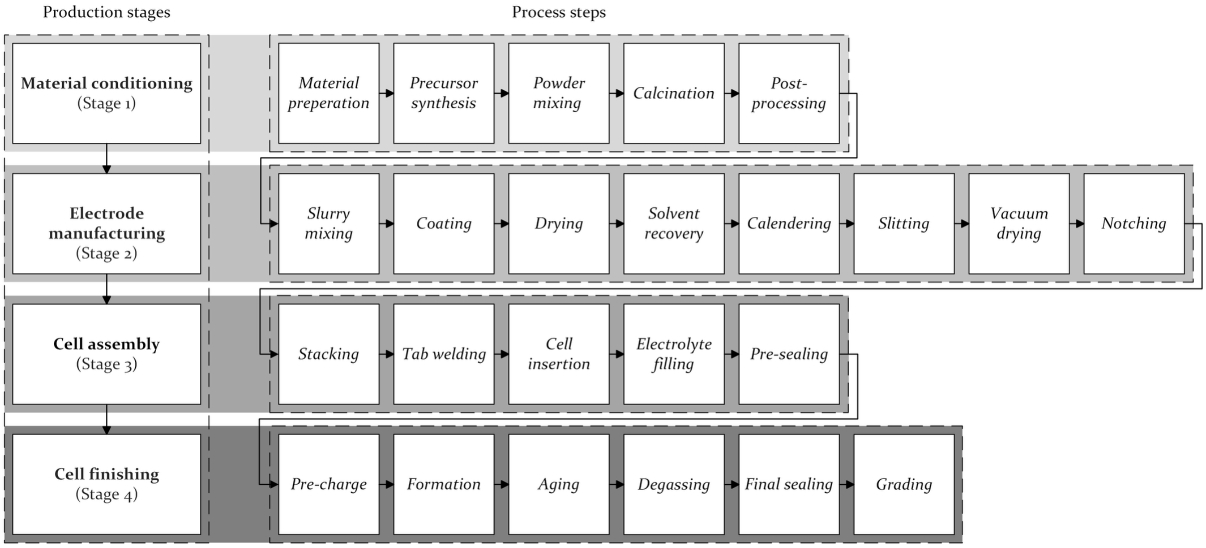


Figure 7. Battery production stages and process steps.

The process begins with material conditioning, where cathode active materials are synthesized through precursor processing and calcination, a highly specialized stage often sourced from expert upstream suppliers (Li et al., 2020). The conditioned materials are then used in electrode manufacturing, where anode and cathode materials are mixed with binders and additives and coated onto metallic foils – typically copper and aluminum – followed by drying and mechanical finishing (Liu et al., 2021, Plumeyer et al., 2023). The electrodes are then assembled into cells, followed by sealing, electrolyte filling, and controlled formation and aging processes to ensure electrochemical performance and quality (Örüm Aydin et al., 2023). Due to the heterogeneous nature of these stages, battery production relies on diverse equipment with varying operational and maintenance requirements, often operating at high speeds (Kwade et al., 2018).

From a digitalization perspective, battery production involves more than 600 input variables related to material properties, process parameters, and environmental conditions, forming over 2,000 cause–effect relationships that directly influence product quality (Kornas et al., 2019, Dahmen et al., 2024). Many of these variables must be controlled within narrow tolerance windows at high production speeds, leaving limited margins for deviation (Goodenough and Kim, 2010). As a result, even minor disturbances in equipment condition or process stability can propagate downstream and lead to significant quality losses or safety risks (Duffner et al., 2021). This makes battery production highly data-intensive, requiring integrated systems to manage all processes.

Consequently, battery production entails digital requirements that partly differ from those of traditional manufacturing industries. Production and maintenance must combine high throughput across multiple factory areas with strict cleanliness and humidity control, as contamination can severely affect performance and safety (Heimes et al., 2019, Chen et al., 2025b). Most processes are conducted in dry-room or clean-room environments, increasing costs while limiting process visibility and communication across production units. In addition, battery cells pose explosion risks in cases of improper handling or equipment malfunction, requiring rigorous safety standards in maintenance (Zhao et al., 2024).

The economic implications of these requirements are substantial, as battery production is highly capital-intensive, with material costs accounting for approximately 75% of total costs (Duffner et al., 2021). Scrap rates are typically very high during early production and ramp-up, reaching up to 90% (Örüm Aydin et al., 2023), creating strong incentives for rapid but efficient ramp-up. Final production performance is heavily influenced by its outcomes, including process maturity and yield losses (Attia et al., 2025). As production scales and shifts toward quasi-continuous operation, cost implications increase accordingly. Under these conditions, effective factory establishment and ramp-up are critical, with equipment design playing a decisive role in ensuring sustainability and profitability (Wolf et al., 2024).

## Maintenance Procedures

Maintenance in battery production is closely linked to decisions made during early lifecycle phases of production assets, particularly during equipment design and procurement (Luo et al., 2021, Bokrantz et al., 2024). In this context, maintenance extends beyond corrective actions to ensure that equipment meets maintainability requirements and supports supply chain considerations, including spare parts strategies and equipment validation (Swedish Institute for Standards, 2022). As a result, maintenance is closely intertwined with project management and procurement during factory establishment and ramp-up, influencing production performance under industrial conditions.

Equipment validation constitutes a central component of maintenance procedures in battery production. It typically includes factory acceptance testing, followed by site acceptance and integration tests to verify functionality under real operating conditions (Krüger et al., 2024). By enabling early identification of defects, factory acceptance testing reduces downstream costs, although it involves trade-offs in terms of cost, time, and potential project delays (International Electrotechnical Commission, 2024). It is therefore most relevant for complex or critical equipment and should be adapted to the application and associated risks, while compliance with regulatory frameworks ensures conformity with health, safety, and environmental requirements (Ballor, 2022).

Maintenance procedures in battery production encompass not only technical aspects of equipment but also structured AM, spare parts planning, and integration with production and quality operation (Kwade et al., 2018). Common maintenance strategies include preventive, CBM, and selective run-to-failure approaches, each requiring appropriate planning, documentation, and supporting information systems. Effective coordination between maintenance, production, and engineering functions is necessary to manage process dependencies and maintain stable production performance.

Previous studies have shown that downtime in battery production entails severe economic and safety consequences, placing exceptional demands on maintenance (Duffner et al., 2021). In contrast to conventional manufacturing, maintenance in battery production operates in hazardous, contamination-sensitive environments and involves charged cells with risks of fire, explosion, and toxic exposure (Ju et al., 2015, Abraham, 2023). Maintenance procedures must therefore be carefully controlled and coordinated to avoid disturbances that may propagate downstream across tightly coupled production stages.

These conditions place high competence requirements on maintenance personnel, extending beyond traditional mechanical skills. In battery production, maintenance personnel must possess electrochemical knowledge, advanced safety training, and the ability to operate in high-speed, quasi-continuous processes (Attia et al., 2025). At the same time, the sector faces challenges in recruiting qualified personnel, particularly in Europe, where shortages in maintenance education and specialized training persist

(Kans et al., 2020). As a result, maintenance in battery production increasingly extends beyond equipment commissioning to include systematic training in how production systems are operated, maintained, and safely managed (Kaasinen et al., 2020).

From an AM perspective, maintenance procedures rely on well-structured asset registers and documentation reflecting the complexity of battery production systems. These systems consist of integrated assets with varying operating conditions and degradation mechanisms across production stages (Heimes et al., 2019, Duffner et al., 2021). Clear asset hierarchies linking equipment, subsystems, and components enable alignment between maintenance decisions and production performance (Amadi-Echendu, 2004, El-Akruti and Dwight, 2013), while supporting risk management and functional assurance (International Organization for Standardization, 2024).

These requirements become particularly critical during early ramp-up, when production systems operate under high uncertainty and asset behavior is not yet stabilized (Attia et al., 2025). In such contexts, knowledge development is closely linked to operational problem-solving and gradual learning, placing high demands on systematic documentation to avoid inefficiencies and repeated corrective actions (Roda and Macchi, 2018, Polenghi et al., 2019). Maintenance procedures must therefore support continuous learning and adaptation in battery production.

In addition, battery production generates large volumes of data due to extensive monitoring and strict quality requirements (Kornas et al., 2019, Dahmen et al., 2024). Effective maintenance procedures depend on well-designed data infrastructures that enable monitoring of machine health, tool wear, and process deviations affecting product quality. Early decisions regarding data structuring and parameter selection are therefore essential to support PdM and organizational learning in battery production (Serradilla et al., 2022), thereby laying the foundation for the development of SM.

# 3

# RESEARCH APPROACH

*The research approach describes the research setting of this thesis, outlines its foundation and design, and explains the methods used in the appended papers.*

## 3.1 RESEARCH SETTING

The research setting is situated at the intersection of SM and the rapid establishment of large-scale battery production in Europe. At the time of study, the conceptualization of SM – maintenance in digitalized production – had recently been established (Bokrantz et al., 2020c), and research had progressed toward understanding how such approaches could be facilitated in industrial maintenance operations (Lundgren et al., 2021). This created a need to explore how the established concept could be implemented in practice.

Battery production constituted a relevant research context for several reasons. First, it was prioritized by the European Union for the climate transition and exemplified how new sustainability-driven industries needed to be established (European Commission, 2022). Second, European and Swedish automotive manufacturers prioritized battery production to navigate this transformation (Schade et al., 2022). Third, battery production was capital-intensive and complex, with numerous process parameters and modern equipment, making SM particularly relevant for enabling efficient greenfield industrialization and ramp-up (Bokrantz et al., 2024).

More specifically, the empirical setting was a lithium-ion battery production facility in Sweden during its initial development (2022–2025), covering equipment installation, industrial commissioning, production ramp-up, and early maintenance operations. This phase provided access to emerging practices and challenges related to factory and equipment design, process issues, maintainability, and digital maturity across stages. It also enabled an examination of whether known brownfield challenges would persist or take new forms in greenfield manufacturing.

Battery production constituted a complex and hybrid research setting, comprising multiple production stages and process steps (details in *Section 2.3*) that combine different manufacturing logics, including both discrete and process-based production (see Figure 8). As maintenance practices typically differ across these manufacturing types, this required the researcher to account for varying maintenance conditions and requirements when studying maintenance in battery production. This hybrid and evolving context challenged established assumptions about maintenance and its integration with digital technologies.

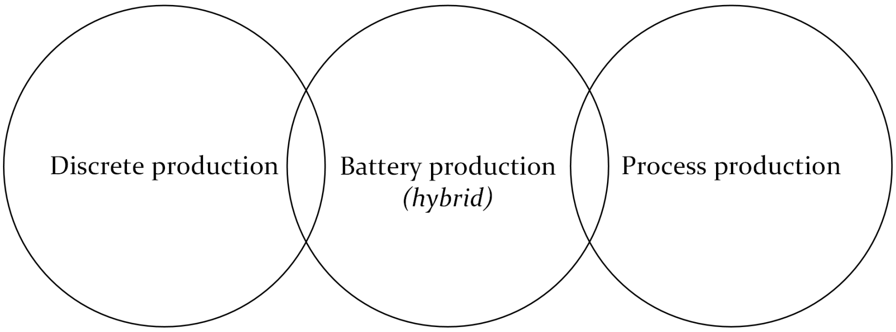


Figure 8. Battery production as the research setting.

The research was embedded within the gigafactory's central maintenance organization, in close collaboration with AM, enterprise-wide systems, and process engineering functions. At the same time, proximity to daily operations and ramp-up activities enabled continuous observation of how maintenance practices developed in situ. The research setting evolved over time, spanning master's thesis work, industrial employment, and doctoral studies conducted across different parts of the gigafactory.

While this research setting is unique and not statistically generalizable, it provides in-depth insights into the implementation of SM in a greenfield battery production context. As such, it contributes empirical knowledge relevant to both academic research and the ongoing greenfield industrialization of battery production in Europe.

## 3.2 RESEARCH FOUNDATION

This thesis builds on and extends a growing body of research on SM, which has emerged in response to the increasing digitalization of industrial production (Roda and Macchi, 2021). The work is positioned within an established research stream where successive studies address SM from complementary perspectives (see Figure 9). This positioning clarifies both the foundation of the thesis and its contribution.

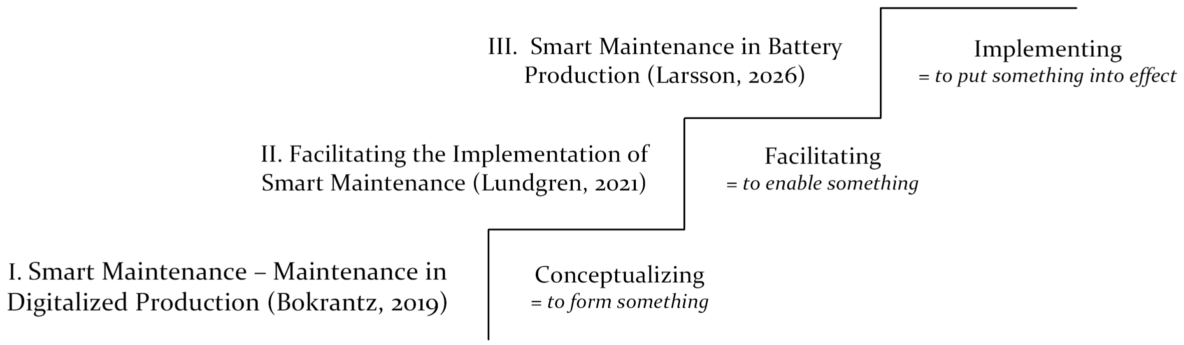


Figure 9. SM trajectory as the research foundation.

Early research focused on conceptualization and operationalization (I). The work *SM – Maintenance in Digitalized Production* (Bokrantz, 2019) established SM as a coherent concept by defining its core dimensions and clarifying the role of maintenance in digitalized production environments. This also included a measurement instrument for SM. This phase was primarily concerned with forming SM as an analytical and conceptual construct, providing a shared language and structure for subsequent research.

Building on this foundation, later research shifted toward facilitation (II). In *Facilitating the Implementation of SM* (Lundgren, 2021) , the focus moved from defining the concept to understanding how it can be enabled in industrial organizations. This work further analyzed the concept by identifying enablers and barriers, as well as organizational mechanisms that facilitate the adoption of SM practices. Methodologically, this phase focused on how something can be enabled.

The present thesis represents the next research step by focusing on the industrial implementation of SM (III). *SM in battery production* examines maintenance digitalization in the context of greenfield industrialization, with a focus on practical scale-up. It addresses how SM is implemented in practice, how it interacts with and impacts daily production, and how it contributes to the future development of production and maintenance in the European battery industry.

Methodologically, this progression can thus be seen as a three-step trajectory of conceptualization, facilitation, and implementation av SM. Each step builds on the previous one, advancing research excellence based on industrial needs and practice. In this thesis, this approach is applied through a pre-study that identified challenges and established development needs for SM in battery production, followed by a set of outlined research avenues and prioritized research and development projects. This phase illustrates how the four dimensions of SM are expressed in implementation and forms the empirical basis of the appended papers.

## 3.3 RESEARCH DESIGN

This thesis constitutes applied research grounded in the scientific research cycle and informed by close interaction with industrial practice (Marotti de Mello and Wood Jr, 2019). It addresses practical implementation of SM in battery production while contributing to academic advancements. The design follows a pragmatic and iterative logic, where ideas are explored, tested, and refined through continuous interaction between theory and practice. This reflects a form of practice-based innovation (Ellström, 2010), used to conceptualize and analyze innovation processes in organizations.

Academic work follows what can be described as the traditional circle of research (Tengblad et al., 2005). This process begins with observation and problem identification in a real-world situation, supported by literature review and reflection. Initial assumptions and problem formulations are then articulated and translated into concepts and tentative designs. These are explored through fieldwork and empirical engagement, followed by analysis, reflection, and interpretation of results. The outcomes inform theorizing and synthesis, generating new RQs and insights that feed back into further exploration. In this sense, the research does not progress linearly but evolves through iterative cycles of abductive reasoning (Tavory and Timmermans, 2014).

The underlying research design of this thesis is grounded in research for operations management (Karlsson, 2016). It draws on narrative reflection, making the implicit explicit, the hidden visible, the unformed structured, and the confusing clarified (Atkinson, 1995) – well suited this research setting. It can be summarized in three iterative phases: exploration and discovery, community analysis and feedback, and benefits and outcomes (see Figure 10, inspired by Arlidge et al. (2017)). The exploration and discovery phase focuses on identifying challenges through industrial engagement and exploratory studies. This is followed by community analysis and feedback, where these challenges are discussed, validated, and synthesized into development needs together with practitioners and academic peers. Finally, the benefits and outcomes phase emphasizes the articulation of research avenues that address these development needs and contribute to theory building. These phases are not sequential but mutually reinforcing, reflecting the iterative nature of scientific inquiry.

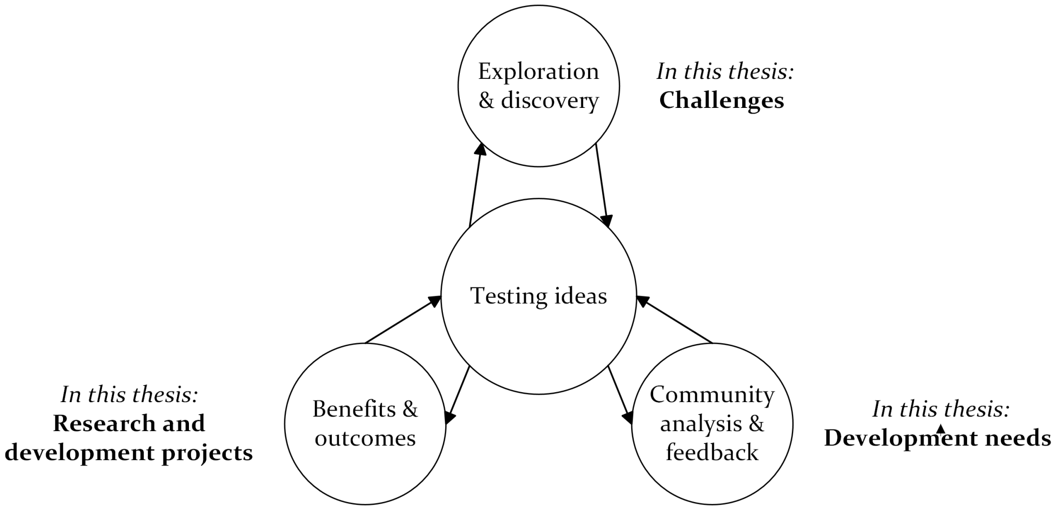


Figure 10. Research design inspired by Arlidge et al. (2017).

The execution of the research was enabled by the position as an industrial doctoral student. This dual role – engineer and researcher – facilitated the integration of practical and theoretical work as practice-based innovation within iterative research cycles. From a practical perspective, the work was driven by operational needs and engineering practice, while from a theoretical perspective, it was guided by research gaps and analytical frameworks. Together, this enabled the identification of challenges, the establishment of development needs, and the outlining of research avenues for maintenance in battery production, resulting in Paper I (see Table 2). This primarily addressed RQ1 (and therefore RQ2 is greyed out in Table 2).

Table 2. RQs for the appended papers.

| **Paper** | **I** | **II** | **III** | **IV** | **V** |
|---|---|---|---|---|---|
| **Purpose** | Pre-study | Research and development projects | | | |
| | Smart Maintenance | Internal integration | Human capital resource | External integration | Data-driven decision-making |
| RQ1 | X | x | x | x | x |
| RQ2 | ▨ | X | X | X | X |

Subsequently, the research progressed through four selected research and development projects, which were conducted separately and resulted in Papers II–V. These projects addressed challenges across SM dimensions and exemplified their contribution to battery production. This primarily addressed RQ2, while also contributing to a further refinement of the answer to RQ1 (indicated in lower case letters in Table 2).

The prioritization of these projects was carried out by the battery manufacturer and was therefore not part of the research design. The prioritization process should thus be considered confidential but can, for academic purposes, be described as a process of balancing technology and pace, as well as novelty and complexity in project management (Shenhar and Dvir, 2007b).

The projects were largely structured in accordance with project management principles (Shenhar and Dvir, 2007a), reflecting how such projects are typically organized in the manufacturing industry. It should also be noted that the research avenues from which each research and development project originates represent broader lines of inquiry that extend beyond a single study. The appended papers should therefore not be interpreted as definitive development needs, but rather as concrete manifestations of how these challenges can be addressed through industrial research and development projects.

## 3.4 RESEARCH METHODS

The five projects or papers included in this thesis employ diverse research methodologies and strategies, each tailored to the specific research objectives and contributions of the respective study. Table 3 provides an overview of the applied research methodologies per the appended papers.

Table 3. Research methodologies for the appended papers.

| Paper | Type of study | Data collection | Data analysis |
|---|---|---|---|
| I | Ethnography | - Documents<br>- Interviews<br>- Meetings<br>- Observations | Thematic analysis |
| II | Case study | - Brainstorming sessions<br>- Coding events<br>- Development activities<br>- User acceptance test<br>- Workshops | Thematic analysis |
| III | Case study | - Interviews<br>- Observations | - Narrative analysis<br>- Thematic analysis |
| IV | Multi-method study | - Documents<br>- Interviews | - Descriptive analysis<br>- Thematic analysis |
| V | Design science study | - Design of experiments<br>- Interviews<br>- Observations<br>- Workshops | - Root-cause analysis<br>- Statistical analysis |

### Paper I

Paper I adopted an ethnographic design to explore maintenance operations in large-scale battery production, identifying challenges, establishing development needs, and outlining research avenues. Ethnography was chosen to study complex socio-technical systems in their natural setting. The empirical setting was one of the battery manufacturer's facilities, where maintenance practices were developed during factory establishment and ramp-up.

The study was carried out through immersion in daily operations, including observations, participation in meetings, informal and semi-structured interviews, and reviews of internal documents. This approach enabled access to both formal structures and informal practices, capturing interactions between processes, technologies, and people over time. The aim was not statistical generalization but analytical insight into a strategically important industrial context.

The data were analyzed using thematic analysis to identify recurring challenges and development needs (see *Section 3.2* in Appended Paper I). These were structured into research avenues, representing actionable directions for future research and industrial development. The socio-technical lens guided the analysis, ensuring that organizational, technological, and social factors were examined as an integrated system. Paper I provides an organized mapping of the maintenance landscape in greenfield battery production, guiding its future development.

### Paper II

Paper II employed an in-depth case study design to examine how maintenance PIs are deployed during the ramp-up phase of battery production. The case study approach enabled the investigation of complex, context-dependent phenomena in an industrial setting where processes, systems, and practices interact dynamically. The focus was on the deployment process – how indicators are established, integrated, and sustained – rather than on their selection or calculation.

The study was part of a collaborative industrial improvement project at one of the battery manufacturer's facilities during its ramp-up phase. Data were collected through active participation in development activities and workshops, including brainstorming sessions, coding events, and user acceptance tests. This approach provided insight into evolving challenges as production maturity increased.

The data were analyzed using thematic analysis (see *Section 3.3* in Appended Paper II). Identified challenges were synthesized into deployment requirements – conditions necessary for effective use of maintenance PIs in greenfield battery production. The analysis also considered the allocation of responsibilities, for example between maintenance and production, reflecting inherent interdependencies. Paper II provides a structure of requirements and recommendations, supporting INI during ramp-up and further research on performance management in SM.

### Paper III

Paper III adopted a qualitative single case study design to investigate worker attributes and training needs for maintenance technicians in battery production. The case study approach enabled in-depth examination of an underexplored phenomenon embedded in organizational practice, capturing how roles, competencies, and training requirements evolve in a rapidly scaling and complex production environment.

The study was conducted across several of the battery manufacturer's facilities through semi-structured and unstructured interviews with technicians, supervisors, engineers, managers, planners, and training specialists, complemented by observations. This approach captured both lived experiences and situated work practices across roles and production stages. Data collection followed an iterative process, where early insights informed subsequent interviews and supported the refinement of key themes.

The data were analyzed using a combination of narrative and thematic analysis (see *Section 3.3* in Appended Paper III). The analysis captured technicians' experiences and identified desired worker attributes, interpreted using the knowledge, skills, abilities, and other characteristics (KSAOs) framework. To enhance trustworthiness, the study applied triangulation, member checking, and peer debriefing. Paper III provides a maintenance framework for workforce development in battery production, along with practical guidance for building HCR in SM.

### Paper IV

Paper IV employed a multi-method research design to study AM integration in greenfield manufacturing, using battery production as its empirical setting. It addressed a research gap, as AM remained underexplored in manufacturing and largely absent in greenfield contexts. By combining literature insights and empirical findings, the study identified, validated, and extended enablers for AM integration.

The study consisted of a meta-review and an interview study at one of the battery manufacturer's facilities. The meta-review followed a structured database search and screening process of peer-reviewed review articles, while the interview study included in-depth interviews with engineers and managers involved in AM development in battery production.

The data were analyzed using descriptive and thematic analysis (see *Section 3.2 and 3.4* in Appended Paper IV). The selected publications were coded to identify enablers, which were then validated and extended by the practitioners. The analysis followed established AM principles and perspectives to enhance conceptual clarity. Paper IV identifies integration enablers, extends AM scholarship to greenfield battery production, and positions it as an EXI process enabling SM.

### Paper V

Paper V adopts an engaged design science research approach, structured as a single embedded case study, to explore how PdM systems can be designed and operationalized as digital servitization in greenfield battery production. The approach addresses a problem resembling a wicked problem, where PdM is underdeveloped and product–process–degradation relationships are initially unknown. Close collaboration with the battery manufacturer, as well as the supplier and a technology provider, enabled the design of a product–service–software solution through ongoing operational use.

The study employed design of experiments, observations, workshops, and interviews at one of the battery manufacturer's facilities and was framed using CIMO (Context, Intervention, Mechanism, Outcome) logic. The study was structured around three embedded units of analysis – actualized, available, and feasible possibilities – demonstrating different levels of outcomes for PdM systems under conditions of high process uncertainty.

The data were analyzed using root-cause and statistical analysis (see *Section 3.4* in Appended Paper V). The first unit examined downtime patterns, the second explored data reconfiguration, and the third developed PdM solutions through sensor integration and model development. The analysis followed an iterative experimentation, where insights informed subsequent interventions. Paper V shows how PdM unfolds as a design trajectory shaped by buyer-driven involvement and provides a design logic for DDD in SM for battery production.

# 4

# RESULTS OF APPENDED PAPERS

*The results of appended papers recapitulate the five appended papers, each representing a prioritized research and development project. For each paper, a short description of the study and its main results is provided, followed by a discussion and conclusion, and its contribution to the RQs.*

## 4.1 CONTRIBUTIONS TO RESEARCH QUESTIONS

The results of the appended papers and their respective contributions to the RQs is presented in Table 4. The table outlines the purpose of each paper and illustrates how they contribute to addressing the RQs, namely: (RQ1) What the main challenges associated with maintenance in battery production are, and (RQ2) how SM can contribute to the development of battery production. The papers are summarized in *Sections 4.2–4.6*, with the full versions included at the end of the thesis.

Table 4. Summary of the main contributions from the appended papers.

| Paper | Purpose | Main contribution to RQ1 | Main contribution to RQ2 |
|---|---|---|---|
| I | Explore maintenance operations in large-scale battery production and identify critical challenges and important development needs associated with implementing SM in gigafactories. | Categorized critical challenges associated with SM in battery production by outlining 31 research avenues across socio-technical components. | ▨ |
| II | Investigate how maintenance PIs can be deployed during the ramp-up of battery production to improve performance management in SM operations. | *Performance challenges:* Deployment of maintenance PIs requires establishing foundations and maintaining the groundwork, including standardization, training, internal integration, management commitment, and data infrastructure. | Shows how *deployment requirements* of maintenance PIs guides *INI* and results digital artifacts for SM in battery production. |
| III | Examine worker attributes and training needs required for maintenance technicians in battery production to support workforce development in SM organizations. | *Workforce challenges:* Maintenance technicians in battery production require specific combinations of 21 worker attributes, which translate into corresponding training needs. | Identifies *worker attributes* for maintenance technicians and develops training frameworks to support *HCR* for SM in battery production. |
| IV | Evaluate what enables the integration of AM in greenfield battery production and how it should be integrated to support SM. | *Integration challenges:* The synthesis identifies 23 enablers in the AM literature, empirically validates 11, and extends eight specifically to greenfield manufacturing. | Establishes *integration enablers* for AM in greenfield battery production that enable the development of *EXI* in SM. |
| V | Explore how PdM systems can be designed and operationalized in greenfield battery production under conditions of high process uncertainty. | *Design challenges:* PdM systems depend on product–process–degradation relationships and should be reconceptualized as a product–service–software solution with active buyer involvement. | Demonstrates how *design possibilities* for *DDD* in SM can be developed in greenfield battery production using possibility theory and design science. |

## 4.2 PAPER I

**Research Avenues for Maintenance Operations in Battery Production**

### Short Description

This paper explores maintenance operations in large-scale battery production and identifies critical challenges and important development needs associated with the implementation of SM. The purpose of the study is to establish a structured understanding of the challenges shaping maintenance operations in greenfield battery production and to outline relevant research avenues for its future development.

The analysis outlines 31 distinct research avenues, reflecting the main challenges associated with the greenfield industrialization of the European battery industry. These avenues provide both academia and industry with strategic guidance and an actionable blueprint for advancing maintenance operations in battery production, highlighting the role of SM in supporting its development.

### Main Results

The study outlines 31 distinct research avenues, organized across six socio-technical components: *goals*, *people*, *processes*, *infrastructure*, *technology*, and *culture*, see Figure 11. These components represent broader clusters of research avenues through which maintenance operations in battery production can be developed to support greenfield industrialization and maintenance digitalization.

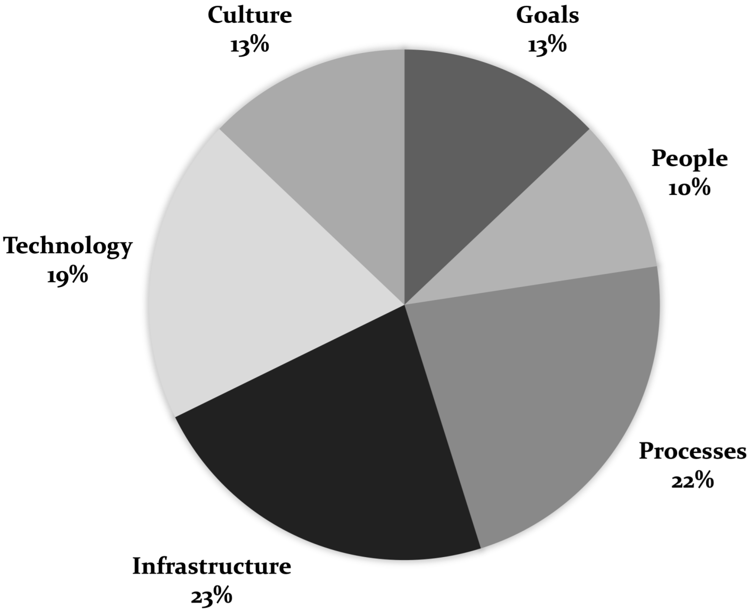


Figure 11. Distribution of research avenues across socio-technical components.

The *goals* component underscores the need for improved strategic alignment between maintenance and corporate decision-making in battery production, including challenges related to maintenance visibility, performance measurement, and benchmarking practices.

The *people* component emphasizes the increasing importance of competencies and workforce development for SM in battery production, highlighting the need for improved skill sets, clearly defined roles, and coordinated training across production sites.

The *processes* component identifies development needs in the operational design of battery maintenance, including best practices for battery production, procurement and sourcing strategies, the role of AM, and feedback loops for continuous learning during ramp-up.

The *infrastructure* component highlights information-related challenges associated with data accessibility, underutilization of maintenance systems, and the need for integrated digital infrastructures to support decision-making and PdM.

The *technology* component addresses equipment-specific maintenance challenges and development needs related to areas such as degradation mechanisms, monitoring technologies, and the use of digital tools for maintenance learning and training.

The *culture* component frames organizational leadership and collaboration as critical enablers for factory establishment and ramp-up, highlighting the importance of data-driven leadership, knowledge sharing, and maintenance excellence.

Together, these findings show that maintenance development in battery production requires coordinated changes across socio-technical components, where organizational, technological, and social elements must evolve together.

## Discussion and Conclusion

The findings demonstrate the complexity of maintenance in battery production and highlight the need for a socio-technical perspective in the development of SM. While maintenance digitalization points to several important development needs, the study shows that many critical challenges in battery production are closely linked to its greenfield industrialization, including organizational design, workforce development, and leadership and collaboration. Maintenance in battery production therefore extends beyond technological implementation and requires coordinated improvements across organizational, technological, and social domains.

For industry, the study provides strategic guidance for SM in battery production. By identifying critical challenges, it supports the prioritization of important development needs during factory establishment and ramp-up, which can increase collaboration in problem-solving between involved actors.

For academia, the study makes substantial scholarly contributions to maintenance digitalization in greenfield industrialization. The outlined research avenues establish an actionable blueprint for future research to further advance the development of maintenance in digitalized manufacturing.

### Contribution towards Research Questions

Paper I was conducted during the exploratory phase of the industrial doctoral research (e.g. pre-study) and serves as the foundation of this licentiate thesis. The study enabled an in-depth understanding of maintenance in battery production and provided the basis for identifying main challenges and development needs for SM.

The findings contribute to RQ1 by categorizing the *main challenges* associated with maintenance in battery production. The study outlines 31 relevant research avenues (see *Section 4* in Appended Paper I), emphasizing that maintenance development centers on managing socio-technical complexity in battery production, in line with SM.

## 4.3 PAPER II

**Addressing Requirements for Maintenance Performance Indicators during the Ramp Up of Battery Production**

### Short Description

This paper investigates how maintenance PIs can be deployed during the ramp-up of battery production. As gigafactories scale, maintenance must ensure high levels of performance, requiring the systematic deployment of maintenance PIs. The purpose of the study is to identify challenges and requirements for deployment and improve performance management for SM in battery production.

The analysis identifies five requirements reflecting deployment challenges during battery production ramp-up. Based on these requirements, the study provides recommendations for different functions to establish the foundations before ramp-up and maintain them thereafter, improving the effectiveness and efficiency of SM in battery production.

### Main Results

The study identifies five requirements for deploying maintenance PIs in battery production: *standardization*, *training*, *internal integration*, *management commitment*, and *data infrastructure*. These requirements represent observed challenges that need to be considered when setting up maintenance PIs during the ramp-up of battery production.

The *standardization* requirement refers to the need for consistent definitions of asset structures, fault codes, and operational data across departments. Differences between production and maintenance created difficulties in data integration and analysis.

The *training* requirement highlights the importance of ensuring that operators and maintenance technicians correctly register data in computerized systems. Inaccurate or incomplete data entry reduced the reliability of maintenance PIs.

The *internal integration* requirement emphasizes coordinated ways of working across functions. Since maintenance PIs rely on data from multiple departments, aligned procedures and shared practices are essential.

The *management commitment* requirement refers to the need for clear responsibility and accountability when deploying maintenance PIs. Strong managerial support is needed to ensure adoption of new practices and maintain data quality.

The *data infrastructure* requirement underscores the importance of integrated and scalable data systems and platforms. Fragmented infrastructure limited the ability to generate reliable maintenance PIs and required additional integration efforts.

Overall, deploying maintenance PIs requires addressing cross-departmental requirements through recommendations to improve performance management during ramp-up and support the implementation of SM.

## Discussion and Conclusion

The study demonstrates that deploying maintenance PIs requires more than selecting appropriate metrics. Instead, maintenance organizations must collaborate with other functions to establish a data foundation that enables effective deployment and use. Based on the identified challenges, two sets of recommendations are proposed: one focusing on *establishing the foundations* and the other on *maintaining them* over time, see Figure 12. These recommendations are directed to different functions within the organization.

The first set of recommendations focuses on *establishing the foundations* required for maintenance PIs to function effectively. Three initial recommendations address standardized nomenclature in a unified database, clear procedures for data input and reporting, and defined roles and responsibilities to ensure accountability across departments.

The second set focuses on developing and *maintaining the groundwork* over time. These emphasize maintaining and scaling the unified database, adapting data procedures as the organization evolves, and continuously monitoring and validating data quality to support the expanded use of maintenance PIs in battery production.

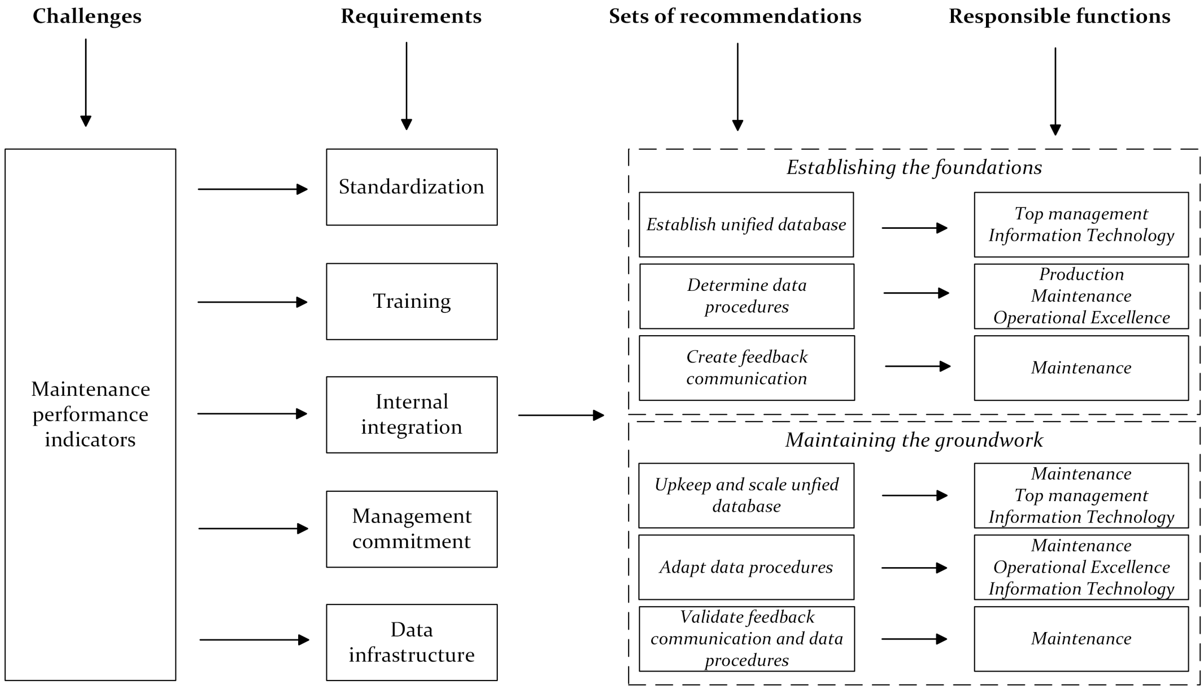


Figure 12. Challenges, requirements and sets of recommendation, with responsible function, to establish and maintain maintenance PIs in battery production.

For industry, the study provides practical guidance for deploying maintenance PIs during ramp-up. By identifying requirements related to standardization, training, internal integration, management commitment, and data infrastructure, it outlines how maintenance organizations can establish and maintain effective performance management in battery production.

For academia, the study provides empirical insights into the deployment of maintenance PIs in digitalized manufacturing. By examining this during the ramp-up of battery production, it identifies challenges that have received limited attention in the literature, despite their importance for greenfield industrialization and maintenance digitalization.

### Contribution towards Research Questions

Paper II builds on the exploratory insights generated in Paper I by examining one of the identified research avenues related to the *goal* component: PIs for maintenance in battery production (see *Section 4.1* in Appended Paper I). The study investigates how maintenance PIs can be deployed during battery production ramp-up to improve performance management in SM operations.

The findings clarify the contribution to RQ1 by showing *performance challenges* associated with deploying maintenance PIs during battery production ramp-up. The findings contribute primarily to RQ2 by showing how *deployment requirements* of maintenance PIs guides *INI* and results digital artifacts for SM in battery production.

## 4.4 PAPER III

**Worker Attributes and Training Needs for Maintenance Technicians: Insights from Lithium-ion Battery Production**

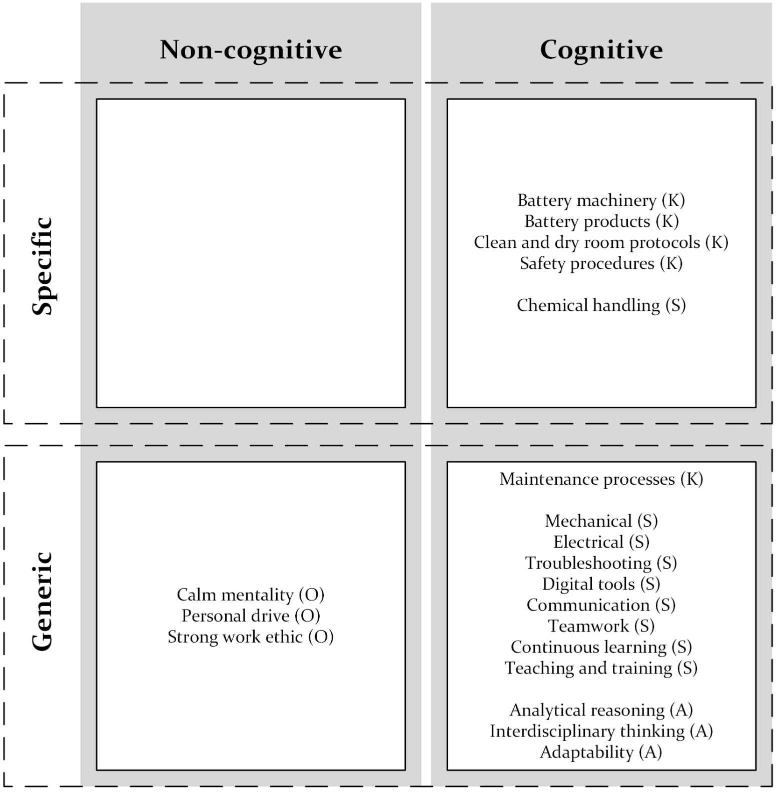
### Short Description

This paper examines the worker attributes and training needs for maintenance technicians in battery production. As battery production is established at scale in newly built gigafactories, maintenance organizations must develop workforces capable of operating and maintaining complex equipment under demanding safety and quality requirements. Understanding required worker attributes and how they can be developed through training is essential for reliable maintenance during ramp-up.

The analysis identifies 21 worker attributes for maintenance technicians and reveals several challenges related to training practices. It captures technicians' experiences and identifies desired attributes based on the KSAO framework. Based on these findings, the study proposes training frameworks for workforce development in battery production, developing HCR for SM.

### Main Results

The study examines a total of 21 worker attributes and classifies them according to the KSAO framework, consisting of five *knowledge* elements, ten *skills*, three *abilities*, and three *other characteristics*, representing the attributes required of maintenance technicians in battery production (see Figure 13).



| | Non-cognitive | Cognitive |
|---|---|---|
| **Specific** | | Battery machinery (K)<br>Battery products (K)<br>Clean and dry room protocols (K)<br>Safety procedures (K)<br>Chemical handling (S) |
| **Generic** | Calm mentality (O)<br>Personal drive (O)<br>Strong work ethic (O) | Maintenance processes (K)<br>Mechanical (S)<br>Electrical (S)<br>Troubleshooting (S)<br>Digital tools (S)<br>Communication (S)<br>Teamwork (S)<br>Continuous learning (S)<br>Teaching and training (S)<br>Analytical reasoning (A)<br>Interdisciplinary thinking (A)<br>Adaptability (A) |

Figure 13. KSAO framework for maintenance technicians in battery production.

The *knowledge* category includes understanding of maintenance processes, battery machinery, battery products, cleanroom protocols, and safety procedures. These knowledge areas provide the technical foundation necessary for technicians to understand how battery production operates and how maintenance affects performance and product quality.

The *skills* category represents the largest group of attributes and reflected the practical nature of maintenance work. Important skills comprise mechanical, electrical, and mechatronic maintenance capabilities, troubleshooting, chemical handling, and the use of digital tools. In addition, several social and behavioral skills were identified, such as communication, teamwork, continuous learning, and the ability to train colleagues.

The *abilities* category consists of analytical reasoning, interdisciplinary thinking, and adaptability. These abilities enable maintenance technicians to diagnose complex failures, combine knowledge from multiple domains, and adapt their work to digital technologies.

The category of *other characteristics* captures dispositional attributes related to work behavior and professional conduct, including calmness in high-pressure situations, a personal drive for problem-solving, and a strong work ethic in demanding environments.

In addition, the study develops a training framework for maintenance technicians related to the generation of the desired KSAOs. The framework features *when, whom,* and *how*, and illustrates the cumulative progression of KSAO development from early to late career for maintenance technicians in battery production.

These findings support workforce development in SM organizations by translating worker attributes into corresponding training needs for maintenance technicians in battery production.

### Discussion and Conclusion

The study develops frameworks for required worker attributes for maintenance technicians in battery production and how they should be trained. The findings show that technicians primarily require generic skills, complemented by specific knowledge that can be developed through training. This is less applicable to other characteristics. Furthermore, maintenance training should combine theoretical and practical instruction. On-the-job training, such as mentorship and apprenticeships, is fundamental for developing practical experience, while digital training tools should complement – not replace – experiential learning.

For industry, the study provides practical guidance for the recruitment, onboarding, and training of maintenance technicians in battery production. The proposed frameworks help managers identify relevant worker attributes and align them with appropriate training approaches, while supporting more systematic and flexible workforce development during ramp-up.

For academia, the study advances workforce development research in industrial maintenance by applying the KSAO framework to battery production. It provides conceptual clarity and a structured way to analyze worker attributes, while offering an empirically grounded KSAO profile that distinguishes between generic and context-specific attributes.

### Contributions to Research Questions

Paper III builds on the exploratory insights generated in Paper I by examining two of the identified research avenues related to the *people* component: maintenance roles and skills in battery production, and industrial maintenance training for new personnel (see *Section 4.2* in Appended Paper I). The study examines worker attributes and training needs required for maintenance technicians in battery production in order to support workforce development in SM organizations.

The findings clarify the contributions to RQ1 by identifying *workforce challenges* related to maintenance technicians in battery production. The findings primarily contribute to RQ2 by translating *worker attributes* into training needs and developing training frameworks that support HCR for SM in battery production.

## 4.5 PAPER IV

### Integrating Asset Management in Greenfield Manufacturing

### Short Description

This paper evaluates how AM can be integrated into greenfield battery production, where new assets must deliver value from the outset. Research has largely focused on brownfield contexts, leaving greenfield manufacturing underexplored and highlighting the need to understand what enables effective integration and how it is established.

The synthesis identifies 23 enablers in the AM literature, empirically validates 11 and extends eight specific to greenfield manufacturing. It challenges the view of AM as primarily operational and tactical, highlighting its strategic role during factory establishment and ramp-up. It further shows that early and full adoption, rather than late and selective, enables more effective integration as manufacturing scales.

### Main Results

The meta-review shows that AM research is primarily concentrated in sectors such as construction, energy, and infrastructure, while manufacturing remains underexplored. Furthermore, the literature focuses predominantly on tactical and operational decision-making in the middle-of-life phase of assets, with limited attention to strategic decisions during the beginning-of-life phase when new factories are established. In total, 23 enablers are identified in the AM literature.

The interview study empirically validates 11 of these enablers and extends eight specific to greenfield manufacturing. These are synthetized according to four principles: *value*, *alignment*, *leadership* and *assurance*, see Figure 14.

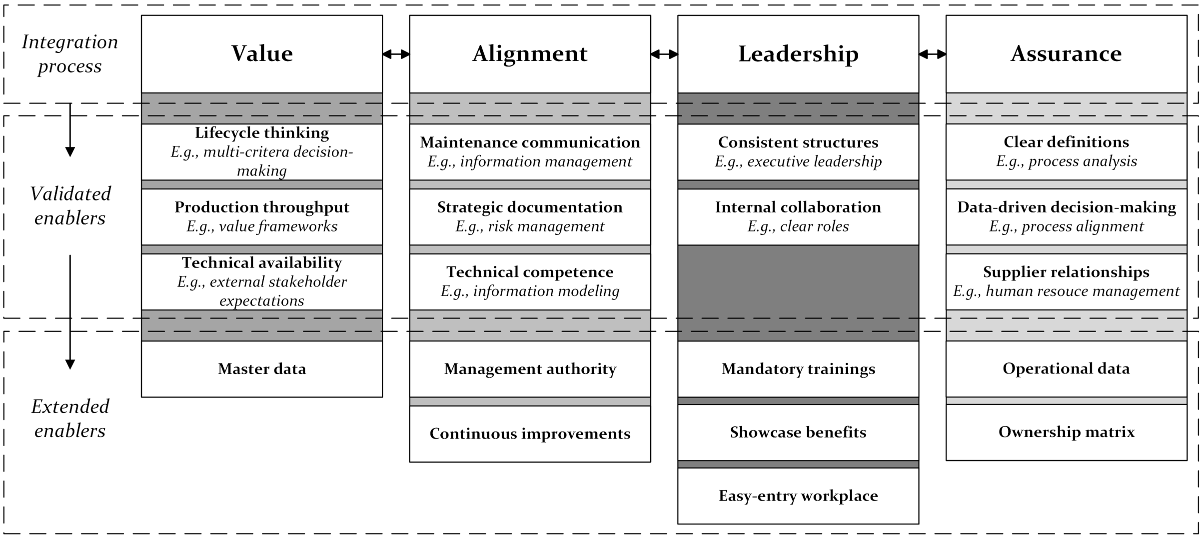


Figure 14. Integration enablers for AM in greenfield manufacturing.

The *value* principle highlights the importance of lifecycle thinking, where asset value is closely linked to production throughput and technical availability, while limited master data constrain the progression of value-creation.

The *alignment* principle highlights maintenance communication during ramp-up, requiring strategic documentation and technical competence for effective integration and evaluation, supported by management authority and continuous improvements.

The *leadership* principle underscores the need for consistent structures and internal collaboration, where mandatory trainings are fundamental, followed by showcasing benefits and an easy-entry workplace, enables integration.

The *assurance* principle requires clear definitions and DDD to ensure asset performance over time, emphasizing supplier relationships and the development of operational data and an ownership matrix for continuous operations.

This positions AM as an EXI process in lifecycle management and organizational design, where integration enablers strengthen organizational structures, technical competence, and data foundations necessary for greenfield battery production.

### Discussion and Conclusion

The findings shows that AM in greenfield manufacturing extends beyond a one-time integration and should be understood as an EXI process, in line with SM. While often associated with technical systems, effective integration depends on the interaction of its enablers, particularly leadership and data management. Without structured asset registers, historical records, and standardized reporting, organizations struggle to integrate AM and thereby support SM development.

For industry, the study provides practical guidance for integrating AM during factory establishment and ramp-up. It shows how its principles and enablers interact as manufacturing scales, and that early and full adoption enables more effective integration in greenfield manufacturing.

For academia, the study contributes to AM research by extending it to greenfield manufacturing. It highlights the importance of understanding lifecycle management and organizational design for AM integration and how its enablers interact.

### Contributions to Research Questions

Paper IV builds on the exploratory insights generated in Paper I by examining one of the identified research avenues related to the *process* component: full or selective adoption of AM (see *Section 4.3* in Appended Paper I). The study evaluates what enables the integration of AM into greenfield battery production and how it should be integrated to support SM.

The findings clarify the contributions to RQ1 by establishing *integration challenges* associated with AM in greenfield battery production. The findings primarily contribute to RQ2 by identifying, validating and extending *integration enablers* for AM that overcome these challenges and enable the development of *EXI* in SM.

## 4.6 PAPER V

**Designing Predictive Maintenance as Digital Servitization in Greenfield Manufacturing**

### Short Description

This paper explores how PdM systems can be designed and operationalized in greenfield battery production under conditions of high process uncertainty. While PdM is widely promoted in academia and industry, its implementation remains challenging in greenfield manufacturing, where product–process–degradation relationships are initially unknown. Drawing on possibility theory and engaged scholarship, the study adopts a design science approach to explore how PdM possibilities can be developed in greenfield battery production.

The findings demonstrate how previously infeasible possibilities become feasible, enabling prediction of critical tool failures with an initial accuracy of 91.7%. It reconceptualizes PdM systems as product–service–software solutions developed through ongoing use rather than standalone digital solutions, and position greenfield manufacturing as a setting where DDD must be actively designed.

### Main Results

The findings demonstrate that PdM systems in unknown product–process–degradation relationships can be deliberately designed along a *trajectory of possibilities* (see Table 5), moving from uncertainty to certainty over the course of the process.

Table 5. Trajectory of design possibilities.

| Unit | Focus | Past possibilities | | Present possibilities | | Future possibilities | |
|---|---|---|---|---|---|---|---|
| | | **Actualized** | **Unrealized** | **Available** | **Constrained** | **Feasible** | **Infeasible** |
| 1 | Downtime analysis, root-cause analysis, correlation analysis | Immediate corrective maintenance, predetermined maintenance, tool failures | CBM, latent signals | Functional reconfiguration | Limited data parameters, low telemetry granularity | Sensing integration | PdM, tool failures |
| 2 | Functional reconfiguration, data generation, data redistribution | Limited data parameters, low telemetry granularity | ▨ | Data-driven modeling, new torque signals | Low sampling frequency, no large datasets | ▨ | Threshold refinement, no physic-based modeling |
| 3 | Design of experiments, sensor integration, model development | Threshold refinement, no physic-based modeling | ▨ | CBM, new signals infrastructure | Sensing integration (investment) | PdM, tool failures | ▨ |

The first unit of analysis focused on *actualized* possibilities by analyzing downtime data, correlations between machine telemetry and downtime events, and root causes of failures in stacking production. The analysis showed that existing equipment primarily supported immediate corrective and predetermined maintenance. Although large volumes of data were generated, they captured machine movements rather than condition-related indicators required for prognostics, making PdM initially infeasible.

The second unit of analysis explored *available* possibilities by examining how existing data infrastructures could be reconfigured for CBM. Through data extraction, preprocessing, and visualization, latent condition indicators were identified within programmable logic controller data. Torque signals were extracted and aggregated into new indicators enabling real-time monitoring and revealing degradation patterns previously constrained.

The third unit of analysis investigated *feasible* possibilities through experimental design, sensor integration, and hybrid model development. Experiments induced typical tool failure modes (for example incorrect cutting depth or increasing mechanical backlash), while additional sensors captured vibration data, enabling a multi-sensor architecture. Hybrid prognostic models combining physics-based and data-driven approaches were developed, achieving initial accuracy of 91.7% in identifying critical tool failures.

The trajectory of findings demonstrates how higher and lower sets of design possibilities evolved across the units of analysis and illustrates how states of uncertainty were transformed into states of certainty.

### Discussion and Conclusion

The study demonstrates that developing PdM requires understanding product–process–degradation relationships that are initially unknown in greenfield manufacturing and must be discovered through active buyer involvement with suppliers and technology providers. Consequently, PdM resembles an operations design challenge aligned with its context and should not be treated as a standalone solution for maintenance digitalization.

For industry, the study provides practical guidance for designing PdM in greenfield battery production. By emphasizing active buyer involvement with suppliers and technology providers, it shows how manufacturers can transform PdM systems into product–service–software solutions through operational use, i.e., digital servitization.

For academia, the study contributes to research on PdM and digital servitization by reconceptualizing PdM as an operations design challenge in operations management. By applying possibility theory in greenfield manufacturing, it provides new insights into DDD under conditions of high process uncertainty.

### Contributions to Research Questions

Paper V builds on the exploratory insights generated in Paper I by examining two of the identified research avenues related to the *technology* component: tool maintenance in battery production, and sensor fusion for PdM (see *Section 4.5* in Appended Paper I). The study explores how PdM systems can be designed and operationalized in greenfield battery production under conditions of high process uncertainty.

The findings clarify the contributions to RQ1 by demonstrating *design challenges* when developing PdM systems in greenfield battery production. The findings primarily contribute to RQ2 by reconceptualizing PdM systems and showing how *design possibilities* for DDD in SM contribute to the development of greenfield battery production.

# 5

# SMART MAINTENANCE IN BATTERY PRODUCTION

*This synthesis draws on the results of the appended papers and interprets them through the four dimensions of SM to better understand how it contributes to development of battery production.*

## SMART MAINTENANCE IN BATTERY PRODUCTION

SM is increasingly becoming an integrated part of manufacturing digitalization, reflecting its strategic function in modern production systems. This is particularly evident in greenfield battery production, where maintenance is digitalized alongside new and partly unknown production systems as part of the industrialization process.

The results of the appended papers show that SM in battery production is characterized by a set of main challenges. As identified in Paper I and described in *Section 4.2*, maintenance needs coordinated development across organizational, technological, and human factors. SM therefore extends beyond digital technologies and should be understood as an organizational transformation in which its four dimensions evolve in parallel.

At the same time, the breadth of development needs makes prioritization essential. In battery production, where ramp-up occurs under high time pressure and process uncertainty, maintenance organizations face more challenges than can be addressed simultaneously. Prioritization therefore becomes a key managerial task, requiring context-specific decisions across socio-technical components.

The research and development projects (i.e., Paper II-V) in this thesis and described in *Section 4.3-4.6*, reflect such prioritizations, made in close collaboration with the battery manufacturer. Each project corresponds to an SM dimension and exemplifies maintenance development in greenfield battery production. Together, the appended papers provide an overview of SM implementation, showing how maintenance digitalization and greenfield industrialization converge to address challenges and opportunities across its dimensions.

Although this thesis is situated in battery production, its insights on SM extend to other manufacturing industries. In other words, the research and development projects could, to varying degrees, have been conducted in other contexts. However, the extreme conditions of battery production amplify the identified challenges, making it a particularly relevant setting for theorizing SM implementation.

The following sections synthesize the results of the appended papers through the four dimensions of SM. This elevates the analysis of how SM contributes to the development of battery production. As a result, it helps address the RQs of this thesis and advances the overall understanding of maintenance digitalization in greenfield industrialization.

### Internal Integration

INI is an enabler of SM in battery production, as maintenance development relies on coordinated activities across functions and requires benchmarking for prioritization and improvement. Since SM extends beyond the maintenance organization, it cannot be managed in isolation, placing clear demands on INI. Mechanisms that support such integration are therefore essential for enabling SM to contribute to the development of battery production.

The findings of this thesis indicate that INI is an early priority in battery production, as processes and infrastructure are still under development and lack a clear starting point for improvement. This is reflected in Paper I, where development needs related to processes and infrastructure are particularly pronounced. In such contexts, this starting point must be established through sustained collaboration and organizational commitment. This reinforces SM as a socio-technical system, where INI depends not only on organizational and technical elements but also on social dynamics within battery production.

Paper II illustrates how INI can be operationalized through the deployment of maintenance PIs. Rather than functioning solely as performance measures, these indicators act as integration mechanisms that guide coordination across functions. Establishing them requires collaboration to enable and sustain performance management. Improved benchmarking also supports development across other dimensions of SM. Without shared practices in performance management, improving overall equipment effectiveness becomes difficult, as technical availability remains unclear.

Maintenance PIs guide INI by structuring information and enabling shared interpretation across functions. Reporting and interpreting data between production and maintenance to distinguish symptoms from root causes creates dependencies that support SM implementation. As maintenance reporting is less automated, these indicators are particularly important during ramp-up. Shared dashboards are one example that enable such collaboration and can be understood as digital artifacts within INI. In this way, INI supports the development of DDD in battery production.

SM implementation thus improves how problems are understood and addressed across functions in battery production. As production and maintenance operate under different logics, performance management enables a shift from local problem-solving to a more systemic view of performance. This is particularly important in greenfield battery production, where disturbances are often treated as isolated events rather than process-related interactions. By aligning perspectives, INI improves prioritization, reduces sub-optimization, and enables maintenance to support scalable production.

Furthermore, the deployment of maintenance PIs contributes to the development of both production and maintenance practices, highlighting their interdependence. As production scales, performance management becomes increasingly important. The challenge lies not in selecting indicators, but in integrating them effectively into organizational practices. This is necessary as maintenance indicators must evolve alongside factory maturity. In decentralized maintenance organizations, this is particularly critical, as maintenance data complement production data in daily decision-making.

In conclusion, INI is an early priority for SM and provides a foundation for addressing root causes that hinder factory establishment and ramp-up. This is especially evident in greenfield settings, where maintenance PIs guide INI while supporting the development of DDD.

### Human Capital Resource

HCR remains fundamental to SM in battery production, as maintenance personnel ultimately ensure technical availability. Despite increasing digitalization, production equipment still fails and requires human intervention for troubleshooting and repair. This also applies to battery production. As equipment becomes more digital, workforce development in maintenance organizations must align with evolving production standards. SM therefore depends not only on technology, but on the human capabilities required to operate and maintain these systems.

The findings of this thesis examine HCR among maintenance technicians, focusing on worker attributes and training needs. As technicians constitute the majority of the maintenance organization, their capabilities are critical for technical availability. In greenfield battery production, the workforce must be developed without prior knowledge and experience, making factory establishment and ramp-up a critical learning phase. This challenges traditional learning logics in industrial maintenance and highlights the need to identify HCR early.

Paper III identifies the worker attributes defining the capabilities required of maintenance technicians in battery production. On the one hand, technicians need battery-specific and cognitive knowledge; on the other, most skills are generic and transferable from other manufacturing industries. This suggests that maintenance in battery production is not unique, but highly demanding due to time pressure and process uncertainty. At the same time, skills take longer to develop than knowledge, which must be considered in workforce development. Ensuring the desired KSAOs is therefore critical not only for establishing the foundation, but also for maintaining it over time.

The predominance of generic maintenance KSAOs suggests that much of workforce development can be initiated upfront rather than during greenfield industrialization. During factory establishment and ramp-up, the focus therefore shifts from training to ensuring that required capabilities are in place. This involves structured approaches to identifying and classifying worker attributes. Maintenance technicians act as both an enabler and a constraint for HCR: strong capabilities accelerate implementation, while insufficient or slowly developed capabilities delay it. This underscores the importance of strategic workforce development processes.

As manufacturing scales, the organization of learning becomes increasingly important. Learning management systems must provide a shared infrastructure for developing the desired KSAOs, particularly when maintenance technicians are distributed across multiple production stages. However, these systems need to be complemented with in-situ and experiential training, which remain essential for maintenance operations. Digital tools should therefore support, rather than replace, hands-on learning in production. The development of HCR is thus less about theoretical instruction and more about practice-based capability building.

Workforce development also places increased demands on maintenance management's understanding of knowledge management and organizational learning. As maintenance skills are difficult to recruit, proactive approaches are required in battery production. Retention becomes particularly important after factory establishment and ramp-up. At the same time, competence requirements vary across roles within the maintenance organization, requiring adaptable training frameworks that combine practical learning with evolving competence needs.

Overall, HCR should be understood as a prerequisite for SM in battery production. By systematically developing maintenance capabilities, organizations support continued digitalization. In greenfield contexts, where knowledge and experience must be built from the outset, HCR are therefore critical for effective factory establishment and ramp-up.

### External Integration

EXI is a long-term enabler of SM in battery production, as maintenance digitalization depends on coordination beyond organizational boundaries. Battery production is capital-intensive and relies on complex equipment, requiring collaboration with external actors to develop and understand how these systems function. Regulatory requirements further increase the need for information exchange. This is particularly important in greenfield battery production, where HCR is still developing and established maintenance practices are lacking. Mechanisms for EXI are therefore essential for enabling SM to contribute to the development of battery production.

The findings show how integrating AM in battery production improves EXI. Maintenance-related information does not originate solely during procurement but must be actively developed by the maintenance organization in line with organizational goals. If SM is not considered from the outset, EXI risks remaining underdeveloped, potentially hindering SM due to a lack of information. This is evident in Papers III and V. SM organizations must therefore be able to identify, acquire, and utilize relevant information, which is enabled by EXI.

Paper IV identifies enablers for integrating AM in greenfield battery production. These improve lifecycle management and organizational design, thereby supporting the development of EXI. As with HCR, this requires maintenance management to remain actively involved and up to date. The earlier these enablers are addressed, the greater the likelihood of successful AM integration. Over time, this reduces the risk of the "valley of death" in greenfield production, as relevant information on how production equipment should be operated and maintained becomes more accessible. AM therefore plays a strategic role in enabling the development of EXI within SM.

The availability and need for information vary across assets and throughout the lifecycle, including maintenance manuals, spare parts lists, and software codes. To understand equipment performance, master data must be linked with operational data. This requires that information is structured and accessible across systems. AM enables this by establishing common structures and a shared language across external actors. Without AM, data collection risks becoming fragmented across machines or departments, requiring larger datasets before data saturation is achieved.

As SM aims to extend asset lifespan through DDD, the integration of AM is directly linked to the digitalization of battery production. Maintenance managers do not need to be AM experts but must understand its fundamentals and ensure that EXI is maintained. This place demands on both leadership and flexible digital structures that can adapt as battery production evolves. Early integration of AM therefore establishes the conditions necessary for scalable and sustainable gigafactory ramp-up.

Hence, AM in greenfield battery production enables EXI in SM by establishing integration enablers and improving lifecycle management and organizational design. EXI thus becomes a central part of both greenfield industrialization and maintenance digitalization.

### Data-Driven Decision-Making

DDD is the most recognized dimension of SM, as digital technologies enable digitalized manufacturing and maintenance, which in the long term may enable dark factories. In greenfield battery production, large volumes of data are generated from the outset, creating significant potential for DDD. However, this potential is not automatically realized for complex production equipment, as the conditions required for PdM are not yet in place.

The findings of this thesis show that DDD is particularly challenging in greenfield battery production, as the relationships between product, process, and degradation are initially unknown. This makes it difficult to determine which data are relevant for prediction. Although new gigafactories generate large volumes of data, it often lacks relevance for maintenance, as it primarily reflects mechanical movements rather than degradation processes. While such information is partially related, it remains insufficient to detect meaningful changes in equipment health.

This constrains the effectiveness of DDD in SM and highlights the need to deliberately design PdM systems where they have the greatest impact on battery production. Such design requires a deep understanding of how maintenance interacts with process and product quality – knowledge that must be developed by the organization through experimentation. As this is a resource-intensive development process, prioritizing critical equipment becomes essential when implementing DDD in SM.

At the same time, production conditions change significantly during gigafactory establishment and ramp-up. Equipment is modified, processes are adjusted, and operating conditions vary, including due to human error, which affects data quality and alters what constitutes data saturation. As a result, early investments in DDD may provide limited value, as development is gradual and cannot be implemented as a one-time-fits-all solution.

Paper V shows that PdM systems must be designed iteratively, with data, models, and system configurations co-evolving and generating industrial know-how. Through experimentation in production, equipment health can be better understood and new data sources established, enabling more advanced analysis and prediction. PdM should therefore be understood as a product–service–software solution that develops through use, rather than as a system that can be implemented directly.

Maintenance data is typically not included in equipment procurement, meaning that DDD capabilities are not available from the outset and may therefore constitute a competitive advantage. Despite this, PdM is often assumed to be a standalone digital solution, creating a misalignment between buyer expectations and supplier offerings. In practice, such capabilities must be actively developed through digital servitization, where PdM systems evolve as integrated product–service–software solutions.

Given the scope of DDD development, prioritization is necessary, as not all equipment can be digitalized simultaneously. Efforts should therefore focus on critical equipment or areas with sufficient data availability, guided by performance management and AM. At the same time, DDD is not limited to PdM but also includes simpler systems that enable fact-based decision-making.

Consequently, DDD should be understood as an outcome of SM rather than its starting point. Possibility theory and design science demonstrate a viable approach for designing and operationalizing PdM systems under conditions of high process uncertainty.

# 6

# DISCUSSION

*The discussion addresses and answers the RQs of this thesis. It further discusses the quality of the research, its theoretical and practical contributions, and concludes with limitations and directions for future research.*

## 6.1 ADDRESSING RESEARCH QUESTION 1

RQ1 asked: *What are the main challenges associated with maintenance in battery production?*

### Main Challenges of Maintenance in Battery Production

Maintenance involves numerous challenges related to both its nature and production characteristics, relying on manual dexterity and human problem-solving that are difficult to automate (Bokrantz et al., 2020b, Sgarbossa et al., 2020). These challenges are amplified by the evolving complexity of battery production, which continuously shapes best practices in maintenance (Kwade et al., 2018, Liu et al., 2021).

Furthermore, stringent requirements for quality, cleanliness, and production speed in battery production increase the consequences of equipment failures, placing significant demands on maintenance (Duffner et al., 2021, Dahmen et al., 2024). At the same time, ongoing rapid changes require maintenance organizations to manage emerging technologies and regulations, thereby continuously reshaping the conditions for maintenance in battery production (International Energy Agency, 2025, Johansson et al., 2024).

It is therefore important to map these challenges to address them effectively. From a socio-technical perspective, they consist of interrelated organizational, technological, and human factors (Beier et al., 2020, Lundgren et al., 2023). To enable prioritization, they must be made explicit and structured. Paper I does so by identifying critical challenges, establishing important development needs, and outlining relevant research avenues, which form the basis for the four research and development projects examined in this thesis.

### Answering Research Question 1:

The findings of this thesis categorize the challenges associated with maintenance in battery production by outlining 31 research avenues across socio-technical components. These challenges can be further described as four interrelated types: *performance*, *workforce*, *integration*, and *design* challenges. Derived from the outlined research avenues, they manifest as the most critical priorities during factory establishment and ramp-up.

*Performance* challenges relate to the INI required for SM to function effectively. The findings show that deploying maintenance PIs requires establishing and maintaining foundational elements, including standardization, training, internal integration, management commitment, and data infrastructure. These requirements address challenges that need to be considered when setting up performance management in battery production.

*Workforce* challenges concern the development of HCR required for SM. The findings focus on maintenance technicians and show that battery production requires specific combinations of 21 worker attributes, which translate into corresponding training needs. Several challenges relate to training practices at scale, including the scarcity of maintenance skills and the need to systematically develop battery-specific knowledge.

*Integration* challenges involve the EXI essential for SM through AM in battery production. The findings validate 11 enablers and extend eight specific to greenfield battery production, including technical competence, and data foundations. These requirements address challenges in aligning maintenance with broader organizational and lifecycle perspectives during factory establishment and ramp-up.

*Design* challenges focus on developing DDD for SM in battery production, particularly PdM systems. The findings show that these systems cannot be treated as standalone digital solutions, as product–process–degradation relationships are initially unknown. Instead, they are reconceptualized as product–service–software solutions developed through active buyer involvement.

Together, these four challenge types clarify the scope of maintenance in battery production and what needs to be developed. Many challenges extend beyond the maintenance organization to broader research and development projects, underscoring that production and maintenance development must be studied as an integrated whole.

## 6.2 ADDRESSING RESEARCH QUESTION 2

RQ2 asked: *How can SM contribute to the development of battery production?*

### The Role of Smart Maintenance in Developing Battery Production

SM is fundamental to battery production, particularly in greenfield settings where high levels of automation increase dependence on integrated and data-driven maintenance (Gopalakrishnan et al., 2022). At the same time, the potential for digitalizing maintenance in battery production is substantial, as newly installed equipment generates large volumes of data from the outset (Kornas et al., 2019, Dahmen et al., 2024). In contrast to brownfield settings, where legacy constraints limit implementation (Deloitte, 2020), greenfield battery production enables the design of data infrastructures and maintenance practices from the beginning, increasing both the opportunities and requirements for SM. As a result, SM becomes closely intertwined with digitalized manufacturing and directly influences production performance in complex and tightly coupled processes (Kwade et al., 2018).

SM (Bokrantz et al., 2020c) contributes to battery production development by addressing important needs and outlining a structured set of deployment requirements, worker attributes, integration enablers, and design possibilities across its dimensions. These provide guidance for maintenance organizations during factory establishment and ramp-up, where uncertainty is high and best practices are still evolving (Johansson et al., 2024). Consistent with prior research emphasizing the socio-technical nature of maintenance digitalization (Bokrantz et al., 2020b, Beier et al., 2020), SM extends beyond technological implementation to include organizational structures and social competencies. In this sense, the thesis extends existing scholarship by demonstrating how SM implementation enhances industrialization in greenfield battery production, repositioning maintenance from a support function to a proactive and more strategic contributor to production development.

At the same time, SM is not merely the deployment of digital technologies, but a strategic development process requiring substantial efforts in resources, learning, and operational alignment (Lundgren et al., 2021, Hein-Pensel et al., 2023). This aligns with studies showing that many digital maintenance initiatives fail due to insufficient organizational readiness and integration (Roda and Macchi, 2021, Akkermans et al., 2024). Early lifecycle decisions – particularly on data infrastructure, asset design, and organizational setup – are critical for enabling future maintenance performance and DDD (Serradilla et al., 2022). In greenfield battery production, early adoption of SM is important, as delays may lead to inefficiencies and challenges during factory establishment and ramp-up (Attia et al., 2025, Örüm Aydin et al., 2023).

### Answering Research Question 2:

The findings of this thesis show how SM can contribute to the development of battery production through prioritized research and development projects. The avenues outlined in Paper I establish several development needs across socio-technical components that can be addressed using SM. The contributions are presented by dimension.

INI contributes early to the development of battery production through the deployment of maintenance PIs. More specifically, deployment requirements must be addressed to enable their effective use. This establishes aligned procedures and shared practices in performance management, supporting SM in battery production. By improving benchmarking as digital artifacts for DDD (where technical availability is central), problem-solving shifts from a local to a system-wide perspective. This drives INI forward and enables shared prioritization and optimization during factory establishment and ramp-up. In this way, it supports organizational development and promote collaboration for implementing SM in battery production.

HCR contributes to the development of battery production by identifying human capabilities and developing training frameworks for maintenance technicians. Notably, worker attributes must be addressed to implement SM, as they ultimately determine technical availability. The systematic development of training practices and learning processes is therefore critical during factory establishment and ramp-up, which also represent fundamental phases for learning. By strengthening in-situ and experiential learning in operations, HCR can be developed and scaled. This supports battery production ramp-up and the retention of knowledge for continuous improvement. HCR should therefore be understood as a prerequisite for SM and battery production.

EXI contributes to the development of battery production by enabling the integration of AM, ensuring that newly installed equipment delivers value from the outset. This requires an increased focus on lifecycle management and organizational design to support coordination with external actors. Enablers structured around AM principles improve the development of asset data and registers across the lifecycle, particularly during factory establishment and ramp-up. Hence, AM assumes a strategic role, and early integration increases the likelihood of establishing an effective foundation for maintaining the groundwork. EXI ensures that SM scales with manufacturing and improves information management to support the development of battery production.

DDD contributes to the development of battery production by demonstrating how PdM systems can be designed and operationalized under conditions of high process uncertainty. This requires understanding product–process–degradation relationships, which are initially unknown, to determine relevant data and design production equipment and maintenance system. Through experimentation and active buyer involvement with equipment suppliers and technology providers, PdM evolves as a product–service–software solution through operational use, i.e., digital servitization. This is enabled by developing a trajectory of possibilities that turns infeasible solutions into feasible ones. Through design science, DDD in SM is developed, contributing to battery production development.

Together, these four dimensions contribute to the development of SM by addressing maintenance challenges during factory establishment and ramp-up, improving performance, workforce, integration, and design in digitalized maintenance.

## 6.3 RESEARCH QUALITY

The research presented in this thesis is grounded in applied research in industrial practice (Marotti de Mello and Wood Jr, 2019), with the overall objective of supporting maintenance in battery production. As described in *Chapter 3*, the research follows an iterative logic, where ideas are explored, analyzed, and evaluated through continuous interaction with industrial practice (Tengblad et al., 2005, Arlidge et al., 2017). In this setting, research quality lies in bridging academia and industry to ensure that real-world challenges are properly addressed (Van de Ven and Johnson, 2006).

A central foundation of the thesis is the pre-study in Paper I, in which challenges, development needs, and research avenues for maintenance in battery production were mapped. The ethnographic approach enabled immersion in a true maintenance organization, allowing observations to be interpreted in relation to ongoing activities (Dumont, 2023). This provided in-depth empirical insights that strengthened the consistency of the theoretical contributions.

The thesis further builds on multiple studies and methods addressing different development needs (Creswell, 2015, Fetters et al., 2013). For example, data were collected through observations, interviews, workshops, experiments, and documents, enabling triangulation across sources and perspectives (Heale and Forbes, 2013). This contributes to a more robust synthesis of the studied phenomenon, as a multi-method approach increases the validity and credibility of the research.

All studies were conducted within the gigafactory, ensuring strong practical relevance and value creation. This reflects engaged scholarship principles (Van de Ven, 2018), which have formed large parts of the practical work in the research and development projects. This thesis argues that such scholarship is important for building trust and balancing the interface between industry and academia, as also argued by Ping Li (2011). Research management has therefore been central to project execution, given the involvement of multiple stakeholders.

## 6.4 RESEARCH CONTRIBUTIONS

The research contributions are divided into theoretical and practical contributions to support improved implementation.

### Theoretical Contribution

This thesis makes four major contributions to academia. First, it advances the scholarship on SM by focusing on its implementation, that is, how to put it into effect. In doing so, it extends existing research on its conceptualization (Bokrantz, 2019) and facilitation (Lundgren, 2021). Moreover, the thesis identifies challenges, establishes development needs, and outlines research avenues, as well as deployment requirements, worker attributes, integration enablers, and design possibilities involved in developing SM in battery production. In this way, it advances research on maintenance digitalization and takes a step closer to Industry 4.0 (Hermann et al., 2016) and 5.0 (Murtaza et al., 2024).

Second, the outcomes of the appended papers constitute theoretical contributions in their own right by exemplifying key activities in maintenance digitalization. As the research and development projects address different dimensions of SM, they exemplify steps of the strategic development process (Lundgren et al., 2021, Larsson et al., 2026), particularly step four (planning key activities) and step five (elevating implementation). This clarifies how key activities are elevated in practice and fills a gap in maintenance digitalization research, particularly regarding how successful maintenance strategies can be implemented under conditions of organizational constraints (Lundgren et al., 2022, Kumar and Galar, 2018, Badri et al., 2018). In addition, the findings clarify the role of human integration across SM dimensions, showing that they are learning-intensive and requires careful preparation.

Third, this thesis represents applied research grounded in industrial practice (Marotti de Mello and Wood Jr, 2019) and shows how research can engage with industrial reality and maintenance organizations to advance maintenance digitalization in manufacturing. It contributes to practice-based innovation (Ellström, 2010) and provides clear guidance for other scholars by exemplifying how different research methods, such as ethnography (Dumont, 2023), case studies (Flyvbjerg, 2011), multi-method approaches (Fetters et al., 2013), and design science (Holmström et al., 2009), can be used to study digital transformation. The research design, inspired by Tengblad et al. (2005) and Arlidge et al. (2017), further highlights the value of not overcomplicating industrial research, but rather streamlining it to keep pace with industrial change.

Fourth and finally, this thesis contributes to the growing field of battery research by studying how SM can support the development of battery production. More specifically, it provides theoretical contributions for how a modern gigafactory operates and how maintenance must align with its production. As a result, it shows how SM can reduce misalignments between battery technology and manufacturing capabilities (Kwade et al., 2018), thereby helping to mitigate the risk of the so-called “valley of death” (Attia et al., 2025). In doing so, the thesis contributes to a better understanding of what operational excellence entails for maintenance in battery production (Ragonnaud, 2025). From a broader perspective, it strengthens the long-term sustainability of European battery production (Johansson et al., 2024).

### Practical Contributions

This thesis contributes to industry by demonstrating how SM can be implemented in battery production. Rather than treating it as a whole, the findings show how its dimensions can be developed through multiple research and development projects aligned with factory establishment and ramp-up.

As a result, the main practical contribution of this thesis is to demonstrate how maintenance in battery production can be developed based on the four dimensions of SM. Paper I identifies challenges, development needs, and research avenues, while Papers II–V exemplify how six of these avenues can be addressed in practice. Taken together, these provide practical guidance of how to put SM into effect in battery production.

More specifically, this thesis outlines deployment requirements, worker attributes, integration enablers, and design possibilities across SM dimensions in battery production. This highlights their breadth and interdependencies and shows that SM cannot be implemented by maintenance alone, but must be developed together with other organizational functions.

In addition, this thesis highlights the importance of prioritization during factory establishment and ramp-up as part of implementing SM. However, prioritizing development needs in battery production is challenging, as most aspects are still under development. The presented research and development projects inherently reflect such prioritization, highlighting what contributes to SM in battery production.

## 6.5 LIMITATIONS

All research in this thesis was conducted at a large battery manufacturer in Sweden. At the time of the study, domestic battery production in Europe was still in an early stage of development, with few comparable cases available for research. The results of the appended papers should therefore be interpreted in light of this unique context, which nonetheless offers contributions to both academia and industry. Hence, the thesis does not aim for statistical generalizability (Flyvbjerg, 2004).

Another limitation concerns the researcher's role as an industrial doctoral student at the battery manufacturer. While this position enabled rich access to data, it also introduced challenges not typically faced by traditional academic doctoral students, such as information filtering and involvement in industrial decision-making regarding project continuation. In other words, the industrial doctoral position provided a greater degree of freedom, which may have influenced the research process. Hence, maintaining methodological rigor was of utmost importance to ensure academic quality.

Furthermore, this thesis builds largely on the results of the pre-study (Paper I), which set the direction of the subsequent research (Papers II–V). As only six of the 31 identified research avenues were examined, it is important to note that the field of SM in battery production remains relatively underexplored and at an early stage. While the selection of research and development projects somewhat constrained the scope of the thesis, it also contributed to addressing the RQs for SM in battery production.

## 6.6 FUTURE WORK

SM in battery production is a body of research that is likely to attract increasing attention in the future as gigafactories become more data-driven and electrification of society and industry continues. Future research should therefore build on this by further addressing the research avenues identified in Paper I. As battery production in Europe matures, the conditions under which SM progresses will evolve. This implies that research in this area will likely need to be continuously revised and refined, and therefore cannot be regarded as fully complete.

Alongside this, future research should examine how SM implementation progresses in industries beyond battery production. As noted in the limitations, European battery production represents a highly unique context. Extending research to other industries would not only support the broader digitalization of maintenance but also help validate and improve the contributions of this thesis. This includes further clarifying the similarities and differences between SM in greenfield and brownfield manufacturing contexts.

Finally, SM should not be viewed as a final state of digitalization, but as a continuous development process. Its implementation is therefore long and demanding, and further research on each dimension is needed. Currently, each dimension remains underexplored, as they are often treated as part of the broader SM concept, which risks oversimplifying them. Future research should therefore examine each dimension separately to improve understanding of how they function as socio-technical systems in their own right, before being integrated and implemented as part of SM.

# 7

# CONCLUSION

This thesis is situated at the intersection of SM and battery production, two rapidly growing research streams that remain insufficiently connected in existing literature. While SM has been conceptually established and increasingly studied in brownfield manufacturing, its implementation in greenfield contexts remains limited. At the same time, greenfield battery production has emerged as a strategically important industry in Europe, driven by major investments in the establishment and ramp-up of gigafactories. Against this backdrop, the thesis set out to examine how SM can be implemented in battery production and how it can contribute to its development, thereby supporting the long-term sustainability of the European battery industry.

Through five appended papers, this thesis identifies critical challenges, establishes important development needs, and outlines relevant research avenues for maintenance in battery production, while beginning to address them in real-world industrial settings. ***The results show that the main challenges (RQ1) lie in addressing performance, workforce, integration, and design in parallel.*** These are structured through 31 distinct research avenues across socio-technical components, illustrating the complexity of establishing and ramping up maintenance in battery production.

The thesis further demonstrates how SM contributes to the development of battery production by elevating these prioritized development needs through four research and development projects, each representing one dimension. Here, the thesis shows how the deployment of maintenance PIs can guide INI and result in digital artifacts, how workforce and training frameworks can be developed to support HCR, how AM through its enablers can establish the conditions for EXI, and how DDD can be designed under conditions of high process uncertainty. ***Together, these contributions (RQ2) result in a structured set of deployment requirements, worker attributes, integration enablers, and design possibilities that support the implementation of SM in battery production.***

In this sense, the thesis advances SM research from conceptualization and facilitation toward implementation in manufacturing. It extends existing maintenance scholarship by showing how SM unfolds when maintenance digitalization and greenfield industrialization are developed simultaneously. This provides practical contributions by demonstrating how maintenance in battery production can be developed using SM, while also advancing theory through its focus on implementation. SM should not be understood as a final state, but as a continuous process of development. This raises important questions for future research, such as how SM can be sustained and further developed beyond ramp-up. Regardless of how future research evolves, the body of SM research will most likely continue to grow, as maintenance digitalization is an enduring feature of digitalized manufacturing and essential for future smart factories, such as the European gigafactories.

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