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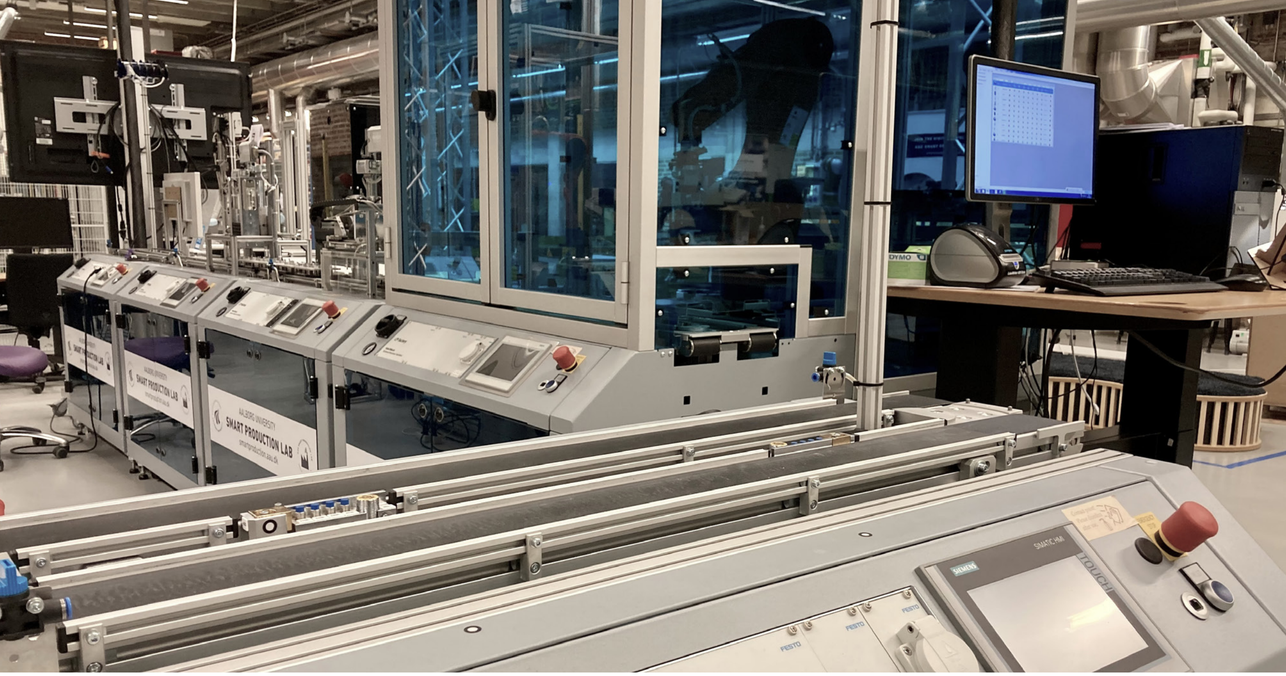
DOI (link to publication from Publisher):
10.54337/aau468604062

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record



ENABLING THE SMART FACTORY WITH INDUSTRIAL INTERNET OF THINGS-CONNECTED MES/MOM

BY
SOUJANYA MANTRAVADI

DISSERTATION SUBMITTED 2022

AALBORG UNIVERSITY
DENMARK

ENABLING THE SMART FACTORY WITH INDUSTRIAL INTERNET OF THINGS-CONNECTED MES/MOM

Ph.D. Dissertation

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Dissertation submitted January 2022

Dissertation submitted: January 28, 2022

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PhD Series: Faculty of Engineering and Science, Aalborg University

Department: Department of Materials and Production

ISSN (online): 2446-1636
ISBN (online): 978-87-7573-945-5

Published by:
Aalborg University Press
Kroghstræde 3
DK – 9220 Aalborg Ø
Phone: +45 99407140
aauf@forlag.aau.dk
forlag.aau.dk

Cover photo by Soujanya Mantravadi,
showing the AAU Smart Production Lab

Printed in Denmark by Rosendahls, 2022

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Soujanya Mantravadi graduated with an MSc (Eng.) from the KTH Royal Institute of Technology, Sweden (2015). She completed her master thesis while interning for Alstom in Paris.

She studied her bachelor in her hometown, Hyderabad, and received a degree (distinction) in mechanical engineering from JNTU-H, India (2011). She has previously worked as a research analyst at Mordor Intelligence, as a trainee at the Paul Scherrer Institut – ETH Domain, and as an engineer at Amada Co. She was employed as a research assistant at Aalborg University, financed by the Manufacturing Academy of Denmark.

Her research focuses on manufacturing digitalization to create solutions based on enterprise information systems. She is a visiting PhD at the Department of Engineering, University of Cambridge.

Abstract

Manufacturing is facing difficulty in evolving and meeting reconfigurability needs because of the prevalence of legacy systems that are heterogeneous and inflexible. This PhD project addresses that challenge by developing design principles that are relevant to the real-world industrial context for manufacturing operations management (MOM). The core system of MOM is manufacturing execution system (MES), which is a factory information system, and its principles aim to enable a *smart factory*. The smart factory is an information technology (IT)-driven enabler for meeting future manufacturing requirements, such as reconfigurability. It has the capacity to solve the customer responsiveness problem by reducing the time to market and supporting product variety.

Intelligent manufacturing methods, such as agent-based approaches, have previously been studied to solve customer responsiveness problems. However, they have all had weak adoption rates in the industry. Current methods for solving customer responsiveness problems require an in-depth analysis of architectures of enterprise information systems, such as MES/MOM, in the Industrial Internet of things (IIoT). The IIoT involves connecting machines and devices to a network, which is crucial for the computer-based automation of manufacturing operations in a factory and its supply chain for enabling reconfigurability in an Industry 4.0 scenario. MES/MOM is a potential centerpiece of an interconnected and interoperable architecture to implement reconfigurable manufacturing systems for distributed manufacturing control.

MES/MOM, based on the ISA 95 standard, has been crucial industrial software for production execution and online management of factory activities for the past two decades. However, enterprises face challenges in deriving the maximum value from MES/MOM due to its low interoperability, low customizability, and monolithic design. In addition, the manufacturing industry is currently unable to effectively use production data due to the prevalence of legacy systems, which are largely unable to share data with MES/MOM.

Using a design science research approach, the thesis develops architectural design recommendations with the support of Unified Modeling Language illustrations. The aim is to develop a next-generation MES/MOM connected to the

IIoT. The design is intended to act as a core of a reconfigurable manufacturing enterprise by supporting the smart factory design principles of (1) information transparency, (2) technical assistance, (3) decentralized decision making, and (4) interconnection. The thesis also establishes the relevance of the ISA 95 standard in an Industry 4.0 context, which has been unclear and undocumented, because ISA 95 does not envision the convergence of IT and operational technology that is required for IIoT.

The empirical basis for the PhD project is the companies of the *Manufacturing Academy of Denmark* (MADE DIGITAL and MADE FAST projects) network. The case companies for the project include three large production companies with global manufacturing footprints, which are trying to leverage their MES/MOM initiatives. The case companies also include two Danish medium-scale IT consulting companies, which provide technology solutions that interact with or are based on MES/MOM. For the empirical foundation of the project, we conducted semi-structured interviews with MES implementation managers of six large companies, and studied the industry needs around MES/MOM through three industrial demonstrators. The industry needs of the MADE companies underpinned the PhD research. Furthermore, the manufacturers' potential benefits from improving the MES/MOM design were deduced using the example of Aalborg University's *Smart Production Lab* and the quality function deployment method (QFD).

Keywords: Industry 4.0, enterprise information systems, architectural design, empirical research, reconfigurable manufacturing systems, interoperability

Dansk resumé

Fremstillingsindustrien står over for vanskeligheder med at forny sig og opfylde behovene for rekonfigurerbarhed på grund af udbredelsen af heterogene og ufleksible systemer. Dette ph.d.-projekt sigter mod at løse denne udfordring ved at udvikle en række designprincipper, der er relevante for virksomheder i en industriel kontekst, for ”Manufacturing Operations Management” (MOM), hvis kernesystem er ”Manufacturing Execution Systems” (MES). MES/MOM er et centralt informationssystem for en fabrik, og dets designprincipper har til formål at muliggøre en ”smart factory”, som omfatter en produktionsvirksomhed og dens globale produktionsfaciliteter i en Industry 4.0-sammenhæng. Den smarte fabrik er en informationsteknologi (IT)-drevet katalysator til at imødekomme fremtidige produktionskrav såsom rekonfigurerbarhed, især med dens evne til at forbedre ”customer responsiveness” ved at reducere ”time-to-market” og understøtte øget produktvarians.

Intelligente fremstillingsmetoder, såsom agentbaserede tilgange, er tidligere blevet undersøgt for at løse problemer med kundernes reaktionsevne, selvom de alle havde svage adoptionsrater i branchen. Nuværende metoder til at løse problemer med kundernes reaktionsevne kræver en dybdegående analyse af virksomhedsinformationssystemernes arkitekturer såsom MES/MOM i selve ”Industrial Internet of Things” (IIoT), som involverer at forbinde maskiner og enheder til et netværk. Dette er afgørende for den computerbaserede automatisering af produktionsoperationer på en fabrik og dens forsyningskæde for at muliggøre rekonfigurerbarhed i et Industry 4.0-scenarie. MES/MOM er et potentielt midtpunkt i en sammenkoblet og interoperabel arkitektur til at implementere rekonfigurerbare produktionssystemer til distribueret produktionskontrol.

MES/MOM, baseret på ISA 95-standarden, har været kritisk industriel software til produktionsudførelse og onlinestyring af fabriksaktiviteter i to årtier. Imidlertid står virksomheder over for udfordringer med at få den maksimale værdi ud af det på grund af dets lave inter-operabilitet, lave tilpasningsmuligheder og monolitiske design. Derudover er fremstillingsindustrien i øjeblikket ikke i stand til effektivt at bruge produktionsdata på grund af udbredelsen af ældre systemer, som har en lav evne til at dele data med MES/MOM.

Ved at bruge en designvidenskabelig forskningstilgang udvikler afhandlingen arkitektoniske designanbefalinger (med støtte fra ”Unified Modeling Language”) til en næste generations MES/MOM forbundet til IIoT. Dets design er beregnet til at fungere som en kerne i en rekonfigurerbar produktionsvirksomhed, der understøtter de smarte fabriksdesignprincipper om (1) informationsgennemsigtighed, (2) teknisk assistance, (3) decentral beslutningstagning og (4) sammenkobling. Afhandlingen fastslår også relevansen af ISA 95-standarden i en Industry 4.0-kontekst, som har været uklar og ukendt, fordi ISA 95 ikke forudser konvergensen af IT og operationel teknologi, der kræves af IIoT.

Det empiriske grundlag for projektet stammer fra virksomhederne i ”Manufacturing Academy of Denmark” (MADE DIGITAL og MADE FAST projekter) netværket. Dette omfatter tre store produktionsvirksomheder med globale produktionsfootprint, der forsøger at udnytte deres MES/MOM-initiativer, og to danske mellemstore it-konsulentvirksomheder, der leverer teknologiske løsninger, som interagerer med eller baseres på MES/MOM. Som det empiriske grundlag for ph.d.-projektet gennemførte vi semistrukturerede interviews med MES-implementeringsledere fra seks store virksomheder og undersøgte industriens behov og forventninger omkring MES/MOM gennem udvikling af tre industrielle demonstratorer. MADE-virksomhedernes behov var drevkraft for ph.d.-forskningen, og producenternes potentielle fordele ved at forbedre MES/MOM-design blev udledt og demonstreret ved hjælp af Aalborg Universitets ”Smart Production Lab” og ”quality function deployment” (QFD).

Acknowledgements

Technological transformations often begin with futuristic ideas that seem unattainable. For example, smartphones seemed unthinkable just two decades ago. Whether we like it or not, many futuristic ideas become reality in society over time, and some even improve the world. In that spirit, this PhD research examines advanced digital technologies and explains their vast potential for application in manufacturing.

This dissertation would not have been possible without the help of several people, whom I would like to acknowledge. First and foremost, my sincere gratitude goes to my supervisors Prof. Charles Møller and Assoc. Prof. Thomas Ditlev Brunoe for helping me navigate Industry 4.0 and letting me put my spin on this topic. It is no exaggeration to say that this design science inquiry would not have been possible without your progressive thinking. Thank you, Charles, for your genuine appreciation for academic discourse and your prompt feedback. The last four years were a smooth journey, working with you. Thank you too, Thomas, for your good advice and support. Your positive attitude is a much-needed approach in academia.

My special thanks go to Dr. Jagjit Srai from the University of Cambridge for his insightful scientific discussions and valuable inputs, especially during my times of confusion. Jag, your input enhanced the quality of my research. Thank you for believing in my work and giving me an opportunity to take it forward. Thanks also to the Institute for Manufacturing at the University of Cambridge for hosting my research stay.

Exchanges with my case companies – LEGO, Danfoss, and LINAK – have positioned me close to real-world problems and have allowed me to observe state-of-the-art manufacturing digitalization in practice. I offer my gratitude to all the interviewees for providing their data. My funder MADE, and my being part of the MADE network, provided very useful interactions with digital innovators and global manufacturers.

Many thanks to my colleagues in the Mass Customization group and my office mates – Alessia, Rasmus, and Stefan. You gave me camaraderie and a pleasant work atmosphere, so that I looked forward to coming to the office every day. I also acknowledge my co-authors, fellow *Smart Production Lab* mates, and colleagues from the Center of Industrial Production for reviewing my scientific work.

Last but not least, my special appreciation goes to my parents for always encouraging me to aspire for my passions. I am also deeply grateful to my husband and my personal network for their immense love and support.

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DOI: 10.1109/IEEM45057.2020.9309989

- Presented at the 2020 IEEE International Conference on Industrial Engineering and Engineering Management, 14–17 Dec. 2020, Singapore (virtual)
- Conference paper published by IEEE

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"An Overview of Next-generation Manufacturing Execution Systems: How important is MES for Industry 4.0?", S. Mantravadi and C. Møller (2019)
DOI: 10.1016/j.promfg.2019.02.083

- Presented at the 14th Global Congress on Manufacturing and Management, 5–7 Dec. 2018, Brisbane, Australia
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"Perspectives on Real-Time Information Sharing through Smart Factories: Visibility via Enterprise Integration", S. Mantravadi, C. Møller, and F. M. M. Christensen (2018)
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List of abbreviations

AI Artificial intelligence

AIML Artificial intelligence Markup Language

ANS Advanced shipping notification

CPS Cyber-physical system

DSR Design science research

EIS Enterprise information system

ERP Enterprise resource planning

GDP Gross domestic product

IIoT Industrial Internet of things

IoT Internet of Things

IoTS Internet of Things and Services

IS Information system

ISA International Society of Automation

IT Information technology

MADE Manufacturing Academy of Denmark

MES Manufacturing execution system

MESA Manufacturing Enterprise Solutions Association

MOM Manufacturing operations management

MQTT MQ Telemetry Transport

OM Operations management

OPC UA OPC Unified Architecture

OT Operational technology

PLC Programmable logic controller

QFD Quality function deployment

RAMI 4.0 Reference Architecture Model Industrie 4.0

RFID Radio-frequency identification

RMS Reconfigurable manufacturing system

RQ Research question

UML Unified Modeling Language

Chapter 1. Introduction

1.1 Motivation and background

The manufacturing sector has been a primary driver of economic development in many countries, ever since the first industrial revolution in 18^{th} century England, which changed society fundamentally. Over the last two centuries, technological innovations have supported economic growth, and countries have been launching programs to boost the manufacturing sector as part of their financial planning to sustain this growth.

One such strategy is Industry 4.0, launched for the German manufacturing industry in 2011. It proposes to "integrate cyber-physical systems (CPS) and Internet of Things and Services (IoTS) with an eye to enhance productivity, efficiency and flexibility of production processes and thus economic growth" [1]. The digital agenda of Industry 4.0 has gained significant attention not only from the industrialized countries that favor automation of manufacturing processes but also from the research community. Industry 4.0 has become a well-established research area, with many overlapping views of *smart manufacturing* and with a smart factory as its central concept. Gartner [2] proposed the following market definition for smart factory:

> The smart factory is a concept used to describe the application of different combinations of modern technologies to create a hyperflexible, self-adapting manufacturing capability. Smart factories are an opportunity to create new forms of efficiency and flexibility by connecting different processes, information streams and stakeholders (frontline workers, planners, etc.) in a streamlined fashion. Smart factory initiatives might also be referred to as "digital factory" or "intelligent factory."

The smart factory is a vision for next-generation manufacturing with enhanced capabilities, using advanced manufacturing technologies built on emerging communication and information technologies (IT) [3]. It is an abstract concept of a manufacturing enterprise that encompasses global manufacturing facilities. A smart factory is data-driven and self-organized and relies on the help of the Industrial Internet of Things (IIoT). In turn, the IIoT connects machines and devices to a network to optimize the production value. Recent scientific studies have indicated that smart factories' technical capabilities are currently being extensively analyzed and upgraded [4].

As an example of a successful smart factory, Siemens upgraded its plant in Amberg, Germany. The plant now uses artificial intelligence (AI), edge computing, and cloud technologies to improve its quality control and to enable predictive maintenance [5]. Considering this success, Siemens built a plant in Chengdu, China, that follows the same processes [6]. Another example is the Schneider Electric plant in Lexington, United States, which is equipped with IIoT to increase its efficiency [7]. Yet another success story is Moderna's digital factory, which, during the COVID-19 pandemic in 2020, manufactured vaccines soon after the virus's genetic code was released [8].

Market uncertainties and supply chain disruptions caused, for example, by the ongoing COVID-19 pandemic, have motivated manufacturing enterprises to reform their manufacturing operations management (MOM). Therefore, the use of digital technologies to develop manufacturing reconfigurability to improve customer responsiveness is of great interest for enabling the smart factory. Furthermore, reconfigurability helps manufacturers to increase their product variety with short product life cycles. Here, a reconfigurable manufacturing system design allows for quick changes to the production capacity and functionalities.

Digitizing data collection and processing to use information effectively is known to positively impact an organization's operations. Information systems are widely studied in operations management; the aim is usually to implement manufacturing initiatives and to boost a plant's performance [9]. There is ample research documenting the significance of information systems in a factory. However, the efficacy of enterprise information systems (EIS) needs further inquiry when those systems are connected to the IIoT.

A manufacturing execution system (MES) is an EIS that can enable a higher degree of flexibility in production systems in Industry 4.0. However, the MES faces challenges regarding data integration and interoperability [10]. Gartner [11] stated that

> Manufacturing execution systems (MESs) manage, monitor and synchronize the execution of real-time, physical processes involved in transforming raw materials into intermediate and/or finished goods. They coordinate this execution of work orders with production scheduling and enterprise-level systems. MES applications also provide feedback on process performance, and support component- and material-level traceability, genealogy, and integration with process history, where required.

We do not view MES only as a software application but also as an implementation of the MOM functionalities of the ISA 95 standard. Hence, we use the terms “MES” and “MOM” together. However, in this thesis, we also refer simply to “MES” at times, for readability.

A smart factory is an implementation of a reconfigurable manufacturing system [12]. Its capabilities – in terms of being data-driven and reconfigurable – depend on the effective utilization of the existing shop floor’s IT assets, such as MES/MOM. This thesis focuses on smart factory implementation in a brownfield environment and one criterion of our research was to develop low-cost solutions that can benefit small and medium-scale manufacturers. While most large companies are embarking on smart factory projects, we believe that a smart factory transformation can be equally beneficial for smaller companies.

Enabling a smart factory requires a complex interplay between continued use of existing legacy systems and acquiring more advanced manufacturing technologies. To manage this complexity, designers must redesign the factory information systems to be interoperable with heterogeneous systems, and we address this design challenge in our research. Our project scope is drawn from four areas, as illustrated in Fig. 1.

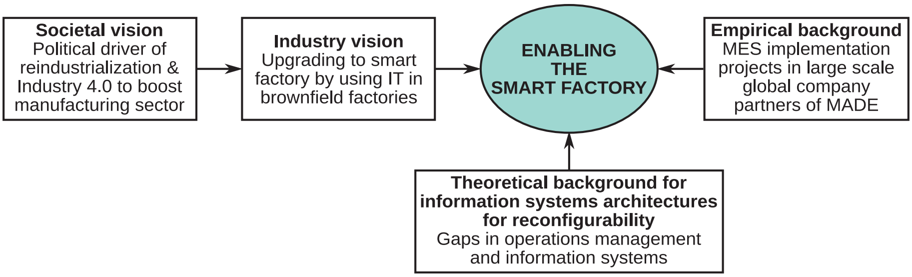

Fig. 1: Drivers for enabling the smart factory

Enterprise information systems for Industry 4.0 – Research domain and issues: Next-generation manufacturing systems for Industry 4.0, such as reconfigurable manufacturing systems mediated by MES/MOM, must support more than just the low-level reconfigurability needs (e.g., rescheduling and rerouting). They should also support high-level enterprise needs. Industry 4.0 requires a seamless data exchange between emerging IIoT devices and MES/MOM in almost real time. This entails improving the interconnectivity beyond what ISA 95 promises to achieve. ISA 95 was developed in the era when manufacturing and business were separate departments. Hence, it promotes compartmentalization and leads to data silos. Therefore, much of the literature on MES/MOM stresses the importance of semantic interoperability between MES/MOM and other systems [13]. Jaskó *et al.* (2020) [14] highlighted the importance of formal models and ontologies for developing MES for Industry 4.0.

Figure 2 illustrates the hierarchy of systems in a modern manufacturing enterprise. Here, it is critical to integrate the machines and enterprise systems using standards such as ISA 95 to automate the information exchange [15]. Figure 2 does not represent the desired network structure of a distributed architecture of Industry 4.0; however, it shows the transformative phase in brownfield manufacturing enterprises.

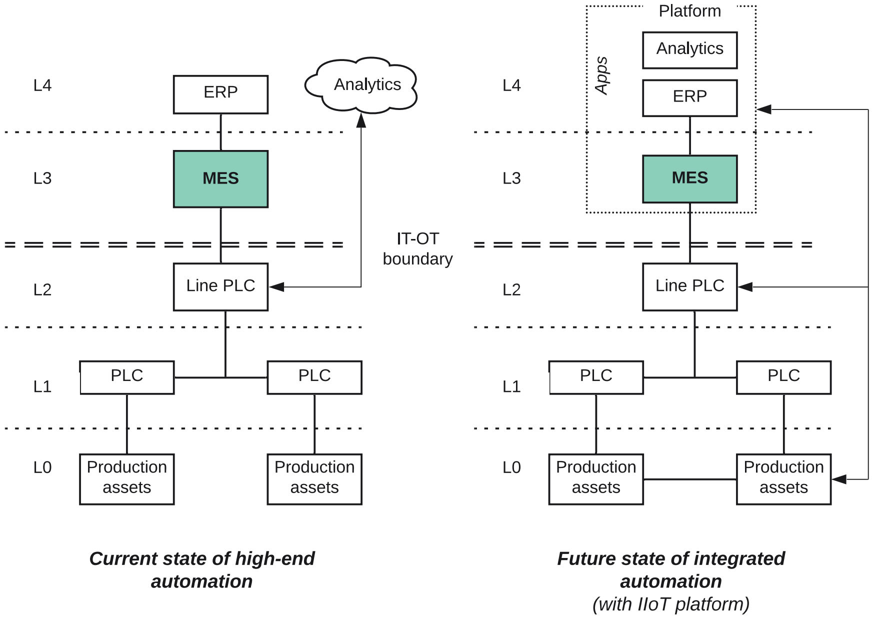

Fig. 2: ISA 95 hierarchy of systems with IIoT interconnectivity [16]

The challenges of interoperability raised by the convergence of IT and operational technologies (OT) in manufacturing are more serious than those which occur between IT systems. Paes *et al.* [17] explained IT/OT convergence as follows:

> IT/OT convergence is the integration of IT systems applied to data-centric computing with OT systems used to monitor events, processes, and devices and make adjustments in enterprise and industrial operations. IT is composed of those hardware and software system technologies that allow for corresponding information processing. OT is supported by physical devices, i.e., switches, sensors, power distribution networks, valves, motors, and software that allow for control and monitoring of a plant and its associated equipment.

In this thesis, we consider MES/MOM to represent IT (IT could also include the IIoT platform, cloud servers, and edge servers). Most of our papers consider programmable logic controllers (PLCs) to represent OT. However, OT could also include computer numerical control systems, smart sensors, and singleboard computers (e.g., Raspberry Pi).

Several researchers have successfully attempted to present MES-based solutions for specific Industry 4.0 and supply chain related problems, for example [18, 19, 20]. Nonetheless, the question of how to optimally apply MES/MOM in conjunction with IIoT to develop a smart factory in a brownfield enterprise remains unanswered. Motivated by this need, we studied MES implementation projects in six large companies. Our methodology included semi-structured expert interviews and field visits, and we analyzed the MES/MOM design requirements to derive design principles for the IT/OT convergence problem to support reconfigurability. This project demanded that we take an abductive approach.

In *The sciences of the artificial*, Simon [21] described *engineering sciences* as those sciences that are concerned with the characteristics of compelling artifacts and the process of designing them. Therefore, we used the design science framework to produce normative and prescriptive knowledge. The intersection of the Venn diagram in Fig. 3 illustrates our focus area.

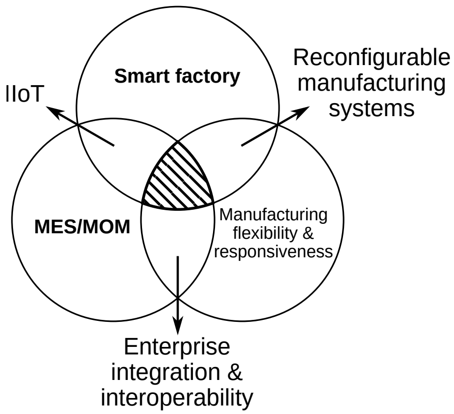

Fig. 3: Research focus

Aims of the study: This PhD research aims to present MES/MOM architectural design guidelines by reiterating the ISA 95 hierarchy of systems to suit the smart factory concept of distributed information and automation. Furthermore, the thesis leverages IIoT technology for production data acquisition and fills research gaps regarding the smart factory design principles. The thesis proposes architecture models by considering modularity, customizability, security, and operator assistance required in Industry 4.0. It contributes to the research on responsive smart factories within the domains of industrial engineering and operations management.

1.2 Definitions

This thesis uses a set of terms from the industrial automation field to establish the conceptual territory of the research in information systems and operations management. Table 1 lists the definitions of the most important terms used to develop a shared understanding.

Table 1: Terms and definitions

Term	**Definition**
ISA 95	"ISA-95 bears the title Enterprise-Control System Integration. ISA-95 is not an automation system, but rather a method, a way of working, thinking, and communicating. [...] The documents contain models (figures) and terminology you can use to analyze an individual manufacturing company" [22, ch. 2.3].
Manufacturing operations management (MOM)	As per ISA 95 standard, "MOM activities within Level 3 of a manufacturing facility that coordinate the personnel, equipment and material in manufacturing" [23].
IIoT	"A system comprising networked smart objects, cyber-physical assets, associated generic information technologies and optional cloud or edge computing platforms, which enable real-time, intelligent, and autonomous access, collection, analysis, communications, and exchange of process, product and/or service information, within the industrial environment, so as to optimise overall production value. This value may include; improving product or service delivery, boosting productivity, reducing labour costs, reducing energy consumption, and reducing the build to-order cycle" [24].
Industry 4.0	Industry 4.0 "will involve the technical integration of cyber physical systems into manufacturing and logistics and the use of the Internet of Things and Services in industrial processes. This will have implications for value creation, business models, downstream services and work organisation" [25].
Manufacturing control	"The manufacturing control is concerned with managing and controlling the physical activities in the factory aiming to execute the manufacturing plans, provided by the manufacturing planning activity, and to monitor the progress of the product as it is being processed, assembled, moved, and inspected in the factory" [26].

Table 1: Terms and definitions (continued)

Term	Definition
Distributed manufacturing control	"Multi-agent-based control and holonic manufacturing control are two suitable examples that address intelligent and distributed manufacturing control. These paradigms, introducing artificial intelligence techniques in practice, have the capability to respond promptly and correctly to change, and differ from the conventional approaches due to their inherent capabilities to adapt to emergence without external intervention" [26].
Manufacturing Execution Systems (MES)	Manufacturing Enterprise Solutions Association (MESA) International put forward eleven manufacturing execution activities: Resource Allocation and Status, Operations/ Detail Scheduling, Dispatching Production Units, Document Control, Data Collection/Acquisition, Labor Management, Quality Management, Process Management, Maintenance Management, Product Tracking and Genealogy, and Performance Analysis. (Level 3 of ISA 95 is also called as MES layer.) [27]
Manufacturing flexibility	"Manufacturing flexibility, a critical dimension of value chain flexibility, is the ability to produce a variety of products in the quantities that customers demand while maintaining high performance. It is strategically important for enhancing competitive position and winning customer orders" [28].
Responsive manufacturing	"Responsiveness is the ability of a production system to respond to disturbances (originating inside or outside the manufacturing organisation) which impact upon production goals" [29].
Reconfigurable manufacturing systems (RMS)	RMS are "designed at the outset for rapid change in structure, as well as in hardware and software components to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements" [30].
Interoperability	"Interoperability is the ability of two or more software components to cooperate despite differences in language, interface, and execution platform" [31].

Table 1: Terms and definitions (continued)

Term	**Definition**
Vertical integration	"In the fields of production and automation engineering and IT, vertical integration refers to the integration of the various IT systems at the different hierarchical levels (e.g. the actuator and sensor, control, production management, manufacturing and execution and corporate planning levels) in order to deliver an end-to-end solution" [25].
Horizontal integration	"In the fields of production and automation engineering and IT, horizontal integration refers to the integration of the various IT systems used in the different stages of the manufacturing and business planning processes that involve an exchange of materials, energy and information both within a company (e.g. inbound logistics, production, outbound logistics, marketing) and between several different companies (value networks). The goal of this integration is to deliver an end-to-end solution" [25].
Enterprise resource planning (ERP)	ERP systems are "comprehensive, packaged software solutions seek to integrate the complete range of a business's processes and functions in order to present a holistic view of the business from a single information and IT architecture" [32].
Architectural design	"Architectural design is concerned with understanding how a software system should be organized and designing the overall structure of that system. [...] It is the critical link between design and requirements engineering, as it identifies the main structural components in a system and the relationships between them. The output of the architectural design process is an architectural model that describes how the system is organized as a set of communicating components" [33].
Model	"Model [is] a useful representation of a specific situation or thing. Models are useful because they describe or mimic reality without dealing with every detail of it. They typically help people analyze a situation by combining a framework's ideas with information about the specific situation being studied [...]. [T]hey help us make sense of the world's complexity" [34, 15].

Table 1: Terms and definitions (continued)

Term	**Definition**
Unified Modeling language (UML)	“The Unified Modeling Language (UML) has been the industry standard for visualizing, specifying, constructing, and documenting the artifacts of a software-intensive system. As the de facto standard modeling language, the UML facilitates communication and reduces confusion among project stakeholders” [35].
Data	Data are facts represented in the form of text, numbers, images, graphics, sound or video [36].
Information	Data placed in a context can be termed as Information [36]. Information is data endowed with purpose and relevance [37].
Information systems	An information system is “A set of interrelated components that collect, manipulate, store, and disseminate data and information and provide a feedback mechanism to meet an objective” [38].
Database	“A database is a collection of interrelated data items that are managed as a single unit. [...] A database object is a named data structure that is stored in a database. The specific types of database objects supported in a database vary from vendor to vendor and from one database model to another. Database model refers to the way in which a database organizes its data to pattern the real world” [39].
Industrial software stack or technology stack	“The industrial software stack is the complete set of software products and tools required to gather data from an industrial end point (a machine), extract some useful information from the data, and either advise or initiate making a decision about how to operate the machine differently or support other decisions made about how to operate the underlying business more effectively” [16].

1.3 Objective

Our research is motivated by the need to design MES/MOM to support the Industry 4.0 paradigm. Therefore, our MES/MOM system design should be evaluated against future requirements rather than just the existing conditions. Because the future needs are only partially known, MES/MOM design enhancements can be approached using auxiliary theoretical perspectives from the computer science domain. These perspectives are based on the design principles of a smart factory, such as [40]: (1) information transparency, (2) technical assistance, (3) decentralized decision making, and (4) interconnection. These design principles are not stand-alone but are interrelated.

Our research contribution is aimed at the operations management field; hence, we deemed the study of all the design principles to be within its scope. We articulated the main research objective as follows:

Develop a conceptual framework for smart factory capabilities and derive design principles for MES/MOM to enable the smart factory.

By *capability*, we mean a collection of physical technologies, knowledge and expertise, managerial systems, and values, which together give an enterprise a competitive advantage [41, p. 18]. In this thesis, *architecture* refers to the fundamental properties of a system embedded in its environment; these properties are determined by the system's components and their relationships to each other as well as its design and evolution [42]. The thesis is intended to facilitate the transition toward a smart factory.

Hence, we posed three main research questions (RQs):

RQ1 Which MES/MOM functionalities can support reconfigurability in a smart factory?

RQ1.1 How do MES functionalities in IIoT support or limit reconfigurability in manufacturing?

RQ1.2 What is the role and importance of MES/MOM in Industry 4.0?

RQ1.3 What is the conceptual framework of smart factory capabilities with IIoT-connected MES/MOM, and how could MES/MOM be designed to support reconfigurability in manufacturing?

To achieve the research objective, this thesis first develops a conceptual framework that is theoretically and empirically grounded. It is essential to identify reconfigurability approaches for smart factory goals and to assess the ISA 95-based MES functionalities for reconfigurability needs. Hence, **RQ1.1** addresses these aspects. Similarly, the role of MES/MOM in the smart factory is addressed through **RQ1.2**. Finally, to conclude the requirements analysis for a smart factory, **RQ1.3** synthesizes the expectations from MES/MOM. In the exploratory phase of the research, we thus developed a conceptual framework for examining smart factory capabilities.

RQ2 How can MES/MOM be used with smart factory technologies to improve the performance of manufacturing operations management?

RQ2.1 How can MES/MOM support the smart factory design principle of *information transparency*?

RQ2.2 Does a user-friendly MES interface with a prediction system (e.g., chatbot interface), intended to improve the shop floor user's quality of results, support the smart factory design principle of *technical assistance*?

RQ2.3 What is the conceptualization of multi-agent MES to support the smart factory design principle of *decentralized decisions*?

RQ2.4 What special considerations are necessary to secure the connection between IT and OT in IIoT, given the need for wireless connectivity and modularity for the smart factory design principle of *interconnection*?

RQ2 builds upon the conceptual framework developed in **RQ1**. The potential ways of enhancing MES/MOM design to implement a smart factory required us to describe the detailed high-level architectural design of MES/MOM. The design in turn required a proof-of-concept with a comparative assessment to verify whether the efficiency of the process supported by MES/MOM had been improved compared to its previous design. For that comparison, we studied four design principles of the smart factory [40], focused on four sub-RQs. In this experimental phase, we proposed the design principles for MES/MOM.

RQ3 What design choices are necessary for MES/MOM to support the smart factory implementation process in a brownfield environment?

RQ3.1 In what way is ISA 95 relevant to the IIoT paradigm for designing responsive smart factories?

RQ3.2 What design choices are necessary for a next-generation MES/MOM that is compatible with IIoT?

*__RQ3.1__ and **RQ3.2** are from [43].

Few empirical studies have examined how ISA 95 models can be adapted to a smart factory in a real-world setting. Given the lack of research, in **RQ3** we address customer responsiveness problems concerning reconfigurability to establish the relevance of ISA 95 (**RQ3.1**). Furthermore, **RQ3.2** focuses on design choices by drawing on the findings from three industrial design demonstrators in which ISA 95-based models were applied in a brownfield manufacturing enterprise. In this instantiation and evaluation phase, we revised the design principles for MES/MOM.

1.4 Thesis structure

This PhD thesis is based on a collection of papers, which is a recommendation from the doctoral school of engineering at Aalborg University, Denmark. It takes a birds-eye view to introduce the PhD research. In-depth research is reported in the appended papers, where five key papers represent the main contributions of the thesis by empirically studying the IIoT at a deeper level (see Fig. 4). The three supporting papers refine the key research contributions. These exploratory papers focus on developing MES/MOM for implementing the smart factory design principles with respect to IIoT and use various auxiliary theoretical perspectives from the discipline of computer science such as distributed AI, machine learning, human-computer interaction, and cybersecurity. For example:

- **Paper 5** studies the Industry 4.0 scenario of *technical assistance* and applies MES/MOM for information retrieval by accommodating a chatbot interface layer to the MES architecture. The interface layer uses natural language processing to add predictive power to MES and improve the efficiency of the processes MES/MOM is intended to support [44].
- **Paper 6** studies the Industry 4.0 scenario of *decentralized decisions* and proposes decision support capabilities on the shop floor for production coordination. This conceptual work presents a MES system architecture combined with a machine learning technique for a multi-agent MES [45].

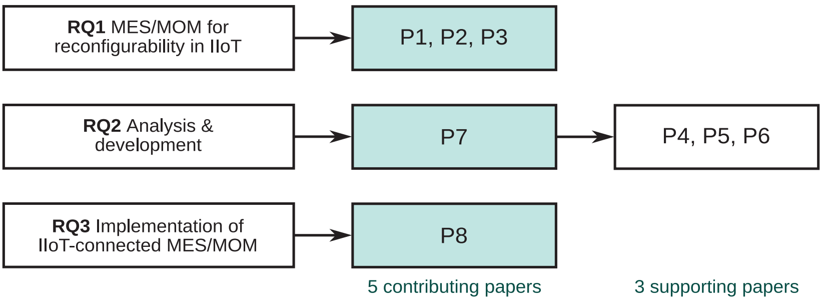

Fig. 4: Thesis structure

After this introduction, Chapter 2 reviews research on the smart factory information architecture and usage of reference models (e.g., ISA 95) in manufacturing. This chapter also reviews the literature on information systems development for a smart factory and focuses on state-of-the-art reconfigurable manufacturing systems development. Finally, Chapter 2 derives a theoretical framework for enabling a smart factory with MES/MOM based on earlier academic and industry research.

Chapter 3 describes the research methodology of the thesis by discussing the empirical elements of research design. This chapter begins with the philosophical perspectives on the research into automation technology and argues for design science as an approach to develop artifacts and prescribe design recommendations. This chapter also presents the details of methods used for this work: (1) a series of seven semi-structured interviews, (2) experiments based on the IT of Aalborg University's *Smart Production Lab* (henceforth referred to as the *Smart Lab* in this thesis), and (3) quality function deployment.

Chapter 4 reports the findings from all the appended papers representing the exploratory, experimental, and prescriptive phases of design science research conducted for this work.

Chapter 5 discusses the findings obtained from the iterative design science study in view of the research questions. It critically analyzes the extent to which the results can be mapped to the research objective. The chapter also discusses the novel contributions that emerge from this thesis.

Chapter 6 summarizes the thesis to draw conclusions. It overviews the key findings, research contributions, and limitations. The chapter explores many new avenues for research resulting from this thesis. Some of these are presented as concluding remarks.

Chapter 2. Theoretical foundation

This chapter establishes the theoretical background of the thesis. It reviews the literature on smart factories in the contexts of reconfigurable manufacturing systems, enterprise architecture, and information systems development. The three main research questions are grounded within those contexts and the links between the RQs are explained in Section 1.3.

2.1 Theoretical challenges in reconfigurable manufacturing systems

2.1.1 Matching supply to demand in Industry 4.0

Enterprises around the world had a combined annual spending on enterprise software of USD 467 billion in 2020. The figure is estimated to reach USD 572 billion by 2022, which is more than 10% growth rate, according to Gartner's forecast [46]. Another study published by McKinsey [47] forecasted that IIoT will be a USD 500 billion market by 2025.

Technology adoption has increased in manufacturing over the years. At the same time, the sector's contribution to the GDP has decreased in many emerging and emerged markets [48]. As technology promises to improve productivity, many strategic initiatives – such as Industry 4.0 – have been announced. The aim is to spare the manufacturing sector the vast stress caused by the changing requirements of the market (and end users).

Currently, the COVID-19 pandemic continues to cause severe market disruptions. The situation requires innovative ways to conduct operations. Such market changes entail short-notice deviations in planned manufacturing processes and require reconfigurable supply chains and manufacturing systems. Next-generation EIS with their design upgrades can facilitate the desired levels of reconfigurability.

Recent studies have illustrated the importance of digitalizing operations [49]. The role of MES/MOM in coordinating logistics in manufacturing supply chains, via vertical and horizontal integration, is becoming crucial. Previous studies have suggested that EIS can positively influence supply chains due to their ability to evolve and match emerging information management needs [50].

In this regard, reconfigurability theory provides a framework for understanding the change enablers in terms of manufacturing technologies, equipment, systems, and organizational strategies [51]. Reconfigurability at the firm level can be understood as the capacity to rearrange the *key elements*, which include the supply network structure; the flow of material and information between and within factory networks; relationships between the supply network partners, such as contractual aspects and changes; and the value structure of a product or service (e.g., product composition and structure and the replenishment mode) [52].

Based on these aspects, MES/MOM can be evaluated for its ability to enable reconfigurability. However, few studies have investigated the application of ISA 95-based MES functionalities for reconfigurability to aid the IT/OT integration.

2.1.2 Aligning process capabilities and product attributes

Numerous researchers believe that reconfigurable manufacturing systems (RMS) are the future of manufacturing systems. In this concept, a self-organizing system for market responsiveness can enable RMS at a low cost and can align the process capabilities with the required product attributes. Interoperable and distributed manufacturing control systems, such as multi-agent systems, can play an essential role in adapting RMS for Industry 4.0. Figure 5 illustrates the cyber-physical connection in an Industry 4.0 context.

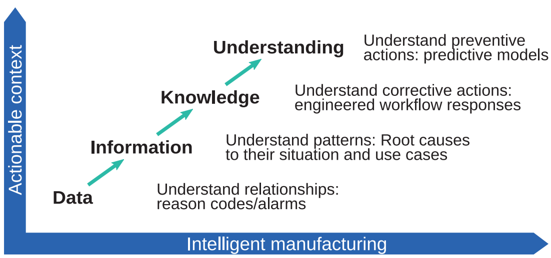

Fig. 5: Stages of data usage toward artificial intelligence (AI) in Industry 4.0 [53]

Reconfiguration typically means adding, removing, or substituting modules in the manufacturing system, thereby changing the system's capacity or functionality. However, legacy manufacturing IT often cannot support these reconfigurations. Therefore, we argue that a future MES/MOM should be designed to support such reconfigurations. RMS can adjust their own production capacity and functionality in response to sudden market changes by making quick changes to the system's structure and to the hardware and software components [30].

Morgan *et al.* (2021) [54] stated that there are eight RMS characteristics: modularity, integrability, customization, convertibility, scalability, diagnosability, mobility, and adaptability. The authors [54] further established that Industry 4.0 machines will demonstrate smart and reconfigurable capabilities. We argue that next-generation manufacturing IT/IS must be designed to facilitate this reconfigurability.

The literature mentions various challenges around developing RMS. The issues relevant to this thesis are listed below:

- Adoption of more rigorous analytic metrics to assess reconfigurability level [54],
- High perceived complexity [54],
- System design [54],
- Lack of development methodologies for reconfiguration and lack of proper reference models for control systems architectures [26], and
- Lack of studies explaining successful industry adoption of RMS practices [55].

In addition, the following research questions need to be answered:

- Is it necessary to include reconfigurability principles in the design phase of production systems? [56]
- Is it possible to introduce reconfigurability principles in an existing production system, without making substantial financial investments? [56]

Information quality could be improved and the effective use of information assets maximized [57] if MES/MOM were to be developed with an intelligent distributed architecture to support reconfigurability in a smart factory. The architectural principle of distributed information using an agent-based approach [58] can be used for MES/MOM design to achieve flexibility on the shop floor. However, MES/MOM should first be made interoperable with legacy systems to obtain the desired state of distributed intelligence.

2.1.3 Implementation of MES/MOM in an enterprise context

The literature suggests that companies that make large investments in technology-enabled initiatives will have a competitive advantage in future volatile markets [59]. Companies thus need to merge their IT strategy – which includes the manufacturing IT – with their business strategy [60].

Many IT projects fail not because of technical errors but because of organizational issues [61]. This point highlights the significance of an organizational context for converting IT investments into productive outputs. We argue that MES/MOM implementation must be viewed as an enterprise initiative instead of a shop floor initiative; furthermore, such implementation should draw outside the existing manufacturing IT governance scope. In addition, a robust evaluation framework is needed to maximize the effective use of MES/MOM regarding specific key performance indicators. This would help manufacturers to evaluate whether the information system projects align with their business needs.

Manufacturing flexibility is one of the key competitive priorities aside from cost, quality, and sustainability. In the aftermath of the COVID-19 pandemic, manufacturers have realized that the future belongs to firms that can rapidly manage market uncertainties [62]. A World Economic Forum report [62] stated that “We may be on the precipice of ‘Operational Darwinism’, wherein mere reductions in costs may not be enough to compete against leaders who make manufacturing a rapid and key part of their digital innovation edge.”

To develop market responsiveness for manufacturers through technology interventions, we first needed to determine the status quo of the available industrial automation, such as smart factory technologies. The organizational spaces within which smart factories operate and the consequent operational changes they can trigger should also be evaluated. One way to achieve market responsiveness is by developing manufacturing flexibility through smart factory design. This point calls for a study on smart factory information management and how ISA 95 can drive data management initiatives.

Rob Thomas, in his keynote at the *IBM Think 2019* conference (as reported on Twitter [63]) stated that “There’s no AI without IA – information architecture. Every client has to go along the journey of the #AI ladder, from how you collect data, organize data, analyze data and finally infuse data.” Information architecture management is about “defining the data needs of the enterprise and designing the master blueprints to meet those needs” [57]. By understanding the data needs of RMS for IT/OT ntegration, RMS can be developed using Industry 4.0 principles. Figure 6 illustrates the stages of Industry 4.0 development.

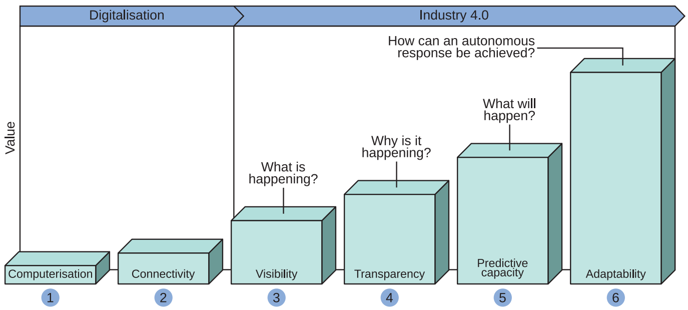

Fig. 6: The stages of Industry 4.0 development [64, 65]

Standards and architectures can be developed based on the manufacturing enterprise's high-level goals [57]. However, it is essential to first determine the requirements for MES to interact with different systems, such as SAP HANA, Salesforce, or Kinaxis, in the IIoT. This step supports reconfigurability. To design such IIoT-connected MES/MOM, the potential MES/MOM functionalities that cater for a reconfigurable smart factory must also be identified, so that its design can be developed in that direction. Given this scenario, we posed the following question:

RQ1: Which MES/MOM functionalities can support reconfigurability in a smart factory?

2.2 Background theory: Enterprise architecture perspective on smart factories

2.2.1 Reference models in manufacturing

Enterprise architecture helps to provide a blueprint for defining an organization's requirements, which are partly based on future needs and couples those requirements with the IT investments needed to implement technological solutions [66]. Therefore, an enterprise architecture perspective on smart factories can help in planning and aligning the manufacturing IT investments (MES/MOM) to develop smart factory capabilities. Jonkers *et al.* (2006) [66] defined enterprise architecture as follows:

> It is a coherent whole of principles, methods and models that are used in the design and realisation of the enterprise's organisational structure, business processes, information systems, and infrastructure. EA captures the essentials of the business, IT and its evolution. The idea is that the essentials are much more stable than the specific solutions that are found for the problems currently at hand. Architecture is therefore helpful in guarding the essentials of the business, while still allowing for maximal flexibility and adaptability.

The IT field traditionally uses reference models to represent components and functionalities for system development. Such reference models also exist in the manufacturing field. Standards such as ISA 95 present models that for decades have defined the kind of data to be exchanged between manufacturing IT systems to achieve computer-based automation. However, ISA 95 was designed at a time when sales, manufacturing, and other operations fell under different departments with separate IT. Hence, ISA 95 does not account for the interconnectivity that is possible with the IIoT. As manufacturing enterprises look to achieve vertical and horizontal integration in Industry 4.0, they must investigate to what degree ISA 95 remains relevant.

The Reference Architecture Model Industry 4.0 (RAMI 4.0) by ZVEI [67] describes the space of Industry 4.0 in three dimensions:

1. The vertical axis represents – as layers – the physical aspect; the integration with IT; and the communication, information, functional, and business aspects of the entities being mapped.
2. The second axis corresponds to the functional hierarchy of ISA 95, with the product added as the bottom level and the connected world at the top.
3. The third axis represents the lifecycle and value stream; it maps the development, production, and maintenance of entities.

The three dimensions are shown in Fig. 7. RAMI 4.0 is a common framework to discuss Industry 4.0. It allows, for example, mapping out standards to identify gaps and overlaps to understand the requirements for a smart factory.

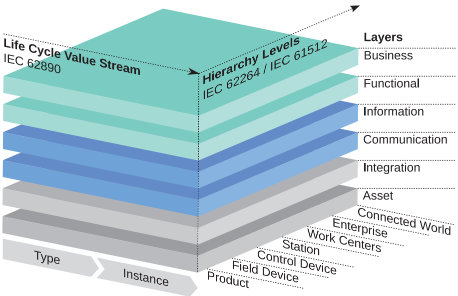

Fig. 7: Three axes of the RAMI 4.0 standard [67]

There is increasing integration of IT in manufacturing operations, and the industry is striving to make use of MES/MOM for future data management initiatives. However, Almada-Lobo [68] identified the traditional MES with a centralized control as an obstacle for Industry 4.0. Therefore, it is essential to develop MES/MOM based on modern requirements. Our work supports this process and contributes to architectural design by drawing on Hermann *et al.*'s [40] Industry 4.0 design principles. We thus explore novel research avenues for MES/MOM design enhancements.

2.2.2 Using the design principles of smart factory

Hermann *et al.* [40] described the desired transformation of smart factories in four themes: (1) information transparency, (2) technical assistance, (3) decentralized decisions, and (4) interconnection. These themes covered a wide range of technologies, including real-time systems, digital twins, AI-based assistance systems, autonomous manufacturing systems, wireless communication technologies, sensors, and modular machines. To present the concepts and issues behind these technologies, we describe the four design principles of a smart factory below.

First is the design principle of **information transparency**. Kagermann (2015) [69] stated that the current tide of innovation is driven by the Internet of Things (IoT), data, and services, where systems and objects communicate in real time. IoT may also require IT systems to be integrated through inter-organizational collaboration to enhance supply chain performance. Implementing MES/MOM allows access to the product's manufacturing information at the unit level because of its *traceability* functionality and consequent real-time information sharing, if required. The authors also stated that in the IoT, any "device can exchange information at high speeds with any other device or person anywhere in the world" [69].

Levermore *et al.* (2010) [70] presented an information system design for digitally connected enterprises. They recommended connecting proprietarily designed and administered enterprise databases of different firms to manage supply chain disruptions. This process would entail forming on-demand information supply chains through the interoperation of independent databases [70].

The great challenge that many supply chains face today, especially in the fresh food industry, is forecasting the supply. Poor forecasting costs billions of dollars in missed sales across industries [71]. If IT systems were to avoid the creation of producing siloed data repositories, supply chain performance would increase substantially.

In their work on defining responsive supply chains, Gunasekaran *et al.* (2008) [72] discussed IT and information systems as one of three main enablers of a supply chain that can cope with changing market requirements and increasingly complex enterprise settings in a networked economy. They explained the concept of *responsive supply chains* through the illustration reproduced in Fig. 8.

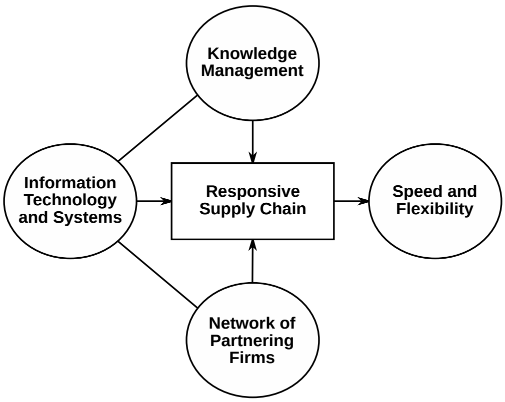

Fig. 8: Concept of responsive supply chains [72]

The ISA 95 standard guides the vertical integration using MES/MOM; it also enables the automation of information exchange within the enterprise [3].

The MES/MOM should be developed to allow the factory to not only retrieve production and process data in real time (from the field devices) but also enable sharing the information with other supply chain parties. Hence, MES/MOM must be connected to the IIoT to maximize everyone's data access. Given this scenario, the scope and role of MES in a smart factory for supply chain visibility needs further study.

Second is the design principle of **technical assistance**. Gorecky *et al.* (2014) [73] envisioned human–machine interaction in the Industry 4.0 era as taking the form of intelligent user interfaces. They proposed that humans will evolve to become "strategic decision-makers and flexible problem-solvers," such that a worker will be the last instance in the decision-making process. The worker will access learning assistance systems to retrieve the required information from the cyber-physical production systems [73].

Maedche *et al.* (2016) [74] stated that "there is a gap between users' abilities and available IT." The authors perceived a lag in the development of users' cognitive abilities compared to the increasing capabilities of IT. They proposed advanced user assistance systems to help users perform their tasks [74] and suggested that such systems would combine high degrees of interaction and intelligence. The authors thus also perceived a need for research to support users in their use of information systems.

There is large body of literature on chatbot applications, which are advanced user assistance systems, across various fields. An exception is the manufacturing field. However, some standards, such as ISA 101, recommend best practices for human–machine interfacing in manufacturing by covering menu hierarchies such as screen navigation conventions, pop-up conventions, and configuration interfaces to databases [75]. Artificial intelligence markup language (AIML) is a popular framework for designing chatbots, such as the chatbot platform Pandorabots. AIML is free and open-source.

Wu *et al.* (2008) [76] studied automatic chatbot knowledge acquisition via ensemble learning. Reshmi and Balakrishnan (2016) [77] implemented an inquisitive chatbot that correctly analyzed a user's query. Stoeckli *et al.* (2018) [78] reported their findings on the use of chatbots in an enterprise context through an example of social information systems (e.g., enterprise instant messengers such as Slack). Their results indicated that chatbots are powerful instruments to enable organizational automation. The authors recommended further research on enterprise platforms and organizational contexts.

In their state-of-the-art study on chatbots, Meyer von Wolff *et al.* (2019) [79] posed open questions to address in future research on chatbots in digital workplaces. Examples include "Which application areas are viable for chatbots in the digital workplace?", "How should chatbots be designed?", and "What are the resulting benefits of the usage of chatbots?" [79]

By contrast, research on the user aspect of MES/MOM is limited. This is despite the fact that MES/MOM is intended to interact with human users to aid them in smooth production management [80, 44]. However, the production workforce can make informed decisions with the help of AI-based intuitive assistant systems, such as chatbots for EIS. MES is viewed as a *manufacturing cockpit* [81] that could be a suitable candidate for chatbot applications. Next-generation MES design should accommodate a technical assistance system for its user interface in Industry 4.0.

Third is the **decentralized decision** design principle. Hatvany and Nemes (1978) [82], in their pioneering work on intelligent manufacturing systems, forecasted that systems would need to acquire resilience regarding unforeseen situations; systems can achieve this resilience by recognizing unusual situations in real time from large amounts of data. Hatvany and Nemes stated that research on AI tools offers potential for creating intelligent manufacturing systems.

Monostori and Prohaszka (1993) [83] discussed various methods for applying artificial neural network techniques in manufacturing through modeling and monitoring of turning and milling processes by incorporating sensors. Shen *et al.* (2000) [84] reviewed learning techniques for improving agent-based technologies for manufacturing systems. They proposed future work to study genetic algorithms and neural networks for new learning mechanisms.

McFarlane and Bussmann (2003) [85] presented rationales for manufacturing control, based on holonic manufacturing systems, for mass customization and market responsiveness. They mentioned autonomy, cooperation, self-organization, and reconfigurability as key properties of holonic manufacturing systems. They argued that the holonic control method serves reconfigurability due to the holons' modular approach that allows themselves to be altered.

Marik and McFarlane (2005) [58] advocated for agent-based technology as an alternative to the centralized systems common in manufacturing. They also illustrated the architecture of a distributed approach, as shown in Fig. 9.

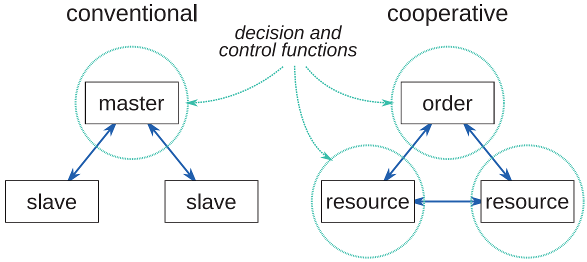

Fig. 9: Conventional and cooperative decision making [58, 26]

Machine learning tools offer promising solutions by making sense of the data generated from production. These tools are used for knowledge synthesis for industrial automation [86]. Furthermore, the revolutionary IIoT, in which objects are connected over the internet, paves the way for efficient intelligent manufacturing systems. Logged production data that is gathered from various IIoT devices can be used to present analytical solutions for optimized production execution for MES. However, traditional MES has a monolithic architecture. This architecture poses a problem for implementing distributed manufacturing control, and such architecture must be broken down to make way for software modularity and easy scalability.

In light of the above discussion, intelligent distributed control architectures can be considered for redesigning MES/MOM. Researchers can employ AI techniques to ameliorate the lack of decision support capabilities of MES [87]. Distributed information and decentralized self-organizing production are two essential steps in intelligent manufacturing control [85], and MES/MOM offers an opportunity to achieve both steps.

Fourth is the **interconnection** design principle. Weiser (1991) [88], in his pioneering work, introduced the term *ubiquitous computing*, which envisions computing happening on any device rather than only a desktop. A vast increase in the processing power of hardware components has occurred over the last decade; in addition, there has been a revolution of smartphones, which act as robust multi-media systems and minicomputers. The internet is an example of the connectedness that is possible between computers worldwide. Similarly, the IoT is an enabling infrastructure that consists interconnected devices.

Inflexible monolithic production systems have made the manufacturing sector slow to adopt a high level of interconnectedness. However, Zuehlke (2010) [89] stated that the smart factory initiative has developed projects based on principles of the (industrial) IoT to allow smart objects in a factory (and beyond) to interact based on semantic services. Similarly, Borgia (2014) [90] commented that the IoT allows smart objects not only to connect and interact but also to trigger actions via the internet.

In their literature review, Manavalan and Jayakrishna (2019) [91] described various opportunities of the IoT for supply chains in Industry 4.0. They identified IoT influences in supply chains as being still at a nascent stage, such that the industry is yet to exploit the opportunities afforded by IoT. To provide empirical evidence supporting the use of IIoT for end-to-end supply chain transparency, Zelbst *et al.* (2020) [92] analyzed data from 211 U.S. manufacturing managers to assess the impact of IIoT. Finally, Hazen *et al.* (2016) [93] argued that by leveraging the cloud and the internet, IoT can interconnect machines, devices, components, and users across multiple manufacturing sites in a supply chain.

Kagermann *et al.* (2013) [25] proposed that the functions of central information systems, namely ERP and MES/MOM, would be transferred to CPS. This would lead to the gradual dissolution of the hierarchical automation pyramid. Similarly, Jeschke *et al.* (2017) [94] stated that, "IIoT leads to the Industry 4.0."

The authors explained that the roots of IIoT date back to the 1970s, when the term *computer-integrated manufacturing* was coined. The authors listed the following reasons for the lack of successful implementation of these ideas in the past [94, p. 5]:

- Immature IT and communication infrastructure,
- Lack of computational power,
- Lack of data storage capacity,
- Limited connectivity and data transfer rates, and
- A lack of openness among software tools and formats for data exchange.

Modern computing devices have subsequently overcome many problems of data transfer rates and processing power, so the hurdles are different today. Boyes *et al.* (2018) [24] warned that although the IIoT connects field devices over a network, the underlying security challenges require a multi-layered security strategy around EIS, especially for IT/OT convergence. To support reconfigurability, we argue that MES/MOM should be designed with the ability to connect to any IIoT device in the factory easily and securely.

Smart factories need edge computing to solve the issues of latency and data overload in cloud computing. Shi *et al.* (2016) [95] described the edge paradigm as “processing the data at the edge of the network” and stated that edge computing is reliable and cost-effective. The authors proposed that the proliferation of IoT is driving edge computing; however, IIoT faces specific security challenges. Yu and Guo (2019) [96] conducted a survey on IIoT security and call for securing critical industrial control systems.

Similarly, Tuptuk and Hailes (2018) [97] explored the challenges around smart manufacturing systems. The authors argued that cyber-attacks, industrial espionage, and sabotage can have catastrophic effects on production and costs and could even lead to loss of life.

In the context of interconnection, OPC UA [98] is an open standard and protocol for machine-to-machine communication. It enables interoperability for devices and information systems among different vendors and contains a security model for securing the connections. The industry is increasingly using PLCs for Industry 4.0, and OPC UA can make interconnection easier due to its openness.

Although industrial cybersecurity standards such as ISA/IEC 62443 exist, there is a knowledge gap regarding security management methods using cryptography for low-power OT devices. (“Low-power” refers to the low computational power available for running cryptographic protocols.) Our impression from the literature review is that research is still nascent on the secure architectural design of MES/MOM, particularly with regards to securing the link between IT and OT devices on different ISA 95 levels.

Understanding the information needs of the manufacturing enterprise and its stakeholders is essential for the journey toward Industry 4.0. A valid design for MES/MOM should deliver both operational and business benefits. Furthermore, studying the properties of MES/MOM in the Industry 4.0 context can identify new opportunities. Therefore, we extended the scope of this study to fulfilling organizational needs instead of merely supporting the needs of existing manufacturing IT governance. In this regard, we posed the following question:

RQ2: How can MES/MOM be used with smart factory technologies to improve the performance of manufacturing operations management?

2.3 Contributing theory: Information systems development in IIoT

2.3.1 Positioning work in the operations management and information systems field

This thesis employs the concept of **smart factory design principles** to overcome the disconnect between the fields of operations management (OM) and information systems (IS). In *Design Principles for Industrie 4.0 Scenarios*, Hermann *et al.* (2016) [40] combined OM and IS characteristics within a single problem area to facilitate the design of future manufacturing systems. Therefore, this thesis does not speak of the solely OM or the IS research field, but rather both together.

One example of such a combination is that of EIS. Fundamentally, OM is concerned with a set of tools that a manufacturer can use to ensure effective business operations. Hence, IT and IS can be viewed as tools that are applied for business operations. Similarly, this thesis examines IIoT interconnectivity problems through MES/MOM design and proposes methods to improve the interoperability. This research problem is not well addressed in the MES/MOM literature. Figure 10 [43] presents the ideas behind such design, based on the issues discussed in Section 2.2.

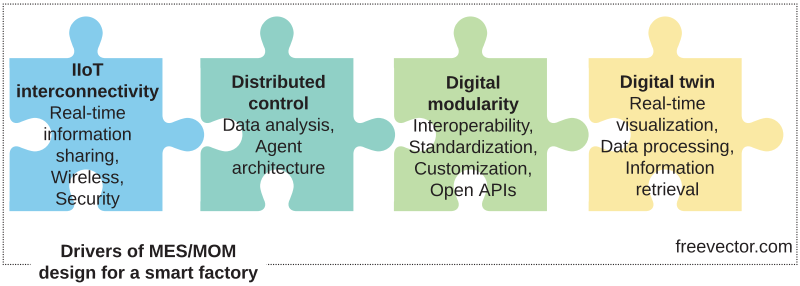

Fig. 10: Drivers of MES/MOM design [43]

Manufacturing operations management and ISA 95: MES, aka MOM systems, perform tasks related to production, inventory, maintenance, and quality, according to the ISA 95 standard. The International Society of Automation (ISA) is an authority in the industrial automation field that develops global standards for manufacturers. To solve the communication issues between the ERP and process control layers in enterprises, ISA developed the ISA 95 standard in 1990 to guide system development for interfaces to be implemented between enterprise and control systems. ISA 95 is a methodology that contains reference models and terminology to aid information exchange. It is divided into five parts, each containing hundreds of pages [15]:

Part 1: Models and terminology
Part 2: Object model attributes
Part 3: Activity models of manufacturing operations management
Part 4: Object model attributes for manufacturing operations management integration
Part 5: Business to manufacturing transactions

ISA 95 states that MOM has the following 12 functionalities [23]: (1) resource allocation and control; (2) dispatching production; (3) data collection and acquisition; (4) quality operations management; (5) process management; (6) production tracking; (7) performance analysis; (8) operations and detailed scheduling; (9) document control; (10) labor management; (11) maintenance operations management; and (12) the movement, storage, and tracking of materials. Figure 11 illustrates the levels of a functional hierarchy [23].

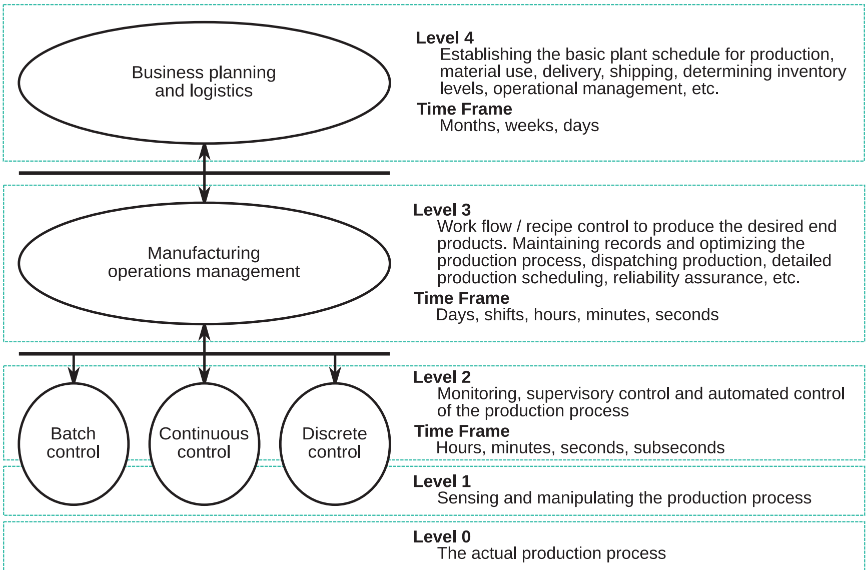

Fig. 11: The levels of the functional hierarchy according to ISA 95 [23]

Over the last two decades, MES/MOM has evolved to play two crucial roles in the factory [80].

1. Automated control: This role supports all forms of automation for activities related to the level three layer; it leads to humans working primarily on business-level activities in the factories. This perspective is in line with the vision of computer-integrated manufacturing.

2. Shop floor support: This role empowers humans to make decisions on the shop floor by giving them real-time insight into the production process.

Schmidt *et al.* (2011) [99] stated that MES/MOM takes a microscopic and granular view of production data in almost real time. The authors further suggested that MES functions can be integrated quickly and precisely in a new factory, whereas there is a challenge with brownfield deployments of MES/MOM due to its overlapping functions with an existing system [99].

Systems design: Rasmussen (2003) [100], in the *Encyclopedia of Information Systems*, described the process of systems design as follows: "The process of systems design includes defining software and hardware architecture, components, modules, interfaces, and data to enable a system to satisfy a set of well-specified operational requirements."

Requirements analysis is the first step of systems design; this involves examining the functional and non-functional requirements. Requirements elicitation techniques include interviewing and ethnography. Different kinds of information are gathered from the stakeholders about the proposed systems, with the aim of establishing the non-functional requirements [33, p. 115]. In this regard, Offermann *et al.* (2010) [101] listed *requirements* as an artifact type in IS design science.

An information system is usually built as a solution to address a set of problems that an enterprise is facing. End users mainly drive the development process to ensure that the system design matches their business needs [102, ch. 13]. Because the context of IS development in this thesis is a manufacturing enterprise, it is imperative to study the information needs of a factory and the manufacturing enterprise.

There are several academic perspectives on systems design in the OM field, especially for production systems design. Almgren (1999) [103] described a "modified" production system as a system that is subjected to a minor technical redesign, in contrast to a "new" system. The latter system undergoes a major technical redesign, which could imply a new factory layout and flows.

Systems engineering is a well-known transdisciplinary theory in systems design and has been used to design IS for factories. Ruffini (1999) [104] listed *design frameworks and strategies* as one of the holistic theories about systems design in OM. Duda and Cochran (2000) [105] suggested that the design elements of a manufacturing system must be linked to a manufacturing strategy – such as cost, quality, or flexibility.

While most of these theories are still applicable in modern-day systems design, it is no longer feasible to use only a traditional waterfall approach that follows a sequence of activities for systems development. Sureshchandra and Shrinivasavadhani (2008) [106] stated that moving from waterfall to agile methodologies, such as scrum methodologies, leads to iterative and shorter development cycles with higher visibility in a crisis-ridden business environment.

Furthermore, a MES/MOM system design must relate to a firm's strategy, such as the firm's manufacturing flexibility. This thesis proposes architectural design requirements to support RMS for a smart factory that prioritizes its manufacturing flexibility.

2.3.2 Potential research avenues for MES/MOM design

It is relatively easy to develop smart factory capabilities when designing a new factory from the start, which is known as a *greenfield* enterprise. However, manufacturing enterprises often seek to upgrade their existing sites to take advantage of smart factory technologies, which is referred to as a *brownfield* enterprise. This thesis focuses on designing a smart factory in a brownfield environment. Given the research issues mentioned in Sections 2.1 and 2.2, the two main focus areas for developing Industry 4.0 capabilities are as follows:

1. MES/MOM for information transparency
2. MES/MOM for the interoperable IS architecture for reconfigurability

In Table 2 below, the relevant issues related to MES/MOM development are summarized.

Table 2: Overview of MES/MOM design challenges related to Industry 4.0

Author(s)	**Challenges identified**
Jaskó *et al.* (2020) [14]	Need for MES to connect all components of CPS, lack of semantic interoperability, lack of ontological standards
Almada-Lobo (2016) [68]	Centralized and monolithic monitoring and control systems, large amounts of data, compliance requirements
Wunck (2019) [107]	Monolithic MES by a single vendor, the difficulty of MES customization, lack of demonstrated business case of smart manufacturing technologies, small lot size

Table 2: Overview of MES/MOM design challenges related to Industry 4.0 (continued)

Author(s)	Challenges identified
Koerber *et al.* (2018) [16]	Increased complexity of integrating machinery operations due to IIoT, need for a business case, ISA 95 not sufficient for digital integration, lack of strategic and organized approach to IIoT

The challenges listed in Table 2 indicate research gaps regarding the future of MES/MOM development in IIoT. This thesis addresses those topics, with the goal of implementing the smart factory. The studies listed in Table 2 also highlight opportunities to deduce the MES/MOM design requirements for IIoT interconnectivity based on ISA 95 principles. Furthermore, empirical research on an IIoT-connected MES/MOM is also lacking. In response to these challenges, we posed the following question:

RQ3: What design choices are necessary for MES/MOM to support the smart factory implementation process in a brownfield environment?

2.4 Summary

This chapter has presented the research directions in smart factories and MES/MOM. It has also identified the dominance of computer science-based contributions in the field of MES/MOM development, which adopt a narrow technical approach. There have been few attempts to present a holistic MES/MOM design that operationalizes a smart factory. Our literature review instilled a sociotechnical systems perspective to such research, and we found almost no real-world case studies on MES/MOM application for smart factory development. This finding indicates the need for empirical research to develop key design principles for MES/MOM in a smart factory, which this thesis aims to address in the areas of IIoT and reconfigurability.

Chapter 3. Research methodology

This chapter links the philosophical perspectives to the epistemological choices of the research, which results in applying a design science approach for the thesis. The chapter outlines various research activities during the PhD project and sheds light on the rationales behind the selected methods.

3.1 Philosophical research position

The beliefs behind research projects vary broadly and could include post-positivist, constructivist, transformative, and pragmatic beliefs. These beliefs greatly influence the research practices and the motives behind the choice of qualitative, quantitative, or mixed-method approaches [108]. Creswell and Creswell [108] explain the four philosophical world views as follows:

1. The postpositivist view represents thinking after positivism and does not support the idea of the absolute truth of knowledge. It is reductionist in nature where the problem is broken down into small, discrete sets to test the hypotheses. This approach to research leans more toward quantitative methods and follows a *scientific method*. Phillips and Burbules (2000) [109] state that the knowledge here is shared by data, evidence, and rational considerations.

2. The constructivist view is typically a qualitative research approach that is often combined with interpretivism, where the researcher poses broad and open-ended questions to make room for input from people through interactions and discussions. Crotty (1998) [110] believes that through inductive research, constructivism generates meaning from the data gathered via interaction with the human community.

3. The transformative view contains a class of researchers that are critical theorists (e.g., Marxists and feminists), predominantly learning from the experiences of the marginalized groups and calling for an action plan beyond a constructivist stance. Mertens (2010) [111] explains that the transformative view follows a research inquiry that begins and focuses on a social issue and involves participants throughout the research process.

4. The pragmatic view does not exclusively commit to qualitative or quantitative approaches but allows the researchers to draw liberally from either of these approaches; therefore, it is more suitable for mixed methods. Rossman and Wilson (1985) [112] suggest that researchers mainly focus on the research problem and use available approaches to understand it.

IS research has been dominated by two research paradigms: positivism and interpretivism [113]. While positivism suffers from the inability to extrapolate findings to a context different from the studied sample, interpretivism focuses on context-based knowledge and challenges the generalizability of findings [113].

Apart from the research philosophies outlined above, Roy Bhaskar [114] formulates critical realism as an alternative to positivism and interpretivism by inculcating the characteristics of both views to form a new paradigm. Bhaskar and Simon (1977) [115], with an example of problem-solving in the thermodynamics domain, explain the importance of combining both standard problem-solving techniques and subject matter knowledge to arrive at a solution.

Furthermore, Bhaskar argues that knowledge should be generated based on clear ontology and must identify causal mechanisms. On this account, Syed *et al.* (2010) [116] believe that critical realism can address the rigor-relevance gap in research by, for example, drawing explicit links between IS technology implementations and their outcomes [117].

We ground our research in critical realism, since it has the power to develop in-depth causal explanations. We view MES/MOM as sociotechnical systems and are interested in studying the causal role of enterprise, user, and technological factors on MES/MOM performance.

This thesis takes a qualitative approach with abductive reasoning and draws from the IS methodology of design science to generate prescriptive knowledge, which is expected from research projects in engineering sciences [21]. Furthermore, design science research is also listed as one of the four forms of engaged scholarship, where Van de Ven (2007) [118] describes *engagement* as a relationship that entails negotiation and collaboration between researchers and practitioners to produce knowledge that advances science while enlightening the practice.

3.2 Design science framework

The PhD project requires design demonstrators to provide empirical grounding as part of its scientific exploration. The design demonstrators translate "scientific activity from the laboratory to the market" [119]. The design science research (DSR) methodology can satisfy this requirement as it uses *design* as a research method or technique with iterative *circumscription* [120] to generate scientifically legitimate knowledge.

It is well-established that technology entails not just the product but also its design principles, which are also identified as outputs of DSR [15]. Design principles are used to specify design knowledge in an accessible form and take the shape of "prescriptive statements that show how to do something to achieve a goal" [121]. Gregor *et al.* (2020) [121] stress the applicability of prescriptive knowledge in design situations where implementers require guidance.

We chose DSR because it contributes to organizational and human aspects of IS and creates learning through building innovative artifacts [16]. Simon (1996) [21] makes a clear distinction between *natural science* and *science of the artificial (design science)* and writes [21, p. 4]:

> As soon as we introduce "synthesis" as well as "artifice," we enter the realm of engineering. For "synthetic" is often used in the broader sense of "designed" or "composed." We speak of engineering as concerned with "synthesis," while science is concerned with "analysis." Synthetic or artificial objects and more specifically prospective artificial objects having desired properties are the central objective of engineering activity and skill. The engineer, and more generally the designer, is concerned with how things ought to be how they ought to be in order to attain goals, and to function.

Simon (1996) [21] further explains that engineering, medicine, business, architecture, and painting are not concerned with how things are but with how they might be (i.e., design). Figure 12 illustrates the activities involved in the PhD research that contribute to the three domains of the design science framework. Several iterations are executed in the form of industrial demonstrators to improve the results. We follow Hevner's [122] three-cycle view to organize our research contributions according to the application, research (design), and knowledge domains of OM and IS.

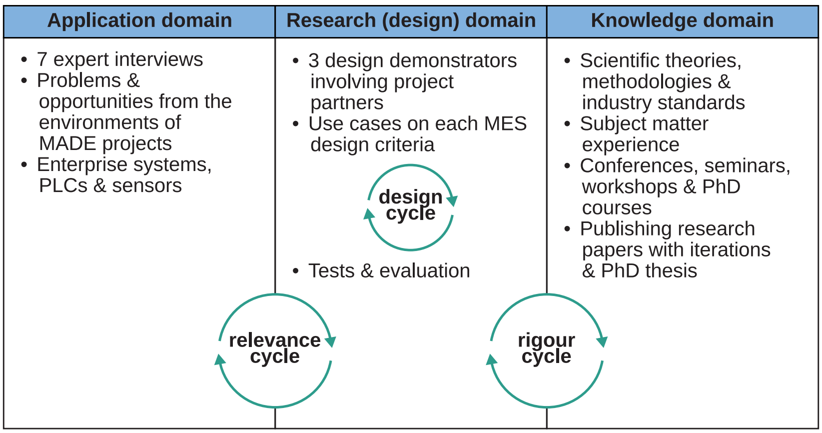

Fig. 12: Activities of the PhD research, set in the design science framework of Hevner [123]

Design criteria are drawn from the smart factory design principles and validated with use cases and simple experiments using prototype software systems. Our artifact type is mainly *models* [17], which we present based on the design requirements. We also instantiate the high-level architectural design of MES/MOM in the *Smart Lab*. Finally, we derive design principles of MES/MOM as an outcome of this research. Our process steps in DSR can be decomposed into three key iterative phases:

- **Problem awareness and suggestion phase:** Findings from the qualitative data collected from interview research helped conceptualize smart factory capabilities with MES/MOM.
- **Synthesis phase:** Experiments on AAU *Smart Lab* setup, prototyping, simulations, and data interpretation using tools and models (e.g., UML for high-level architectural design) helped develop artifacts.
- **Evaluation phase:** The three use cases covering each design principle for MES/MOM and the data models for the prototype software systems (developed for the industrial demonstrators) showed us the constraints and requirements that MES/MOM must satisfy to enable the smart factory.

3.2.1 Project mapping, research activities, and iterations

The research activities and the appended papers published between 2018 and 2021 are supported by three demonstrators on vertical integration, interoperability, and order customization. They span two research projects, both funded by the *Innovation Fund Denmark* – MADE Digital WP 5 and MADE FAST, where FAST is an acronym for flexibility, agility, sustainability, and talent. These projects are concerned with enabling smart and integrated factories by working closely with large-scale global manufacturers based in Denmark. Figure 13 presents the timeline of publications and illustrates the research activities that supported them, showing the iterative nature of our research. We also group the publications by the research questions.

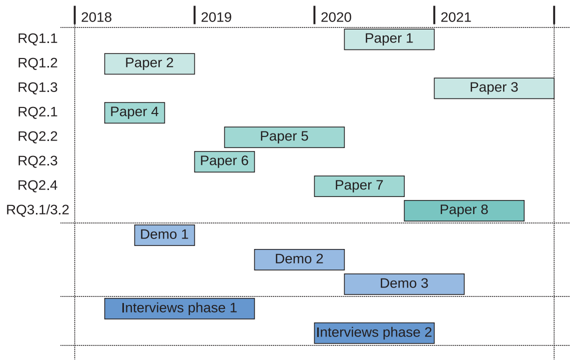

Fig. 13: Timeline of publications and research activities

3.2.2 Method selection

The interdisciplinary nature of Industry 4.0, reviewed in Chapter 2, indicates that no single theoretical perspective can sufficiently justify the knowledge creation on enabling the smart factory with an IS. Furthermore, generalizing the smart factory needs to apply MES/MOM requires an in-depth understanding of the organizational and contextual factors on technological capabilities and reconfigurability needs. A single research method cannot cover all the phases of design science inquiry into enabling the smart factory. Therefore, we choose a combination of research methods. Table 3 outlines the research methods deemed helpful for the appended papers and presents the choice of methods for the research objective of each paper.

Table 3: Overview of selected methods for each article

Paper	Research objective	Research design and methods used	Contribution type
1	Develop a framework for reconfigurability for smart factory using MES/MOM	Exploratory study, using QFD analysis for a *Smart Lab* case [124, 125]	Assigning reconfigurability objectives for MES/MOM functionalities (requirement analysis)
2	Review the MES/MOM role in Industry 4.0	Systematic literature review, developing hypotheses [126]	Review of the evolution of MES/MOM in Industry 4.0 and theoretical propositions
3	Identify themes and develop a conceptual model for smart factory capabilities	Thematic cross-case analysis, 6 cases from 7 interviews with MADE companies [127, 128]	Second-order themes and illustration of synergies between reconfigurability needs and technological capabilities (requirement analysis)

Table 3: Overview of selected methods for each article (continued)

Paper	Research objective	Research design and methods used	Contribution type
4	Develop a position on enterprise integration using a smart factory design principle of *information transparency*	Exploratory study using a single case study to verify claims [127, 129]	Position paper
5	Use smart factory design principle of *technical assistance* for MES/MOM design	Prescriptive study: selective literature review, empirical research, and an experiment [125]	Systems analysis and architectural design
6	Develop a position on interoperability using a smart factory design principle of *decentralized decision*	Exploratory study: proposal of multi-agent system architecture for MES/MOM [130, 125]	Position paper
7	Use the smart factory design principle of *interconnection* for security in MES/MOM design	Prescriptive study: QFD for requirements [125, 124, 122]	Systems analysis and architectural design
8	Develop design principles for MES/MOM	Prescriptive study: QFD for requirements [125, 124]	Systems analysis, architectural design, and design principles for MES/MOM

3.3 Research design

Design science research uses the richness of the phenomenon under study and its connection to the real-life context to develop innovative artifacts and yield impactful results. Yin [127] argues that case studies allow for in-depth analysis of contemporary phenomena, where the evidence converges from multiple data points. Therefore, most of the appended papers use case study research design, which is also a preferred method for OM problems due to it being a field-based method [131]. Case studies helped answer the *how* questions of MES/MOM design and application for a smart factory. Yin [127] also explains that the *what* question is also a form of a *how much* and *how many* line of inquiry. The appended papers that use case studies complied with the processes suggested by Yin [127] for case study research.

3.3.1 Expert interviews and field studies for requirements

Interviewing is also one of the requirements elicitation techniques for systems design, and Sommerville [33] states that eliciting domain knowledge through interviews is difficult. Kvale [128] argues that conversations are the most basic form of human interaction, and interviews are a powerful tool for systematic knowledge production (e.g., Freud's psychoanalytic interviews and primary empirical evidence for Piaget's work). Therefore, we used interviews during our problem awareness phase of MES/MOM design, following the seven stages of interview research suggested by Kvale [128]: thematizing, designing, interviewing, transcribing, analyzing, verifying, and reporting. This ensured the *rigor* factor.

The PhD project's partners are large-scale global manufacturing companies, currently tackling MES/MOM-related production data management initiatives for Industry 4.0. Inputs from the project partners ensured the relevance aspect of the research problem. Hence, an interventionist approach is chosen to gather qualitative data (predominantly semi-structured interviews from case companies) to document the requirements. Table 4 presents the details of the cases. Findings from this research method directly answered **RQ2.1**, **RQ1.2**, and **RQ1.3**, and indirectly benefited **RQ3.1**, **RQ2.2**, and **RQ2.4**.

3.3.2 The *Smart Lab* for requirements specification

Working with a concrete case study allows for a better understanding of the smart factory's operation, challenges, and components and their interaction. For that purpose, this thesis uses the *Smart Lab*. The lab is a "small Industry 4.0 factory" [125] and allowed studying the IT/OT convergence problem in detail through connections between MES and PLCs in an IIoT environment.

The *Smart Lab* (see Fig. 14) by Festo is a learning cyber-physical production line that serves as a model of a smart factory for training and research. The design principles we hypothesized for MES/MOM are tested on the *Smart Lab* using demonstrators with industrial applications. This experimental setup for scientific exploration served the *rigor* of our research. The demonstrators designed and developed prototype software systems for smart factory solutions based on a homegrown AAU open-source MES/MOM. This is done in close collaboration with the project companies to ensure the *relevance* factor. The

Table 4: Details of the case studies [65]

	Smart factory vision	Case selection criteria	Respondent details	Data collection approach	Data collection protocol and triangulation
Case 1: Dairy products	Digitalize supply chains to create value from the IIoT data [132]	Open standard ISA 95 data models, RAMI 4.0, and an enterprise IoT platform	Senior IT Architect (MES & Automation), Product owner	Interview, cloud manufacturing workshop, field visit	• 55 min interview on Skype for business in March 2018 • Two one-day workshops in 2018 and 2019 involving formal presentations on the company's Industry 4.0 strategy and MES roll-out, followed by a discussion • Company documents, annual reports, and company website
Case 2: Wind turbine and electrical equipment	Market development by leveraging data processing and analytics expertise to enhance digital capabilities [132]	Strategy for MOM and a core MES platform roll-out	Head of global IT	Interview, factory visits, workshops	• 75 min interview on Skype for business in March 2018 • One-day workshop in 2018 involving formal presentations on the company's MOM architecture • Company documents, company website, annual reports, and email correspondence for validation
Case 3: Meat processing of pork and beef	Be a knowledge-driven enterprise by discovering, articulating, and utilizing the data [132]	Strategy for shop floor solutions to improve fresh food supply chain planning using real-time information	Director, solutions and innovation, Global IT	Interview, warehouse visit	• 90 min interview on Skype for business in March 2018 • Follow-up correspondence with IT department and supply chain planner for case validation • Company presentation on shop floor solutions with back end MES, validation from external sources such as Industrial PhD students, annual report, and company website
Case 4: Energy equipment	Utilize IoT data for better decision-making in design, supply chain, training, logistics, and equipment monitoring	Business unit with fully mass customized production platform and the goals to have scalable IT architecture for global factory networks	Director for global smart automation systems	Interview, cloud manufacturing workshop, project meetings, factory visits, design demonstrator in winter 2019	• Agile approach open innovation project in 2019 for 6 months with monthly design sprints and weekly status discussions • 1 hour interview on Skype for business in January 2019 • A one-day workshop in 2019 involving formal presentations on the company's cloud architecture and system landscape to scale up Industry 4.0 capabilities • Email correspondence and company reports for validation
Case 5: Electric actuator equipment	Have a digital twin infrastructure for automatic data collection from products in the market	Goals to reduce changeover times and a strong focus on enterprise architecture	Project engineer, digital production	Interview, cloud manufacturing workshop, project meetings, design demonstrator in winter 2019	• Agile approach open innovation project in 2019 for 6 months with monthly design sprints and weekly status discussions • 1 hour interview on Skype for business in December 2019 • Two one-day workshops in 2019 and 2020 involving formal presentations about the company's projects on "smart integrated factory" and "paperless production" • Email correspondence and company articles on IT strategy in an internal magazine for validation
Case 6: Plastic toys	Become a data-driven company, mainly to optimize production equipment and maintenance	Building logic into systems to handle the synchronization of orders, edge analytics for machine-level automation, and better supply chain management	Two senior solution architects	Interviews, follow-up interview, virtual factory visit, design demonstrator in winter 2020	• Agile approach open innovation project in 2020 for 6 months with monthly design sprints and weekly status discussions • Two 1 hour interviews on MS teams in June 2020 • Company website, annual reports, internal documentation, master student projects at AAU smart production lab based on the company • Email correspondence and company reports for validation

AAU open-source MES platform takes the form of a module for Odoo, an open-source platform for business applications that can integrate to become a complete ERP and a basic MES/MOM.

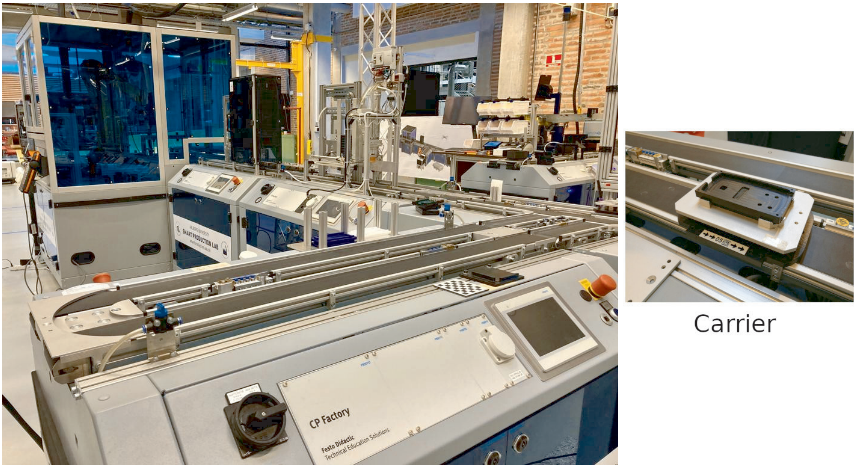

Fig. 14: The *Smart Lab*, an Industry 4.0 learning factory in Aalborg, Denmark

The *Smart Lab* is composed of several production modules with two workstations each, each of which performs one step of manufacturing the *Smart Lab*'s products (dummy mobile phones). The workstations are connected by a conveyor belt, on which several carriers run through the *Smart Lab* in a loop. The products are assembled on these carriers as they pass by the workstations [43].

MES/MOM and ERP: The role of the ERP is taken by Odoo (see Fig. 15), running on the cloud. The MES/MOM functionalities are served by both Odoo's built-in manufacturing module and the custom AAU open-source MES module [43]. This allows studying which functionalities of MES/MOM should interact with the IIoT platform and devices and how they do it.

IIoT platform: In place of a full-blown IIoT platform, a custom middle layer script written in Python and running on a local machine serves as an intermediary between the IIoT devices and the MES/MOM.

IIoT devices: The *Smart Lab* uses Festo CECC-LK PLCs to control the workstations. These PLCs take the role of IIoT devices. They connect to the machine running the IIoT platform script via Ethernet. The PLCs represent the typical properties that an IIoT device may have, thus allowing us to derive requirements for and study the feasibility of hypothetical design principles.

Communication: When a carrier arrives at a workstation, it is identified by the station's PLC via radio-frequency identification (RFID). The station then

Fig. 15: Home screen of Odoo ERP/MES [43]

sends the carrier's identifier to the MES (through the IIoT platform script), which responds with the list of operations, if any, that need to be executed on this carrier. Once these operations are carried out, the PLC informs the MES about the completion, which then responds with the instruction to send the carrier to the next station when it is ready.

3.3.3 Systems analysis and design

We use quality function deployment (QFD) and UML as tools to derive and communicate our research findings on MES/MOM design. These tools support the process of MES/MOM system modeling, including the MES/MOM data model design based on ISA 95.

System modeling is the act of developing abstract models to represent a system using graphical notation [33, p. 140]. These models are beneficial for engineers to discuss design proposals with the stakeholders and can partially implement the systems in a model-driven approach [33, p. 140]. Sommerville [33] writes that

- an abstraction picks the most essential system characteristics and deliberately simplifies the system design, and
- graphical notations can be used flexibly, and details (and rigor) of the notation can be calibrated based on how it is intended to be used.

QFD for translating design requirements between domains: QFD [124] was first developed for industrial engineers in Japan in the late 60s. It is a method for translating high-level requirements and customer desires for a product or a system to low-level design requirements and technical characteristics. It uses a tool called the *House of Quality*, which consists of a matrix with rows corresponding to high-level requirements and columns corresponding to low-level requirements. Its entries show how much each low-level requirement contributes to each high-level requirement. This thesis uses QFD to derive design requirements for MES/MOM in a smart factory, which helps present design recommendations. Findings from the QFD analysis method directly answer **RQ1.1**, **RQ3.1**, and **RQ2.4** and indirectly serve the research objective of **RQ1.3**.

UML for representing system models and architectural design: UML is a standardized graphical language for system modeling, mainly in software engineering. It consists of 13 diagram types, roughly divided into [33, p. 139]

- structural diagrams, which model the components of a system and their relationships, and
- behavioral diagrams, which model the dynamic behavior of a system.

This thesis contributes mainly toward the structural improvements of MES/MOM in a smart factory. Therefore, we use structural UML models such as class and object diagrams to show the high-level architectural design of MES/MOM and their relationships with other IT and OT systems in a smart factory. **RQ3.1** and **RQ2.4** are predominantly answered through UML representations, apart from the usual text-based statements to prescribe the design.

3.3.4 Evaluation

The design requirements MES/MOM must satisfy to comply with the Industry 4.0 paradigm are extrapolated using the experience from demonstrators based on the AAU open-source MES platform. Finally, based on the knowledge derived from the design, a normative theory is developed on the properties of MES/MOM for smart factory capabilities. During the three demonstrators, we collaborate closely with the project companies and receive industry feedback at every step of the design process to evaluate our MES/MOM model applicability.

Moreover, the demonstrators follow the agile methodology (scrum) underpinned by design thinking. This methodology is suitable for improving already existing MES/MOM, where our agile team breaks the complex demonstrator project tasks into smaller and manageable design sprints for multiple iterations. Our two-week design sprint ensures constant feedback from the practitioners and improves the design accordingly. Hence, a strong evaluation is guaranteed through the scrum framework from the conception of the PhD project.

3.3.5 Research quality

Research quality refers to the rigor of scientific research and is necessary to ensure the trustworthiness of findings. We explain the *trustworthiness* of our research using the stringent four-dimension criteria set by Lincoln and Guba [133] for qualitative research:

1. **Credibility:** To ensure the truthfulness of the findings, we follow a strict internal validity mechanism by constant engagement with the project practitioners and disseminating the findings at several stages of case research and demonstrator projects.

2. **Transferability:** To ensure the applicability of the findings in contexts different from the one studied in this PhD, we ensure external validity through cross-case analysis. This step allows us to generalize the findings on MES/MOM design requirements such that the prescriptive knowledge on MES/MOM design can cater to any context that enables the smart factory with MES/MOM.

3. **Dependability:** Furthermore, the rigorous peer review process we faced while publishing the appended papers ensures the validity of contribution to the theory and assures that the findings are reproducible.

4. **Confirmability:** To avoid biases in the research process, we triangulate the data inputs that feed the research process. This ensures that project stakeholders and research networks shape the findings on MES/MOM design.

3.4 Summary

This thesis uses a design science framework to make architectural design recommendations for MES/MOM by developing design principles. This chapter justifies the design science approach as a means of inquiry for this research and formalizes the research process. Research in MES/MOM design for smart factories has only to a small extent been studied empirically with case inputs from practitioners. Therefore, this chapter presents the research strategy of using interviews to build artifacts and generate prescriptive knowledge in this complex research domain, which has characteristics of both IS and OM. Chapter 4 reports the findings from this interventionist investigation.

Chapter 4. Research findings

This chapter summarizes the eight appended papers, briefly describing the background, methodology, and implications of each paper and listing the questions the paper attempts to answer.

4.1 Smart factory capabilities: A conceptual framework

Paper 1: Exploring Reconfigurability in Manufacturing Through IIoT Connected MES/MOM

S. Mantravadi, J. S. Srai, T. D. Brunoe, and C. Møller, "Exploring Reconfigurability in Manufacturing Through IIoT Connected MES/MOM," in *2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, IEEE, Dec. 2020, pp. 161–165. DOI: 10.1109/IEEM45057.2020.9309989

Background: A smart factory is expected to support future manufacturing needs such as reconfigurability, which pertain to short product life cycles and high product variety. These goals draw from the theories in manufacturing flexibility. The supply chain disruptions caused due to the COVID-19 pandemic made manufacturers realize the value of reconfigurability; therefore, manufacturing flexibility has lately become a key competitive priority for many enterprises. We focus on establishing reconfigurability as a capability of a smart factory.

Since we are concerned with the research on MES and its implementation in IIoT that requires the integration of IT and OT, we study the problem of how MES/MOM could be implemented for Industry 4.0 to support reconfigurability goals. Our impression from the literature is that MES/MOM design and implementation for reconfigurability is still a developing topic. Its role for enabling enterprise operations in Industry 4.0 is still uncharted since business and shop floor have traditionally used different action plans. This problem has become a significant roadblock for MES/MOM development and usage in Industry 4.0.

Methodology: To establish a common understanding of making a smart factory reconfigurable, we developed a framework to define reconfigurability for a smart factory. Since reconfigurability's scope extends beyond RMS, and its definition is attaining a broader scope, we use mass customization concepts in a factory changeability context to define low-level reconfigurability at operative and tactical levels. High-level reconfigurability in a supply network context is used for the strategic level. The *Smart Lab* case is used as a "small Industry 4.0 factory" to obtain requirement specifications. For requirements analysis, the QFD method is used, and *Smart Lab* serves to write user stories and features on reconfigurability. An example of a user story in the *Smart Lab* on low-level reconfigurability is [134]:

> **As a** shop floor worker
> **I want (the feature)** to change the number of fuses put into a phone based on the manufacturing instructions with minimum effort or delay
> **So that** I can produce different versions of phones

Implications: The study partly answers **RQ1** and explains the necessity to align MES/MOM functionalities for reconfigurability goals. This paper further contributes to establishing a future research agenda on the topic. The reconfigurability assessment tool developed in this paper can promote IT/OT integration by bringing both departments to the same table to discuss and mutually chalk out an MES implementation plan.

This paper aims to answer the following question [134]: "How do MES functionalities in IIoT support or limit reconfigurability in manufacturing?" (**RQ1.1**)

- Reconfigurability approaches using MES functionalities in Industry 4.0 are developed in this paper. By providing a framework of assessment, we also identify the relative importance of each functionality for each reconfigurability goal. The *Smart Lab* case attains high percentages of importance for scheduling and performance analysis with 20% and 22%, respectively.
- The QFD template in Fig. 16 is a reconfigurability assessment tool for smart factory development, where theoreticians and practitioners can use the template to get scores based on their state of IS and priorities.
- Findings indicate that besides supporting low-level reconfigurability goals through production execution, MES functionalities can also reconfigure the business operations in a manufacturing enterprise. However, the high-level reconfigurability is challenging because manufacturers must first understand where and how to apply MES. Due to improved real-time production data collection in IIoT, MES functionalities present opportunities for supply network reconfiguration.

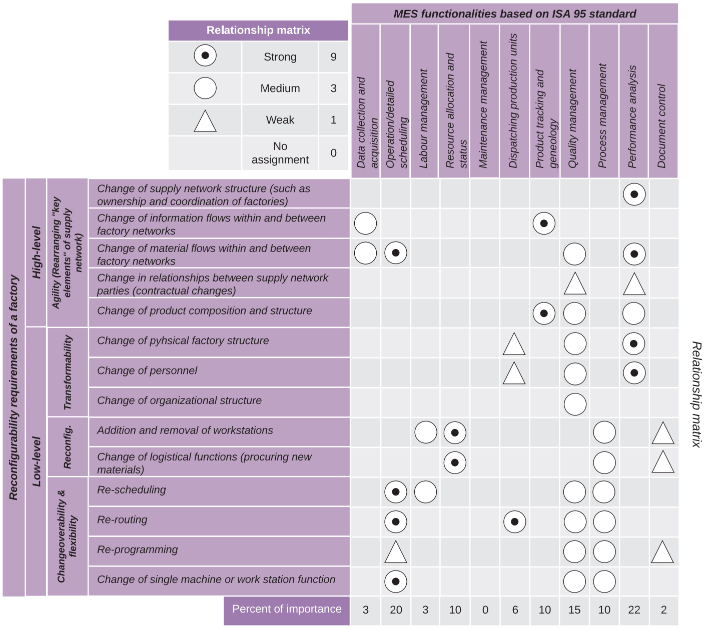

Fig. 16: House of quality (QFD) matrix to link MES functionalities with reconfigurability requirements [134]

Paper 2: An Overview of Next-generation Manufacturing Execution Systems: How important is MES for Industry 4.0?

S. Mantravadi and C. Møller, "An Overview of Next-generation Manufacturing Execution Systems: How important is MES for Industry 4.0?" *Procedia Manufacturing*, vol. 30, pp. 588–595, 2019. DOI: 10.1016/j.promfg.2019.02.083

Background: To achieve a competitive advantage, many manufacturing companies are increasing their investments in technology-enabled initiatives to face future volatile markets [59]. Manufacturing enterprises are also increasing their investments in manufacturing IT, including their EIS that support the information flows, business processes, and data analytics. Romero and Vernadat [10] classify EIS into six types: (1) enterprise resource planning, (2) supply chain management, (3) MES, (4) customer relationship management, (5) product lifecycle management, and (6) business intelligence. Owing to the Industry 4.0 paradigm and its enhanced data collection mechanisms from production operations, manufacturers can plan and execute their production better by utilizing their EIS, such as MES/MOM. More empirical research is needed on why and how manufacturing enterprises are driving the MES evolution for Industry 4.0.

Methodology: First, a systematic literature review is conducted using the protocol suggested by Moher *et al.* [126] to flow information through different phases of a systematic review. The review is done on the latest research contributions on MES. Databases such as Google scholar and Scopus are used to study literature from 2010–2018. Keywords such as MES, MOM, ERP, Industry 4.0, smart factories and smart manufacturing are searched. Second, to empirically support the hypotheses on MES's role in Industry 4.0, a multiple case study approach is followed [127], as it is a highly trusted method to develop new theories in OM [131]. The case companies are a large Scandinavian manufacturer of dairy products, a large Danish slaughter house, and a prominent player in renewable energy headquartered in Denmark.

Implications: The paper guides the theoreticians and practitioners by presenting an overview of MES as a tool to implement Industry 4.0 initiatives and how it can be designed for Industry 4.0. Future research directions on the topic are discussed to support the manufacturing industry through innovative software-enabled solutions.

This paper aims to answer the following question [132]: "What is the role and importance of MES/MOM in Industry 4.0?" (**RQ1.2**)

- A systematic literature review is done on "Manufacturing execution systems" to understand the evolution of MES in the digital transformation era. Studies on MES with links to Industry 4.0 objectives are mapped accordingly.
- The findings from both literature review as well as the cross-case analysis of data collected from the three manufacturing companies are used to verify the below hypotheses:
  - H1) MES software is crucial to enable smart factories. Thus, it plays a crucial role in Industry 4.0 manufacturing systems.
  - H2) Manufacturing enterprises will take more initiatives to invest in MES to serve their future factories.
  - H3) Next-generation MES can improve process performance through *visibility* in manufacturing operations.
- The paper concludes that next-generation MES is a process digital twin of future factories due to its ability to connect in real time and provide a digital image of the manufacturing process. This feature can also aid in optimizing business performance. The traceability function of MES/MOM can be further used to involve customers in the production design phase and lead to supply chain transformation through enterprise integration.

Paper 3: Application of IIoT-connected MES/MOM for Industry 4.0 supply chains: A Cross-case analysis

S. Mantravadi, J. Srai, and C. Møller, "Application of IIoT-connected MES/MOM for Industry 4.0 supply chains: A Cross-case analysis," *Computers in Industry*, for submission

Background: Industry 4.0 states that manufacturing enterprises must use their digital capabilities to transform their shop floors into a marketplace for capacity [68]. This implies that the collected data must be analyzed to enable a data-driven enterprise. Therefore, the MES/MOM development needs to have a blueprint or an architecture determined before implementation and the domain requirements can be elicited (and analyzed) iteratively by interacting with the stakeholders [33]. Our selective literature review on building reconfigurability using Industry 4.0 principles found few empirical studies that deduced the design requirements for MES/MOM to support reconfigurability.

Methodology: Interviewing is a popular technique for requirements elicitation used in the software development field. It is also a research method for systematic knowledge generation for qualitative studies. We use a semi-structured interview research design for this paper. We follow Kvale's seven-stage framework of interview research [128]: thematizing, designing, interviewing, transcribing, analyzing, verifying, and reporting. The selection criteria of interviewees for expert interviews are from five very large (>10,000) and one large (around 2,000 employees) global manufacturing companies. A cross-case analysis from case study research is followed to determine the design requirements to derive second-order themes from the empirical data.

Implications: Besides answering the research question, the findings help expand the conceptual framework for smart factory capabilities. The findings also contribute to developing a normative theory for MES/MOM architectural design. Figure 17 illustrates the steps toward achieving these goals to enable Industry 4.0 supply chains. The case findings are also used to compare the lab observations.

This paper aims to answer the following question [65]: "What is the conceptual framework of smart factory capabilities with IIoT-connected MES/MOM, and how could MES/MOM be designed to support reconfigurability in manufacturing?" (**RQ1.3**)

- The paper explores how next-generation MES/MOM should be developed and used in IIoT to increase manufacturing flexibility. We use empirical data collected via six case studies to perform cross-case synthesis (see Table 5), primarily through seven semi-structured interviews.

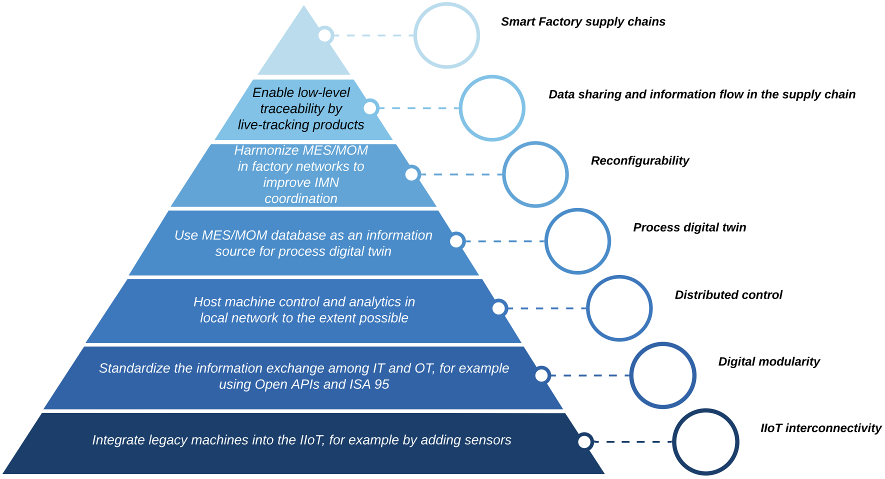

Fig. 17: Steps to enable the smart factory with IIoT-connected MES/MOM [65]

- The paper develops a conceptual framework for smart factory capabilities (see Fig. 18). Gray boxes represent the dimensions of interest, which also are the coding dimensions for thematic analysis.

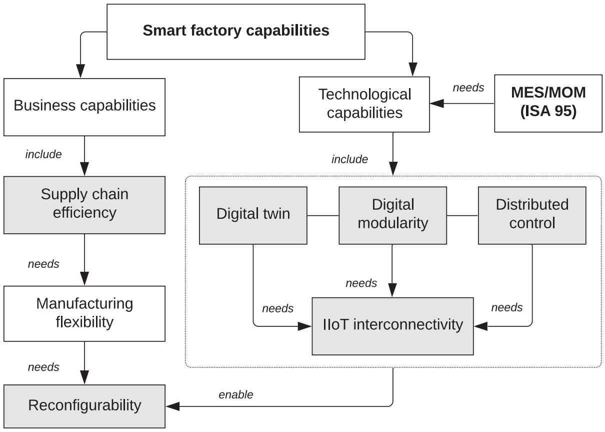

Fig. 18: Conceptual framework for smart factory capabilities [65]

Table 5: Summary of cross-case analysis of six cases using Nvivo [65]

Coding dimension	Case 1: Dairy products	Case 2: Wind turbine and electrical equipment	Case 3: Meat processing of pork and beef	Case 4: Energy equipment	Case 5: Electric actuator equipment	Case 6: Plastic toys	Second-order themes
Supply chain efficiency	The company aims to own the data, including the suppliers' data.	The company aims to have digital solutions with a focus on **global traceability and genealogy**.	Real-time scheduling and making a daily plan on what to produce could be achieved using **data extracted from shop floor** solutions. **Traceability** of all material movements.	**End-to-end data visibility** and **traceability**	The company aims to reduce stock with better forecasting, for which they are looking into using **improved information sharing**.	Improving planning by implementing **traceability at lower levels**	Enable traceability at material & component level (2,3,4,6) Real-time information sharing (3,4,5)
Recon-figur-ability	They need to reconfigure a live system without stopping production. Also, IT systems integration with acquisitions to ensure **internal supply network coordination**	Their many legacy machines make it difficult to **reconfigure** the work stations and **factory structure**; therefore, they want to enhance machine connectivity.	They want a backend MES solution to improve scheduling efficiency on the shop floor. They want increased **data visibility** to support the distribution of orders to sites for better use of slaughtered animals.	They want to optimize **business processes between them and their vendors** to **improve the speed** and quality of material supply for mass customization.	They are digitizing material allocation and workflow planning to improve delivery speed and **reduce change over time** by investing in better shop floor planning software.	The company aims to empower human users and have operator assistance for **changing** colors, shapes, molds, and ancillary equipment in their process. They have a good level of **supply network coordination** due to a globally harmonized IT infrastructure.	Reduce changeover time and increase delivery speed (4,5) Supply network coordination using IT (1,2,4,6)
Process digital twin	Real-time data via the **MES layer** and vertical integration. Plans to implement cloud-based digital twin for visibility of factory processes.	To have dashboards and visual factory at MES layer **Establish core MES platform** also to enable their global traceability and genealogy platforms.	**MES is used as a key shop floor solution** to collect operational parameters for quality control and labor assistance. Real-time visibility also for inventory management, especially to reduce inventories	They have a special focus on enterprise architecture, which includes a **dedicated MES solution (SAP ME) for aligning data foundations**.	Plan to extract shop floor data; however, they do not have a dedicated MES. Ability to simulate products (actuators) to predict their lifetime and performance	Deploying cloud-based data aggregation and analytics	Using MES/MOM layer for real-time information retrieval (1,2,3,4)
Distribu-ted control	Considering purchasing IT tools to do detailed scheduling below MES level. MES is the point of contact of PLC in a factory.	MES is on premise to avoid latency and internet connectivity issues.	Automated certain manual meat processing operations using **reinforcement learning**.	Some of their processes (such as PCB assembly) are fully automated. Big data analytics with machine learning in the cloud	Implementing IIoT platforms to support production control and execution	Making legacy machines "smart" with **automatic control through machine learning** on edge devices	PAT (process analytics technology) Edge analytics (3,6)
Digital modular-ity	Standardization of production data based on **ISA 95 models** Using IIoT platform for **unified communication** to OT. Semantic protocols and standards	**Standard interfaces** between IT and OT are preferred (e.g., **OPC UA**)	**Standardization of interfaces** between ERP and MES (e.g., Rest API) Considering **ISA 95** for vertical integration	Moving toward **standardization** (**OPC UA and PackML**) Using **ISA 95** as a reference.	Currently **using ISA 95** as a guideline to organize their systems landscape	Currently using microservice-based MOM architecture with **open APIs** **Standard protocols for IT/OT integration** (**OPC UA**)	ISA 95 (1,2,3,4,5) Open standards (1,2,4,5,6) Open APIs (3,6)
IIoT intercon-nectivity	Batch data acquisition through MES Use of **open standards/protocols** for interconnection (such as OPC UA, MQTT)	Looking to extract data from **legacy machines** through **adding sensors**. **Standard interfaces** are not available for some legacy systems.	Considering **adding sensors** for operator assistance	**Data collection from machines is lacking.**	Can collect some data from actuators. More data collection is desired but challenging due to **legacy machines**.	Connecting machines in process, but some **legacy systems** not worth connecting Adding **sensors** to machines Wireless only where necessary Focus on secure interconnection	Difficulty with legacy machines (2,4,5,6) Adding sensors to existing machines (2,3,6)

4.2 IIoT-connected MES/MOM for a smart factory: A technological perspective

Paper 4: Perspectives on Real-Time Information Sharing through Smart Factories: Visibility via Enterprise Integration

S. Mantravadi, C. Møller, and F. M. M. Christensen, "Perspectives on Real-Time Information Sharing through Smart Factories: Visibility via Enterprise Integration," in *2018 International Conference on Smart Systems and Technologies (SST)*, IEEE, Oct. 2018, pp. 133–137. DOI: 10.1109/SST.2018.8564617

Background: Hermann *et al.* [40] propose *information transparency* as one of the design principles of the smart factory, which can be achieved through enterprise integration by inter-organizational collaboration. McClellan [136] argues that collaborative manufacturing could be accomplished by using IT systems and the internet. Supply chain management literature also suggests the importance of information sharing as a predominant way of ensuring effective decision-making and efficient flows to manage supply chain disruptions.

It is common practice to exchange information (manufacturing and product data) between supply chain parties (see Fig. 19), and MES/MOM has been improving supplier management by disseminating information on products, orders, and delivery processes in almost real time. However, Industry 4.0 can realize the full potential of collaborative manufacturing that takes this simple passing of information one or two dimensions higher to confirm meeting the committed performance requirements, as suggested by McClellan [136].

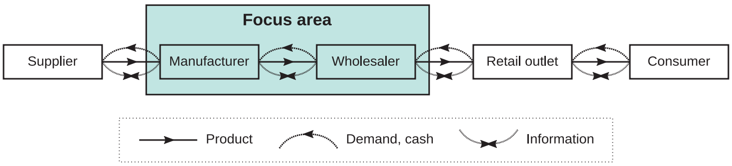

Fig. 19: Flows in between supply chain stages [135]

Methodology: First, a selective literature review is done on MES/MOM's relation to real-time information sharing for supply chain management. Second, an exploratory case study on one of Scandinavia's largest slaughterhouses (representing a manufacturer) and a large wholesaler verifies the claims made based on the literature review. Finally, semi-structured interviews with an IT architect at a manufacturer and product manager at a wholesaler are conducted for data collection.

Implications: The position paper presents perspectives on how a next-generation MES/MOM can be used for *information transparency* by sharing product-centric information in almost real-time. A case of fresh food supply chain planning is studied because perishable products have limited shelf life down to a few days, making information sharing crucial. It is common to exchange information on over- or undersupply of deliveries (apart from fax, mail, or telephone) through advanced shipping notifications (ANS); however, ANS are not sent when the disruption arises but only when the order is placed. We propose a next-generation MES/MOM to solve this issue and enable visibility in supply chains through enterprise integration.

This paper aims to answer the following question [135]: "How can MES/MOM support the smart factory design principle of *information transparency*?" (**RQ2.1**)

- This position paper explores the role of manufacturing IS (beyond the ERP layer) to define the scope/role of smart factories to enhance supply chain visibility. The findings contribute to developing a hypothesis that MES in smart factories at a *manufacturer* can provide critical product-centric data to the *wholesaler*, thus enhancing supply chain performance.
- In contrast to MES, the live tracking of the production conditions and exchange is not available at the enterprise level with ERP systems. Hence, MES is better equipped to provide real-time information on the product to the wholesaler (to aid planning). Moreover, MES also promotes collaborative manufacturing better than ERP because it can provide traceability on the unit level and give live production status reporting.
- We identify three out of eleven functionalities of MES/MOM as the critical functionalities of MES/MOM for supply chain visibility in Industry 4.0: detailed scheduling, dispatching production units, and product tracking and genealogy.

Paper 5: User-Friendly MES Interfaces: Recommendations for an AI-Based Chatbot Assistance in Industry 4.0 Shop Floors

S. Mantravadi, A. D. Jansson, and C. Møller, "User-Friendly MES Interfaces: Recommendations for an AI-Based Chatbot Assistance in Industry 4.0 Shop Floors," in *Intelligent Information and Database Systems. ACIIDS 2020. Lecture Notes in Computer Science*, vol. 12034, Springer, 2020, pp. 189–201. DOI: 10.1007/978-3-030-42058-1_16

Background: Hermann *et al.* [40] propose *technical assistance* as one of the design principles of smart factory, which entails the production workforce receiving intuitive assistance. Due to the improved hardware processing power and availability of vast amounts of data, AI capability is an asset for MES/MOM to manage operations much more effectively. However, even though MES/MOM is designed to interact with humans in the factory to orchestrate production, literature shows that MES user interfaces have not been studied extensively [80]. Furthermore, literature also suggests that research on chatbot application in enterprises is still nascent [79].

Methodology: First, we conduct a selective literature review to determine the existing roles of the two user groups of MES, namely, operator personnel and management personnel. We develop a hypothesis to improve production monitoring by foreseeing the inventory shortages and managing orders by combining AI techniques with MES/MOM data. Furthermore, we identify the potential of chatbots to retrieve information from MES/MOM. Second, we use three case examples to determine the AI-based assistance requirements for MES users. Third, we develop a prototype chatbot and connect it to a web-service endpoint as an experiment, mimicking a web-based MES database. Finally, we use an example of retrieving order information to assess how easily a user receives a response (see Fig. 20) compared to a regular MES database search.

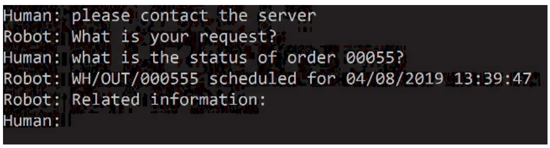

Fig. 20: Assessment of a conversational MES interface for order management [44]

We present architectural recommendations for AI-based chatbot assistance in Industry 4.0 shop floors based on this.

Implications: Architectural design choices such as web-based MES also benefit easy scaling-up and adding clients and functionalities. These design choices eliminate the monolithic MES architecture and prepare it to easily integrate applications (e.g., using service-oriented architecture) and connect to the network services. Furthermore, due to the design criterion of technical assistance, MES users can engage in dynamic operations with improved responsiveness.

This paper aims to answer the following question [44]: "Does a user-friendly MES interface with a prediction system (e.g., chatbot interface), intended to improve the shop floor user's quality of results, support the smart factory design principle of *technical assistance*?" (**RQ2.2**)

- The results indicate that the chatbot interface for MES is beneficial to the shop floor workforce and provides easy information extraction compared to the traditional search techniques. We also recommend using natural language to interact with MES/MOM as it promotes easy information extraction for novice users.
- The paper contributes to the manufacturing IS field and demonstrates a human-AI collaboration system in a factory. Our design's artificial neu-

ral networks are trained on the transformed MES user input, which is processed to suggest relevant information.

- Findings also recommend how MES-based technical assistance systems can be developed for easy information retrieval. We also recommend deploying an in-house chatbot solution based on MES for the shop floor purpose. The proprietary virtual assistants available in the market (e.g., Google's Assistant) might come with features not necessary for shop floor purposes.

Paper 6: Multi-agent Manufacturing Execution System (MES): Concept, Architecture & ML Algorithm for a Smart Factory Case

S. Mantravadi, C. Li, and C. Møller, "Multi-agent Manufacturing Execution System (MES): Concept, Architecture & ML Algorithm for a Smart Factory Case," in *21st International Conference on Enterprise Information Systems (ICEIS)*, Scitepress, May 2019, pp. 477–482. DOI: 10.5220/0007768904770482

Background: Hermann *et al.* [40] propose *decentralized decisions* as one of the design principles of smart factory, which requires manufacturing systems to be interoperable first. Chen *et al.* [4] state that smart factory uses MES to implement production scheduling in real-time through intelligent data acquisition and analysis. To develop context-aware manufacturing systems, MES architecture can be designed to make the best use of logged production data to find meaning, relations, and dependencies from the data that are not obvious. Literature also suggests that MES lacks decision support capability [87]; therefore, it is motivating to support MES design with data analytical capabilities to optimize production execution. Figure 21 illustrates the research topics relevant to decentralized decisions.

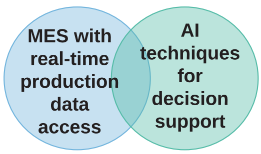

Fig. 21: Research focus for *decentralized decisions*

Methodology: Machine learning techniques are widely used in manufacturing to make sense of the data generated from production. To introduce a machine learning algorithm into multi-agent-based MES and use MES/MOM to assist humans by autonomous production execution, we use the concepts of centralized multi-agent systems [130]. For this conceptual paper, a problem of anomaly behavior of unusual drilling speeds and an unusual number of parts finished per minute is chosen for the AAU *Smart Lab* production line. The central agent runs on the MES server, and sub-agents run on the Raspberry Pi of each piece of equipment on the production line. The critical steps of our approach that help us present an architecture and an algorithm are monitoring, modeling, anomaly detection, group decision-making, and behavior adjustment.

Implications: We also argue that a systems engineering approach is needed to develop intelligent MES platforms rather than machine learning tools to solve specific production problems. This position paper contributes to the well-established field of intelligent manufacturing systems [82] and holonic manufacturing approaches for distributed intelligent manufacturing control [85] by presenting a research agenda for AI-embedded MES for a smart factory.

This paper aims to answer the following question [45]: "What is the conceptualization of multi-agent MES to support the smart factory design principle of *decentralized decisions*?" (**RQ2.3**)

- This position paper establishes the potential of applying AI to the factory floor to leverage the existing manufacturing IT tools of the MOM layer (per ISA 95 standard).
- Findings indicate that an agent-based approach is suitable for MES implementation in the smart factory context. We propose a next-generation MES with embedded AI, that is, a MES system architecture combined with a machine learning technique for multi-agent MES (see Fig. 22).

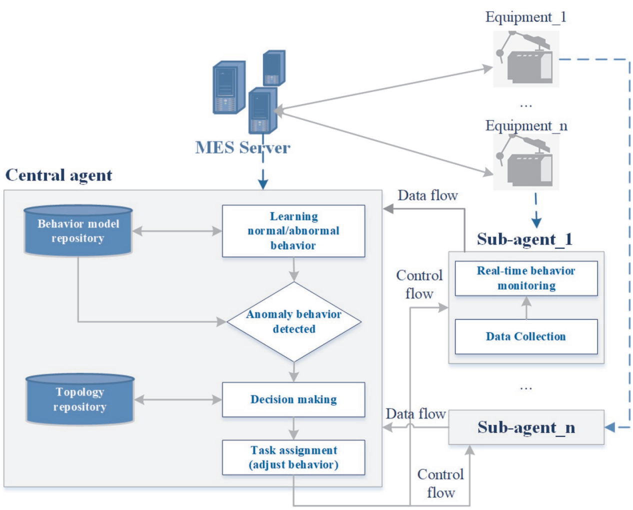

Fig. 22: System architecture of machine learning based multi-agent MES [45]

- A concept is developed to establish the future research agenda on combining AI with MES. In addition, system architecture and an anomaly detection algorithm that can run on top of MES to execute decisions on the production line are proposed to verify the concept.

Paper 7: Securing IT/OT Links for Low Power IIoT Devices: Design Considerations for Industry 4.0

S. Mantravadi, R. Schnyder, C. Møller, and T. D. Brunoe, "Securing IT/OT Links for Low Power IIoT Devices: Design Considerations for Industry 4.0," *IEEE Access*, vol. 8, pp. 200 305–200 321, 2020. DOI: 10.1109/ACCESS.2020.3035963

Background: Hermann *et al.* [40] propose *interconnection* as one of the design principles of smart factory, which refers to linking machines, sensors, devices, and people through the IIoT [94]. However, the manufacturing industry seems ill prepared to handle cybersecurity challenges around its wireless network infrastructures. Due to the failures in industrial cybersecurity, many manufacturing facilities worldwide have been subject to attacks. Examples include the famous case of Stuxnet in Iran in 2010, when several uranium centrifuges were destroyed [138], the TRITON attack on Saudi Arabia Petrochemical in 2017, and an attempted attack on a Tesla factory in Nevada. Boyes *et al.* [24] argue the need for a multi-layered security strategy around EIS to mitigate security challenges in IIoT. This entails securing the IT/OT links using cryptographic solutions for designing a secure smart factory.

Methodology: First, we conduct a selective literature review to study the state-of-the-art security challenges in IT/OT interconnection, pointing toward the gap in security in the connection between MES and OT devices of the ISA 95 architecture. We also study the literature to describe cryptographic solutions for IT/OT links in IIoT. Since most research is not conducted on the basis of a concrete example, we assess the suitability of certificateless cryptographic schemes in the case of the *Smart Lab* to propose an architectural design (see Fig. 24) that secures the communication between MES and PLCs (representing OT). We use the QFD method on the *Smart Lab* to determine the smart factory's security requirements (see Fig. 23).

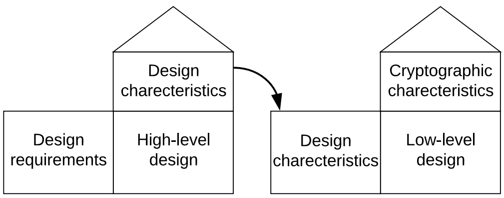

Fig. 23: The two phases of QFD for secure interconnection [137]

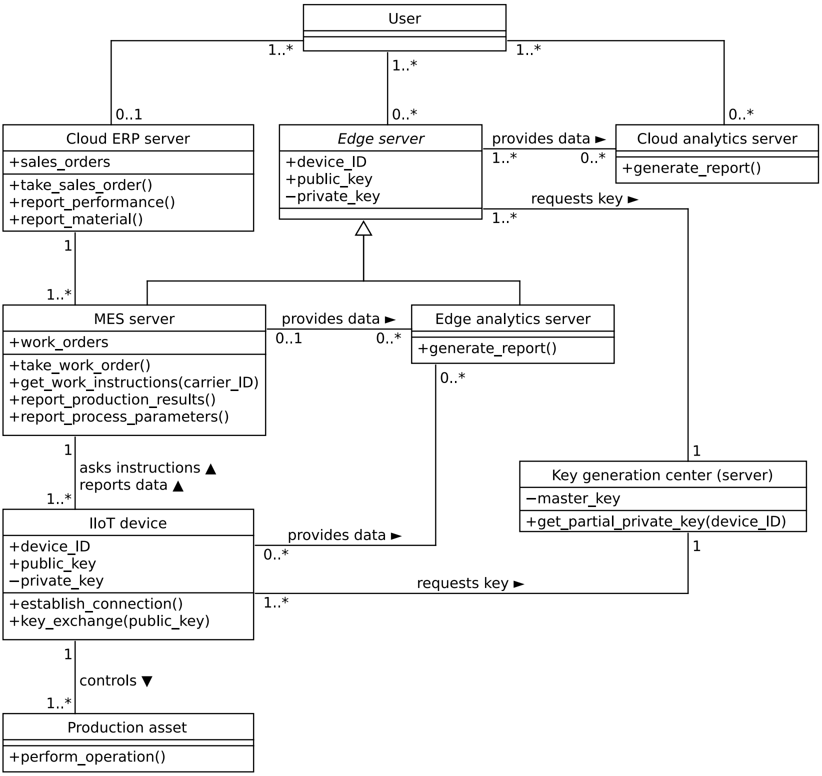

Fig. 24: Proposed architecture for a smart factory, describing the entities and the relationships between the systems [137]

Implications: A smart factory has CPS communicating and coordinating over IIoT [40], which can be supported by edge computing. IT/OT integration is the foundation for the vertical and horizontal integration required for Industry 4.0. This article addresses the security gap of making a secure IT/OT integration. Our work also makes a case for standardization and the development of open protocols in a distributed control architecture by utilizing legacy systems.

This paper aims to answer the following question [137]: "What special considerations are necessary to secure the connection between IT and OT in IIoT, given the need for wireless connectivity and modularity for the smart factory design principle of *interconnection*?" (**RQ2.4**)

- We determine that the IT/OT link (such as the data exchange between the MES and PLCs) is a weak point in a factory as far as cybersecurity is concerned. This is due to the often-limited computational resources of OT devices.

- Findings help conclude that designing security for a smart factory is a sociotechnical challenge, and securing the link between MES and PLCs in the IIoT can be a step toward it. This forms one crucial layer in a secure architecture for a smart factory.
- We propose design recommendations for securing the IT/OT link, using a QFD tool to translate between high- and low-level requirements. We propose an architecture for a secure smart factory, describing it in a UML class diagram (see Fig. 24).

4.3 Implementation of IIoT-connected MES/MOM: An enterprise context

Paper 8: Design choices for next-generation IIoT-connected MES/MOM: An empirical study on smart factories

S. Mantravadi, C. Møller, C. LI, and R. Schnyder, "Design choices for next-generation IIoT-connected MES/MOM: An empirical study on smart factories," *Robotics and Computer-Integrated Manufacturing*, vol. 73, p. 102 225, 2022. DOI: 10.1016/j.rcim.2021.102225

Background: The market uncertainties caused by the ongoing COVID-19 pandemic have motivated manufacturers to become responsive through manufacturing flexibility. Smart factories are RMS that can support flexible and agile manufacturing, especially for mass customization. Due to the interoperability requirements on the IT side, MES/MOM design based on ISA 95 standard demands re-evaluation, as ISA 95 was developed in the era of a low degree of interconnection. MES/MOM faces new design challenges arising in the Industry 4.0 era of IIoT: standardization, interoperability, software customization level, and modularity.

Methodology: First, we conduct a selective literature review on MES/MOM design challenges in Industry 4.0, emphasizing studies from the last five years. The research gaps drive the research questions that require us to use a real-world case. Therefore, we study a reconfigurable cyber-physical factory – the AAU *Smart Lab* – and explore an order management scenario for mass customization. Second, we design and implement an IIoT-connected MES/MOM data model based on ISA 95 models. This data model is implemented using three industrial demonstrators over two years for iterative research. Finally, we use a QFD method to deduce design choices for next-generation MES/MOM connected to the IIoT.

Implications: Findings address the interoperability needs of IT systems for implementing RMS. The architecture proposed for MES/MOM-centric smart factory is instantiated in the *Smart Lab*. To accommodate the data management needs of Industry 4.0 in a brownfield environment and mitigate the traditional inflexibilities of MES/MOM, we propose three design principles for MES/MOM to enable the smart factory: principle of reconfigurability, principle of user assistance, and principle of security.

This paper aims to answer the following two questions [43]: "In what way is ISA 95 relevant to the IIoT paradigm for designing responsive smart factories?" (**RQ3.1**), and "What design choices are necessary for a next-generation MES/MOM that is compatible with IIoT?" (**RQ3.2**)

- We present an ISA 95-based data model design for MES/MOM in IIoT. The system overview is shown in Fig. 25.

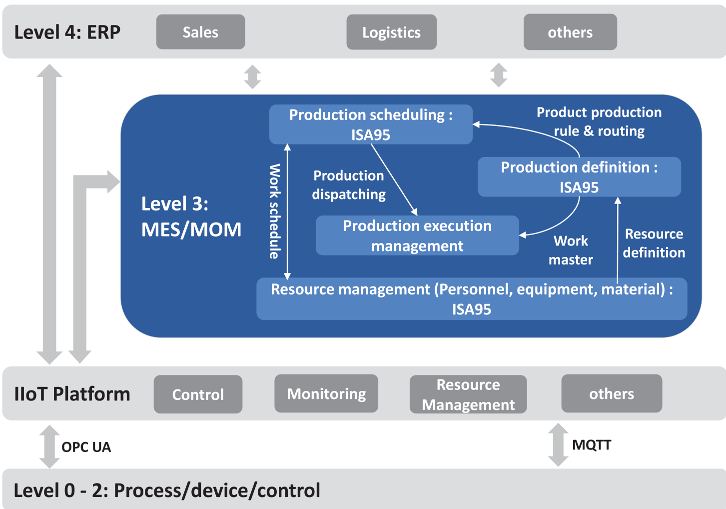

Fig. 25: Proposal for a system architecture for a responsive smart factory based on an IIoT platform [43]

- We implement and iterate our data model through three industrial design demonstrators at the *Smart Lab* by building an open-source and interchangeable solution. The three demonstrators aim to solve the three Industry 4.0 challenges of vertical integration, interoperability, and order customization, respectively. Based on the results from the *Smart Lab* IT, we develop the QFD tool in Fig. 26.
- We combine an analysis of the findings of our case study with the QFD assessment to present design recommendations for an architecture for next-generation IIoT-connected MES/MOM that can enable responsive smart factories. QFD analysis indicates interoperability (with the highest relative importance of 31%) as the essential characteristic for designing a responsive smart factory. Figure 27 shows the high-level secure distributed architecture of the IS in a smart factory.

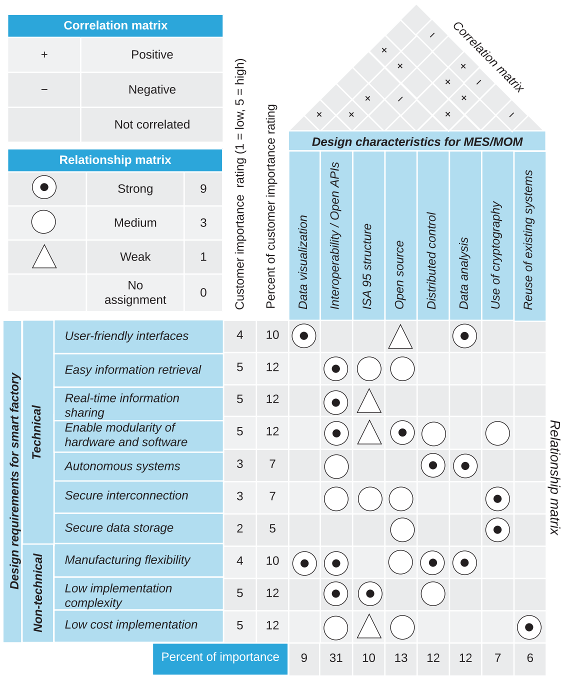

Fig. 26: The House of Quality – linking the design characteristics of MES/MOM with the design requirements for a smart factory (based on the *Smart Lab*) [43]

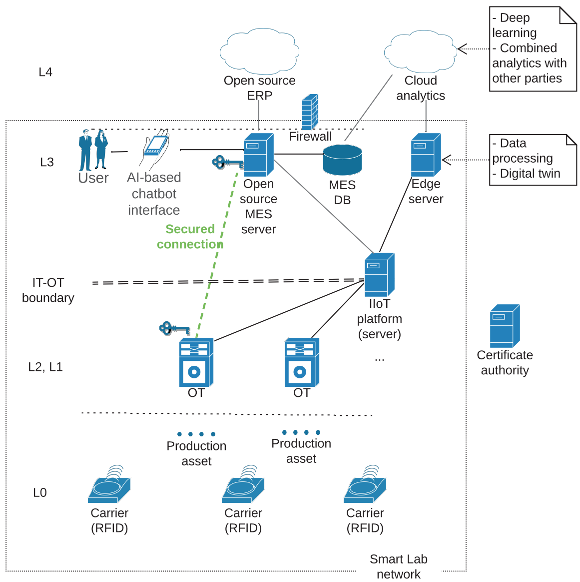

Fig. 27: Proposed high-level architecture for an IIoT-connected MES/MOM [43]

4.4 Summary

The publications appended to this thesis are grouped into three phases. The first (exploratory) phase presents the case study findings based on the empirical data collected from the six case companies and offers a theoretically and empirically grounded conceptual framework of what it means to implement a smart factory with MES/MOM.

The second phase of experimental studies based on smart factory use-cases focuses on developing and applying a MES/MOM architecture for each smart factory design principle. Most of the papers appended under this phase use some form of prototype software systems that represent MES/MOM and are developed based on the design principles of a smart factory. The descriptions of these artifacts serve as proofs-of-concept, and the learnings from the studies are also integrated into the framework created in the earlier phase.

The third phase, built upon the work from the first two phases, evaluates the homegrown MES/MOM data model design based on ISA 95 and derives design principles for MES/MOM to enable the smart factory. This phase synthesizes the findings from the four-year design science study to determine the role of MES/MOM in an IIoT enabled enterprise (brownfield). In the following chapter, we discuss how the work in these three phases contributes to the research objective of the thesis.

Chapter 5. Discussion

The research objective of this thesis is **to develop a conceptual framework for smart factory capabilities and to derive design principles for MES/MOM to enable the smart factory**. This chapter examines the relevance of the research findings from our individual papers regarding that objective. The chapter concludes by highlighting our main research contributions; it also provides an outlook for enabling the smart factory in a brownfield environment.

5.1 Contributions to the research objective

Smart factory capabilities: The smart factory concept of Industry 4.0 has been defined in many ways in academic literature. Wang *et al.* [12] characterized the smart factory as a self-organized multi-agent system that uses data analytics to enable decision making. This definition can be linked to Leitão [26], who discussed agent-based distributed manufacturing control and identified a lack of sufficient development methodologies.

This thesis has designed a manufacturing IT system that can support self-organizing multi-agent systems to implement flexible and agile manufacturing [12]. The focus is mainly on the more immediate challenges of interoperability with legacy systems, which is necessary to create the autonomous systems of Industry 4.0 in a brownfield manufacturing enterprise.

The development of RMS is becoming increasingly important to meet the volatile global market demands and to manage disruptions in manufacturing supply chains that, for example, the COVID-19 pandemic has caused [54]. This thesis contributes to specific areas around developing RMS. For example, our work in **Paper 1** addresses the shortcomings of previous rigorous analytic metrics for assessing reconfigurability [54] in a smart factory context.

IT investments must satisfy valuable business needs [61]. Similarly, a MES/MOM investment should cater for the business needs of a smart factory, such as manufacturing flexibility. Manufacturing flexibility is a critical competitive priority for improving the supply chain efficiency that can be achieved via

RMS. This thesis has established *reconfigurability* as a smart factory capability through various design contributions to enhance customer responsiveness. Furthermore, reconfigurability can be considered an *enabling capability* according to the classification framework of Leonard [41], because it is essential to be competitive in today's volatile markets.

To further clarify reconfigurability through the lens of MES/MOM, we developed a framework for smart factory capabilities based on Hermann *et al.*'s design principles [40]. Figure 28 illustrates the proposed framework for smart factory capabilities. The figure shows the interrelatedness of the concepts employed in this thesis. While the thesis focuses on improving the MES/MOM design, the model also illustrates how reconfigurability principles can be included in the design phase of a manufacturing information system [56].

As a starting point, the requirements of an ISA 95-based next-generation MES/MOM for Industry 4.0 are reviewed in **Papers 1** and **2**. **Paper 3** corroborates and synthesizes these requirements using the inputs from the case companies. Based on the design requirements, the IIoT interconnectivity concept is studied in depth in **Papers 4**, **5**, **6**, and **7** through various iterations, culminating in **Paper 8**, in which we design and implement a data model for an IIoT-connected MES/MOM. Here, IIoT interconnectivity is described as a foundation for three other technological capabilities, namely the digital twin, digital modularity, and distributed control.

Figure 28 portrays the research contributions from the individual papers. It is evident that the papers complement the framework and provide novel insights regarding the concepts depicted in the boxes.

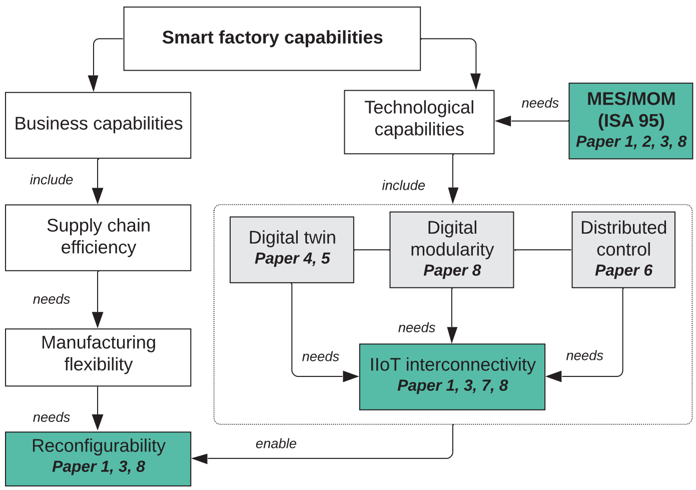

Fig. 28: Mapping the contributions onto the framework for smart factory capabilities

Design principles for MES/MOM: The above discussion about smart factory capabilities indicates that the needs of a smart factory should drive the MES/MOM design. Hence, reconfigurability cannot be left out of the system development process, and the IIoT-connected MES/MOM must be appropriately specified and implemented.

We synthesize the findings from the case studies and experiments into the design principles discussed below for MES/MOM, to enable the smart factory. We stress that these principles predominantly concern architectural design recommendations. They form the basis for designing and developing a MES/MOM system that can exchange data with the IIoT through its interoperability with the heterogeneous legacy systems in a factory. The architectural design principles thus address the existing challenges of MES/MOM concerning interoperability [14], modularity [107], decentralization [68], and IIoT connectivity [16].

1) Design for reconfigurability

We studied the phenomenon of enterprise integration and IT/OT convergence for Industry 4.0 to formalize a method to assess reconfigurability in smart factories [134]. For this purpose, we reviewed the literature on mass customization strategies with RMS.

Morgan *et al.* [54] found that optimizing the system design is a challenge for developing RMS. Bortolini *et al.* [56] queried whether it is possible to introduce reconfigurability principles into an existing production system with relatively little investment. Our research on brownfield implementation partly addresses the issue of cost as we prioritized the reuse of existing legacy systems [43]. Furthermore, to mitigate the challenges of using MES/MOM for distributed manufacturing control, we offer potential solutions in [45] that provide decision support capabilities for MES/MOM for data analytics via a multi-agent architecture [87].

Against this backdrop, we derived the design choices for next-generation MES/MOM that would enable RMS in IIoT [43]. This work also relates to the smart factory design principle of decentralized decisions as outlined by Hermann *et al.* [40], because decentralization aids reconfigurability [85]. Thus, we proposed the **principle of reconfigurability**, which specifies that MES/MOM design should support the reconfigurability needs at both the low level and the high level. The low level refers to operative-level change objects, such as software and hardware components, whereas the high level includes strategic firm-level change objects, such as supply network structure and ownership [43, 134].

2) Design for user assistance

We examined the developments and issues around MES user interfaces. A recent study [80] explained how MES empowers human users by supporting their decision making. However, our review on this topic revealed that academic literature on user-friendly MES/MOM interfaces is underdeveloped.

To address that issue, we focused on improving MES user interfaces with conversational virtual assistants for information retrieval. This approach enables the MES/MOM user to participate in dynamic manufacturing operations with the rapid responsiveness required for Industry 4.0 [44]. We surveyed the potential of chatbots to serve as a conversational IS, and we tested the hypothesis that "A chatbot interface is a user-centric design enhancement for MES, and it serves to monitor manufacturing operations by easy retrieval of information on demand" [44]. We tested a chatbot with a prediction system as an interface layer for MES.

We have discussed the possibilities for implementing MES-based technical assistance systems. In addition, we have partially addressed the questions raised by Meyer von Wolff *et al.* [79] on viable application areas for chatbots and their benefits and how they should be designed. Our work also addresses some of the concerns raised in the smart factory design principles of information transparency and technical assistance by Hermann *et al.* [40]. Thus, we proposed the **principle of user assistance**, which specifies that the MES/MOM connected to IIoT must have an AI-based intuitive user interface that allows humans to retrieve production-related information in real-time [43].

3) Design for security

We have reviewed studies on cyber security for IIoT in the context of ISA 95. Boyes *et al.* [24] pointed out the security risks that arise from the new connectivity between IT and OT systems, which is characteristic of the IIoT. Yu and Guo [96] identified the connection of previously isolated industrial control systems as a security risk. Tuptuk and Hailes [97] similarly stated that the traditional security strategies for manufacturing, which require segregating smart manufacturing systems, are no longer suitable.

To address these issues, we focused on the security risks of linkages between IT and OT, such as the data exchange between MES/MOM and IIoT devices. We surveyed cryptographic approaches and protocols that aim to secure this link by providing key management and key exchange functionalities between IT and OT devices. The restricted computational power of many OT devices is relevant here.

We then determined the design requirements for secure smart factories. We have provided recommendations on how to design a smart factory, taking security into account. This point addresses one of the concerns about the smart factory design principle of interconnectivity as expressed by Hermann *et al.* [40]. Thus, we proposed the **principle of security**, which specifies that MES/MOM should be able to connect to OT devices securely – that is, encrypted and authenticated – in an ad-hoc manner [137, 43].

5.2 Novelty

The thesis advances state-of-the-art manufacturing digitalization by exploring the motivation and methods for developing smart factory capabilities using MES/MOM. We have leveraged the theory around modern hardware and computing to contribute to IS in the fields of manufacturing and IIoT. The limitations in previous research, which this thesis addresses, were as follows:

- There was no consensus about using IS to develop smart factory capabilities;
- MES/MOM was a suggested solution for information management in a manufacturing enterprise; however, those suggestions were unspecific and did not address the question of applicability in the presence of IIoT;
- There was insufficient empirical research on developing smart factories using ISA 95; and
- The benefits of MES/MOM for developing smart factory capabilities had never been tested.

This research has made the following key contributions: (1) clarification of the concept of smart factory capabilities; (2) description of the application of MES/MOM for various information management problems; (3) theory building and prescriptive understanding of MES/MOM architecture to include IIoT platforms; (4) providing proofs-of-concept for further development; (5) articulating design principles for the next-generation MES/MOM; (6) recommending design guidelines and an assessment framework for reconfigurability in manufacturing; and (7) establishing the relevance of ISA 95 in Industry 4.0.

5.3 Implications

A new outlook is necessary to enable smart factories in brownfield environments while cost-effectively integrating advanced manufacturing technology. To improve customer responsiveness with smart factories, academic researchers and practitioners can reflect on the following points:

- **The smart factory concept in existing work:** Although research describes the smart factory as a form of cyber-physical system and IIoT implementation, there has been insufficient emphasis on capability building for IIoT connectivity. Enterprises require an action plan that considers both the business and practical needs so that they can select the right components for IIoT.
- **Linking smart factory implementation and MES/MOM design:** An IIoT-connected MES/MOM that follows the above three design principles in Section 5.1 would itself form part of a smart factory implementation. It would support practices such as intelligent data acquisition and

data-driven control.

- **Organizational efforts to find operational solutions rather than just examining technical details:** We believe that the technical design of information systems is not as important as gaining clarity about the operational challenge that the technology is intended to solve. MES/MOM design for reconfigurability must give control to the manufacturers to facilitate future changes. For example, the 5G promise of low latency and high reliability could prompt some manufacturers to adopt wireless factories, and they should be able to steer an existing MES/MOM toward wireless connectivity.

Chapter 6. Conclusions

In this PhD thesis, we have considered likely future manufacturing requirements. We have introduced the concept of *smart factory capabilities* and studied it from the perspective of MES/MOM. Although Industry 4.0 started as a strategic initiative in Germany to boost the country's manufacturing economy, its underlying technical principles can be applied to any manufacturing enterprise globally. We drew on existing research about the design principles of smart factories – such as information transparency, technical assistance, decentralized decisions, and interconnection – to improve our MES/MOM design. Furthermore, we have outlined the challenges of enabling smart factories and have examined state-of-the-art RMS to propose solutions that utilize MES/MOM.

Our approach used a DSR methodology, and our findings on MES/MOM design can enhance reconfigurability, cybersecurity, and human–computer interactions. The architectural design recommendations are directed to designing interoperable IT systems for RMS in IIoT. The data collected from case companies for this thesis was thoroughly analyzed at almost every stage of this four-year iterative research project. The findings highlighted the diverse expectations that stakeholders hold regarding a MES/MOM implementation, and we used this data to refine our models. We also synthesized the findings from the eight appended papers into design principles that are highly pertinent to enable the smart factory.

Our research involved industrial demonstrators, which entailed designing and implementing a data model for MES/MOM in IIoT. This process resulted in artifacts, which included detailed descriptions of the proposed high-level architecture for a smart factory and design assessment tools based on QFD. Furthermore, this research provides a normative theory for understanding how MES/MOM can be developed for Industry 4.0.

In presenting this framework, we have combined the perspectives of the OM and IS fields. In doing so, we articulate how a smart factory can be enabled with IIoT-connected MES/MOM, which is a growing body of research. Our academically rigorous research and the findings of the analysis can be summarized in the following propositions:

- **ISA 95 is relevant for Industry 4.0:** We used the ISA 95 structure in several instances of our research. ISA 95 models can serve as a basis for MES/MOM design and can help to standardize data models and flows for EIS. This applies especially to a brownfield implementation of a smart factory if the company has already followed several ISA 95 principles. The right-side panel of Fig. 29 illustrates the contribution of this thesis in the form of a design for a modular and decentralized architecture of systems. This design is, however, still based on ISA 95 structure.

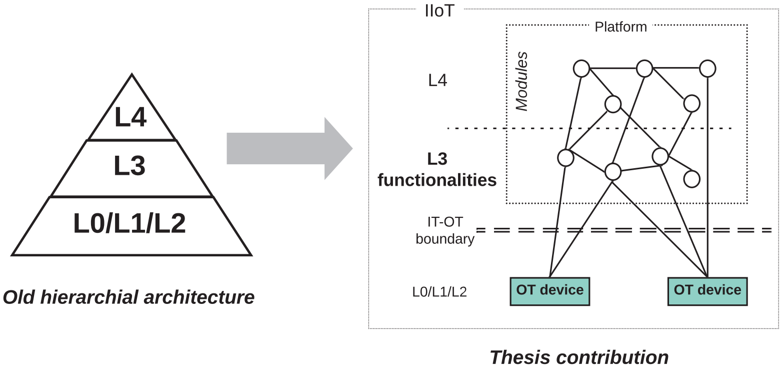

Fig. 29: Toward an Industry 4.0 networked architecture in a brownfield factory [139]

- **Maneuvering MES/MOM for Industry 4.0:** Only a few MES/MOM implementation projects succeed with a clear business case. Such projects have a better chance of succeeding – especially in Industry 4.0 – if MES/MOM is designed and developed for reconfigurability from the beginning. In place of monolithic proprietary MES, open-source and interoperable services can significantly aid reconfigurability. A MES/MOM implementation that can retrieve lower-level production data from connected (legacy) machines expedites smart factory development. The reason is that MES/MOM can provide a unified interface for high-quality production data, which is essential for analytics according to the principle of "garbage in, garbage out."

- **Enabling the smart factory through use case approach:** Implementing smart factories by merely acquiring modern technologies might incur failure. Enterprises lack sufficient technical information on MOM's idiosyncrasies and therefore do not know what kind of manufacturing performance to improve. Hence, an iterative design thinking approach can be used to introduce solutions for specific problems.

6.1 Research contributions

In this section, we summarize the contributions of this thesis regarding each research question.

***RQ1**: Which MES/MOM functionalities can support reconfigurability in a smart factory?*

- Our work has enhanced the understanding of essential MES/MOM functionalities for smart factories by assessing ISA 95 MES functionalities against reconfigurability needs. **Paper 1** employed the example of the *Smart Lab* to identify the most critical MES/MOM functionalities through QFD analysis. **Paper 2** reviewed the literature, and **Paper 3** analyzed the empirical data from case companies.

***RQ2**: How can MES/MOM be used with smart factory technologies to improve the performance of manufacturing operations management?*

- In **Papers 4**, **5**, **6**, and **7**, we demonstrated how MES/MOM architectural design can be improved by using smart factory technologies to better the performance of MES activities. We also developed prescriptive knowledge in these papers.

***RQ3**: What design choices are necessary for MES/MOM to support the smart factory implementation process in a brownfield environment?*

- We developed high-level architecture for a smart factory, with different ERP and MES/MOM functionalities as modules in a business platform, targeted at a brownfield environment. In **Paper 8**, we identified *interoperability* as the most important design choice for MES/MOM.

6.2 Limitations, reflections, and future work

This research has presented one method of applying MES/MOM for Industry 4.0; there are other possible approaches too. Our study has incorporated many outside concepts from computer science, such as chatbots and cybersecurity. Because this is a pioneer work incorporating these concepts into MES/MOM design, our proposals for the architectural design must be viewed as an initial attempt to develop smart factory capabilities. Future research is needed to validate these interventions and refine the approaches presented in this thesis. In the spirit of design science, we studied the topic only to the extent deemed necessary for making substantive generalizations. This process resulted in limited time being available to test and evaluate the architectures. The research field would benefit from implementing the recommended architectures in companies to generate practical knowledge that could influence MES/MOM investment decisions.

The research process required a theoretically informed analysis of case data at every stage. It was particularly challenging to interview the representatives from several companies to determine an ideal system design. This process was time-consuming and demanded thorough knowledge of the technical language used in the industry. An even closer engagement with the case companies through interactive inquiry, in the manner of action research, would have been an alternative approach to the research problem. We believe that such an undertaking may have been fruitful.

This thesis contributes to practice by highlighting the best practices of deploying MES/MOM connected to IIoT; in addition, it provides tools to navigate the IT/OT integration. The framework we provide for smart factory capabilities supports practitioners in planning and organizing their systems. Future research could document the challenges of developing smart factories with MES/MOM. Questions worth investigating include, "What are the solutions for attaining interoperability between heterogeneous and inflexible systems for a smart factory?" and "How do the infrastructural challenges of IIoT implementation differ between small and large manufacturing enterprises?"

Finally, since the onset of the industrial revolution, the global environment has steadily degraded due to the overuse of natural resources. The ongoing fourth industrial revolution, which includes Industry 4.0, has a chance to rectify the damaging anthropocentric practices associated with economic development. However, to achieve this goal, technology must rapidly evolve toward creating sustainable and equal societies. In the manufacturing sector, complex global supply chains must be simplified to make room for more localized production. It follows that IS for smart factories must be designed to meet future needs.

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Appendix A. A philosophical perspective on automation technology in manufacturing

The essay below is an abridged version of the position paper that I submitted for the PhD course *The Philosophy of Technology*, University of Agder, Norway (Nov 2019). It explores how we can relate to automation technology concerning a smart factory implementation. Spirited discussions mediated by Professor Einar Duenger Bohn during the course are acknowledged.

Manufacturing is about turning raw materials into finished products. All the consumer goods we use today, from cars to processed food (or oil), undergo a series of manufacturing processes. Trade, which is about bartering goods and services, has been prevalent among humans since prehistoric times. In the modern world, trade and commerce are linked to exporting (and importing) raw materials and manufactured goods. The manufacturing sector generates revenues for governments, and many modern national economies are highly dependent on foreign trade. However, a negative aspect of industrialization is its contribution to climate change, inequality, and unemployment.

The manufacturing industry has a proactive approach to advanced manufacturing technologies, and the Industry 4.0 vision correlates a high IT adoption rate with improved productivity. Business and technological drivers lead the industry to adopt these technologies for automation. However, there is a widespread belief that the application of AI to automate manufacturing tasks can lead to an unemployment crisis. This problem could also be relevant to Industry 4.0 because smart factories advance automation by minimizing human involvement in the low-level tasks and promoting humans to supervisory positions through data-driven strategies (AI-based).

This essay focuses on the threat that an AI-based automation technology poses to human jobs. We argue that an automation technology does not have the intrinsic property of creating an unemployment crisis; the manner in which it is utilized determines whether this technology creates a positive impact.

Therefore, I reflect on the question: *Should manufacturing adopt automation of human tasks?*

There are arguments against the automation of human tasks in manufacturing:

- Computer-based automation can replace the worker for manual tasks, whereas AI-based automation can replace the thinking capacity of humans to perform cognitive tasks that follow explicit rules [140].
- AI-based industrial automation can disrupt the job market and can create mass unemployment.

However, automation does not necessarily have to replace humans entirely; instead, it can support them, for example, through intuitive virtual assistant systems for production-related tasks, which can help the factory workforce to make informed decisions.

For future factories, studying AI applications in the light of the Industry 4.0 context can bring new opportunities for human development. There have been cases in the past where some human tasks that were physically challenging and unpleasant were automated, resulting in improved human conditions. For example, for most of the 19th century, the automotive factories had humans welding and spray painting. Some of these tasks had a negative impact on worker safety and health. Today, industrial robots can carry out these tasks.

In many cases, the jobs that are easy for humans and difficult for computers could receive a boost. For example, a janitor job, which is considered a low-skilled task because it is not cognitively challenging, cannot be replaced using AI-based automation [141]. As a result, some low-wage jobs might become more important than before. Shannon Vallor, a contemporary philosopher and AI Ethicist, writes [142, p. 14]:

> AI is only one of many emerging technologies – from genome editing and 3D printing to a globally networked "Internet of Things" – shaping a future unparalleled in human history in its promise and its peril.

Nevertheless, artificial general intelligence is highly unlikely because AI systems lack human emotions and wisdom. Moreover, the unemployment problem can be handled through labor laws. As long as the policymakers cannot set a legal framework to minimize societal costs, technology might not have answers to offset the problems caused by manufacturing activities. Therefore, alteration of job skill demands and new job creation is the way forward [143].

Each epoch of industrialization has had its distinctive material, ideological, political, and cultural features and implications. The fourth industrial revolution is an opportunity to mitigate the issues that came with previous industrial revolutions, which can be associated with extravagance and consumerism. Negatives apart, industrialization has also had positive impacts on the world. It contributed to the reward of ingenuity. Industrial societies improved the standard of living of large populations by ridding them of many of the troubles of their predecessor (feudal societies). The level of industrialization of a country is also the measure of its development. Industrialized countries have a high rate of economic growth, labor productivity, and a better standard of living, where technology has been a driving force behind the transformation toward such development.

On this premise, it is highly relevant to visit the famous work of Heidegger on technology [144]. He makes no clear conclusions on how one should relate to technology but makes us ponder modern technology. In lay person's terms, Heidegger infers:

- Technology is more about *Techne*, which is knowledge. Techne is an Aristotelian thought where *design principles* are intellectual virtue but not the *design* alone. Knowledge can be about good and bad ways of doing a craft. Automation technology is likewise neutral.
- Technology's essence is in its *enframing* and the human way of revealing it. This thought suggests that automation technology can be interpretative.
- On how one must relate to technology, Heidegger mentions its pluralism and its *non-static ness* (a tree's tree-ness is not the same as technology's technology-ness). According to him, technology is about how people establish a relationship with it, a human choice.

Therefore, we can conclude that one must relate to automation technology by understanding its nature and risks and putting it to the right use.

Appendix B. Appended papers

(1) S. Mantravadi, J. S. Srai, T. D. Brunoe, and C. Møller, "Exploring Reconfigurability in Manufacturing Through IIoT Connected MES/MOM," in *2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, IEEE, Dec. 2020, pp. 161–165. DOI: 10.1109/IEEM45057.2020.9309989

(2) S. Mantravadi and C. Møller, "An Overview of Next-generation Manufacturing Execution Systems: How important is MES for Industry 4.0?" *Procedia Manufacturing*, vol. 30, pp. 588–595, 2019. DOI: 10.1016/j.promfg.2019.02.083

(3) S. Mantravadi, J. Srai, and C. Møller, "Application of IIoT-connected MES/MOM for Industry 4.0 supply chains: A Cross-case analysis," *Computers in Industry*, for submission

(4) S. Mantravadi, C. Møller, and F. M. M. Christensen, "Perspectives on Real-Time Information Sharing through Smart Factories: Visibility via Enterprise Integration," in *2018 International Conference on Smart Systems and Technologies (SST)*, IEEE, Oct. 2018, pp. 133–137. DOI: 10.1109/SST.2018.8564617

(5) S. Mantravadi, A. D. Jansson, and C. Møller, "User-Friendly MES Interfaces: Recommendations for an AI-Based Chatbot Assistance in Industry 4.0 Shop Floors," in *Intelligent Information and Database Systems. ACIIDS 2020. Lecture Notes in Computer Science*, vol. 12034, Springer, 2020, pp. 189–201. DOI: 10.1007/978-3-030-42058-1_16

(6) S. Mantravadi, C. Li, and C. Møller, "Multi-agent Manufacturing Execution System (MES): Concept, Architecture & ML Algorithm for a Smart Factory Case," in *21st International Conference on Enterprise Information Systems (ICEIS)*, Scitepress, May 2019, pp. 477–482. DOI: 10.5220/0007768904770482

(7) S. Mantravadi, R. Schnyder, C. Møller, and T. D. Brunoe, "Securing IT/OT Links for Low Power IIoT Devices: Design Considerations for Industry 4.0," *IEEE Access*, vol. 8, pp. 200 305–200 321, 2020. DOI: 10.1109/ACCESS.2020.3035963

(8) S. Mantravadi, C. Møller, C. LI, and R. Schnyder, "Design choices for next-generation IIoT-connected MES/MOM: An empirical study on smart factories," *Robotics and Computer-Integrated Manufacturing*, vol. 73, p. 102 225, 2022. DOI: 10.1016/j.rcim.2021.102225

ISSN (online): 2446-1636
ISBN (online): 978-87-7573-945-5

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