Application of MES/MOM for Industry 4.0 supply chains

A cross-case analysis

Mantravadi, Soujanya; Srai, Jagjit Singh; Møller, Charles

Published in:
Computers in Industry

DOI (link to publication from Publisher):
10.1016/j.compind.2023.103907

Publication date:
2023

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

Computers in Industry 148 (2023) 103907

Contents lists available at ScienceDirect

Computers in Industry

journal homepage: www.sciencedirect.com/journal/computers-in-industry

Application of MES/MOM for Industry 4.0 supply chains: A cross-case analysis

Soujanya Mantravadi [a,*], Jagjit Singh Srai [a], Charles Møller [b]

[a] Department of Engineering, University of Cambridge, UK
[b] Department of Materials and Production, Aalborg University, Denmark

ARTICLE INFO

Keywords:
Information systems
System requirements
Enterprise architecture
Expert interviews
Reconfigurability
Software
Interoperability
ISA-95
Brownfield implementation
Digital transformation

ABSTRACT

Manufacturing is facing challenges in integrating information technology (IT) with operational technology (OT) and implementing Industrial Internet of Things (IIoT) concepts in the industry to increase manufacturing flexibility. This paper addresses the research gap in designing and using next-generation manufacturing execution systems (MES)/manufacturing operations management (MOM) in IIoT to improve manufacturing flexibility through reconfigurability. For this, we follow an abductive research design and build on the literature on Industry 4.0′s information architectures and models to propose a framework for building *smart factory capabilities*. Using the framework, we collect empirical data on MES/MOM implementation objectives for smart factories for six case studies conducted over a 4-year research project in Denmark (2018–2021), primarily through semi-structured interviews.

Through cross-case analysis, we identify seven dominant themes that capture focus areas for MES/MOM implementation for IT/OT integration. We use these findings to present generalized design recommendations for IIoT-connected MES/MOM to support reconfigurability for Industry 4.0 supply chains. Our findings indicate that despite considerable investments from many companies in Industry 4.0 initiatives such as artificial intelligence-based analytics and digital twins, the industry is not yet in a state to extract the data from all its legacy production equipment. Therefore, we present design recommendations to enable Industry 4.0 supply chains with IIoT-connected MES/MOM by using the data from OT devices. Our analysis helps us conclude that open standards and open application programming interfaces (APIs) are key requirements for enhancing IIoT interconnectivity and interoperability to achieve end-to-end integration in supply chains.

1. Introduction

A smart factory of Industry 4.0 can be developed to successfully handle sudden market disruptions by making the best use of its manufacturing assets, including its digital tools. However, manufacturers face challenges in successfully using digital tools to implement the Industrial Internet of Things (IIoT), mainly due to the lack of real-time data exchange between information technology (IT) and operational technology (OT). To address this issue, this article synthesizes the objectives and approaches of different manufacturers to apply information systems such as manufacturing execution systems/manufacturing operations management (MES/MOM) for Industry 4.0 data management initiatives. Our primary focus is on manufacturing flexibility, particularly the capability of reconfigurability in Industry 4.0.

The manufacturing flexibility concept captures the idea of managing a company's production resources to tackle market uncertainties, and Zhang (Zhang et al., 2003) suggests that customers value volume flexibility and mix flexibility more than a company's internal capabilities

Abbreviations: AI, Artificial intelligence; API, Application programming interface; B2C, Business-to-consumer; CRM, Customer relationship management; ERP, Enterprise resource planning; IIoT, Industrial Internet of Things; ISA, International Society of Automation; ISA-95, An international standard; IT, Information technology; MES, Manufacturing execution system; MOM, Manufacturing operations management; MQTT, Message Queuing Telemetry Transport (a communication protocol); OEE, Overall equipment effectiveness; OPC UA, OPC Unified Architecture (a communication protocol); OT, Operational technology; PackML, Packaging Machine Language; PLC, Programmable logic controller; QFD, Quality function deployment; QR code, Quick response code; RAMI 4.0, Reference Architecture Model Industrie 4.0; REST API, Representational state transfer API; RFID, Radio-frequency identification; SAP ME, SAP Manufacturing Execution (a software product from SAP company).

* Corresponding author.
E-mail address: sm2608@cam.ac.uk (S. Mantravadi).

https://doi.org/10.1016/j.compind.2023.103907
Received 15 June 2022; Received in revised form 20 March 2023; Accepted 22 March 2023
Available online 3 April 2023

(Zhang et al., 2003). Zhang (Zhang et al., 2003) further states that volume and mix flexibilities can be achieved only through the conscious development of manufacturing competencies such as material handling and routing as well as management plans such as mass customization strategies. In this context, our study explores the application of MES/MOM for smart factory development to increase volume and mix flexibility and thereby enhance an enterprise's manufacturing flexibility.

Industry 4.0 principles enable improvements to the manufacturing processes and supply chains by establishing networks that operate their machinery, warehousing systems, and production facilities in the form of cyber-physical systems capable of autonomously exchanging information (Kagermann et al., 2013). Moreover, the ecosystem of Industry 4.0 has the potential to manage supply chain disruptions and provide personalized products to consumers.

Industry 4.0 supply chain is characterized as a network that is end-to-end integrated through interoperable systems and visible data in near real time. Because of this, supply chains can benefit in various ways, such as through shorter product life cycles or reductions in inventory. Zhou et al. (Zhou et al., 2015) state that Industry 4.0 is the realization of three integrations: horizontal integration, vertical integration, and end-to-end integration. Horizontal integration concerns IT systems integration along the supply chain, and Kagermann et al. (Kagermann et al., 2013) define horizontal integration as the following:

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.

Many manufacturing companies worldwide are embracing smart factories to tackle supply chain disruptions. Moderna's digital factory is a well-known example of successfully manufacturing COVID-19 vaccines for the world on short notice soon after the virus's genetic code was released (Ustinova, 2020). In smart factories, IT/OT links are central to building an IIoT infrastructure for an end-to-end integration, and IT/OT integration is an emerging area in most companies, seen as an opportunity to improve productivity. However, the method that should be followed to implement IT/OT integration is often unclear because there are not many holistic studies on it. Furthermore, the business case for IT/OT integration is often lacking. Motivated by this need, we examine the IT/OT integration problem for the supply chain and explore the solutions through smart factory design. This study is based on a cross-case analysis of six case studies from the process as well as discrete manufacturers with an international manufacturing footprint. We draw the research scope from three areas, as illustrated in Fig. 1.

1.1. Research issues

Developing manufacturing flexibility through smart factory design: Manufacturing companies are prioritizing digitalization to achieve competing priorities such as cost, sustainability, and flexibility. Of these, manufacturing flexibility is becoming an essential priority as companies are increasingly becoming aware of the severe market disruptions caused, for example, by the COVID-19 pandemic or 2022 Russia-Ukraine war. However, the following are the challenges companies are currently navigating:

- The radical roadmap set by the Industry 4.0 vision in which manufacturing enterprise needs to make its shop floor a marketplace of capacity (supply)
- The increasing integration of IT in the manufacturing operations, which needs to be curated using enterprise architecture to achieve a data-driven manufacturing enterprise
- An industry striving to make use of the data generated by enterprise information systems such as MES/MOM in IIoT for analytics and artificial intelligence (AI) applications
- The convergence of IT/OT demanding various departments in an enterprise to collaborate for digital transformation

Enabling Industry 4.0 supply chains requires the effective use of information systems; however, there are gaps in knowledge regarding the successful industry adoption of reconfigurability and information use. Therefore, this paper addresses research issues related to system design for reconfigurability (Morgan et al., 2021), centralized and monolithic information systems not compliant with Industry 4.0 data management (Almada-Lobo, Jan. 2016), and the cost-effective introduction of reconfigurability principles in existing systems (Bortolini et al., 2018).

From our impression, the academic literature on IT/OT integration in smart factories has mostly benefited from the domains of computer science and automation—however, there have been limited studies from an operations management and strategy perspective. Therefore, this paper 1) focuses on operationalizing IIoT-connected MES/MOM for smart factories to achieve manufacturing flexibility and 2) studies these problems through field research (e.g., case study analysis).

Section 2 reviews the literature on information architectures, models, and industry standards for a smart factory design. Section 3 describes the methodology of the multiple case study research based on semi-structured interview data. Section 4 showcases the case study data and presents the findings of the thematic cross-case analysis. Section 5 offers a discussion on the findings and presents recommendations on applying MES/MOM for Industry 4.0 supply chains along with a framework for enabling Industry 4.0 supply chains. Finally, conclusions are drawn in Section 6.

2. Background

2.1. Building reconfigurability using Industry 4.0 principles

Reconfigurability is a key driver of manufacturing flexibility because the modern manufacturing industry requires the ability to be responsive to changing market demands. This capability is supported by both technical and managerial aspects at both the factory and supply network level. Reconfigurable manufacturing systems involve low-level operative changes in a factory, where hardware and software components can be rapidly changed to adjust production capacity and functionality in response to sudden market changes (Koren, 1999). Pansare et al. (Pansare et al., 2022) highlight the role of reconfigurable manufacturing systems in meeting Industry 4.0 requirements. Meanwhile, supply chain reconfigurability is becoming increasingly important as future factories become modular and mobile, making it easier to relocate and keep

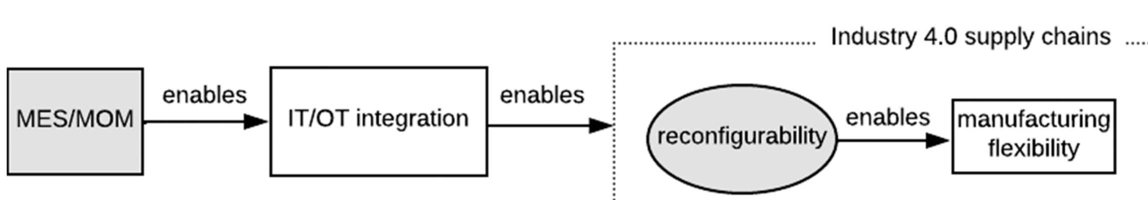

Fig. 1. Research scope.

manufacturing closer to the consumer (Fountaine, 2020). Dolgui et al. (Dolgui et al., 2020) define reconfigurable supply chains as follows:

A reconfigurable supply chain is a network designed in a cost-efficient, responsive, sustainable, and resilient manner that is increasingly data-driven and dynamically adaptable and capable for rapid structural changes in physical and cyber spaces, by rearrangement and reallocation or change of its components in order to quickly adjust supply and production capacities and functionality in response to sudden changes.

Digitalization is an important enabler of supply chain reconfigurability, and connected partners can deliver value with improved supply chain visibility. Fountaine et al. (Fountaine, 2020) state that smart manufacturing programs in companies must align with supply chain objectives such as the following:

- Supplier side—ensuring availability and pricing of supply
- Manufacturing operations side—optimization of production resources, increasing productivity, and keeping the costs of manufacturing assets low
- Customer side—ensure product quality and prompt delivery, agility to meet changing customer demands, and ability to effectively enter or exit markets

Industry 4.0–based digitalization enabled by digital twins and information systems provides real-time insights into manufacturing and supply chain operations. We believe that digitalization for mass customization strategies can automatically yield manufacturing flexibility. To drive digitalization in Industry 4.0, reconfigurability can be understood from the following two perspectives:

1) **Low-level reconfigurability in a factory changeability context**: For example, the ability to rapidly change machines or workstations, switch workpieces, or make structural changes in a factory (Wiendahl, 2007)
2) **High-level reconfigurability in a supply network context**: For example, the ability to rearrange "key elements" such as supply network ownerships and coordination of factories, the flow of material and information, interrelationships between supply network parties or product composition (Srai and Gregory, 2008)

Industry 4.0 represents the idea of reconfigurability as an adaptable system in which flexible resources of manufacturing and assembly systems automatically adjust production processes for different types of products and changing conditions (Garbie and Parsaei, 2021). Garbie et al. (Garbie and Parsaei, 2021) argue that reconfigurable manufacturing enterprises are integral to the Industry 4.0 vision. Fig. 2 shows the stages of digital maturity in the smart factory of Industry 4.0; the most advanced scene of Industry 4.0 is depicted with autonomous self-organizing and adaptable systems that support reconfigurability.

2.2. Background to smart factory information management and hierarchy

The smart factory is a key ingredient for horizontal integration because it can, for example, provide real-time product-centric data that could improve traceability across the supply chain. The smart factory employs advanced manufacturing capabilities using communication and information technologies (Sauer, 2014). Hermann et al. (Hermann et al., 2016) identified four design principles for a smart factory: *interconnection*, *information transparency*, *decentralized decisions*, and *technical assistance*—some of which can be used by academicians to develop reconfigurable manufacturing systems based on the principles of intelligent manufacturing control for manufacturing flexibility. We developed Fig. 3, which represents the hierarchical structure of systems in an enterprise as prescribed by the ISA-95 standard, which is evolving into a distributed platform–based architecture as the industry embraces IIoT. Therefore, in Fig. 3 we include the IIoT platform (e.g., ThingWorx IIoT Solutions Platform) in the ISA-95 structure and represent it as a Level 2 system responsible for monitoring and controlling IIoT devices.

The ISA-95 structure is still relevant in Industry 4.0 because it can help standardize data models and flows for manufacturing enterprise information systems such as MES/MOM (Mantravadi, 2022). Moreover, many companies already follow several principles of ISA-95 because the purpose of the standard was to propose a methodology to implement interfaces between the business and shop floor systems to automate information exchange (Scholten, 2007). However, the ISA-95 method might fall short in IIoT, which interconnects heterogeneous devices for data extraction and control in the smart factories—especially for inter-firm data exchange. Therefore, it is essential to steer integration projects such as the ISA-95 and MES/MOM to comply with Industry 4.0.

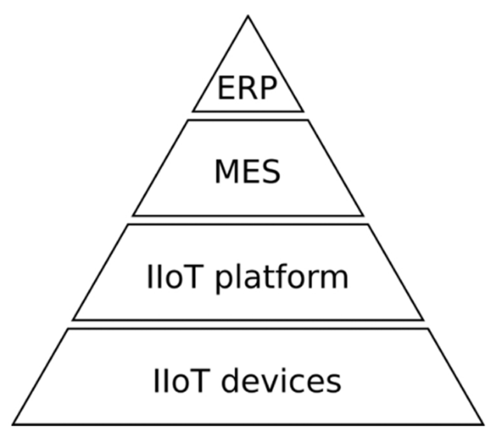

Fig. 3. ISA-95 hierarchy of systems in Industry 4.0.

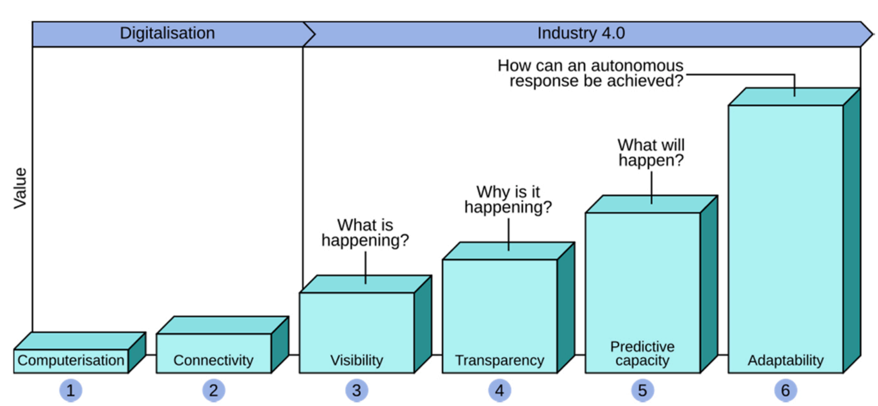

Fig. 2. Stages of Industry 4.0 (Schuh et al., 2017).

2.3. Related work on MES/MOM implementation for Industry 4.0 supply chains

MES/MOM, also referred to as a "manufacturing cockpit," is an enterprise information system that provides factory information in near real time to be a valuable source of product-level details that could improve supply chain efficiency. An IIoT-connected MES/MOM can consolidate data even from shop floor legacy devices, making it a unified interface for production data and an enabler of operations for Industry 4.0 supply chains that require flexibility.

In our previous work (Mantravadi et al., Dec. 2020), we presented a framework for applying reconfigurability approaches using MES functionalities for a smart factory. We developed a matrix (see Fig. 4) based on the quality function deployment (QFD) method that facilitates IT/OT integration for supply chain goals through reconfigurability. Based on an individual factory's case, scores can be obtained for the matrix. Our study served as a requirements analysis phase for developing MES/MOM functionalities to support reconfigurability based on the principles of autonomous reconfigurable manufacturing systems. However, we extend our study in this paper to synthesize the empirical data we collected over the last 4 years to further explore this topic.

Table 1 summarizes the selective literature review we conducted mainly through the Scopus database to understand the state-of-the-art MES/MOM implementation requirements for Industry 4.0 supply chains. Several recent studies have focused on the digitalization of logistics and exposed the challenges of developing systems for end-to-end supply chain integration. Pan et al. (Pan et al., 2021) highlight the importance of interoperability for interconnected supply networks while suggesting approaches and contributing technologies. Helo et al. (Helo and Hao, 2021) cover the concepts of the deployment of artificial intelligence–based systems for improving supply chain performance. Some studies also discuss the challenges and design principles for information system development for Industry 4.0 (Jaskó et al., Dec. 2020), (Cândido et al., 2009). Even though some of these studies do not explicitly write about Industry 4.0, they still study the information and communication technology trends highly relevant to smart factories.

Several studies have proposed improvements for information systems architecture design for logistics (Helo et al., May 2014), (McFarlane et al., 2016); however, these studies offer solutions to specific supply chain problems. A knowledge gap exists on optimally designing and applying MES/MOM for Industry 4.0 supply chains. From the literature review, we also note that there is limited knowledge of MES/MOM architecture that can support reconfigurability in IIoT. Moreover, for research contribution to be relevant to the practitioners, it is essential to consider the real-world scenarios in which many manufacturing environments are brownfields; i.e., the production facilities still use legacy manufacturing and IT assets. Therefore, our research objective is to study brownfield implementations of MES/MOM and Industry 4.0 projects in the companies, and we pose the following questions in this paper:

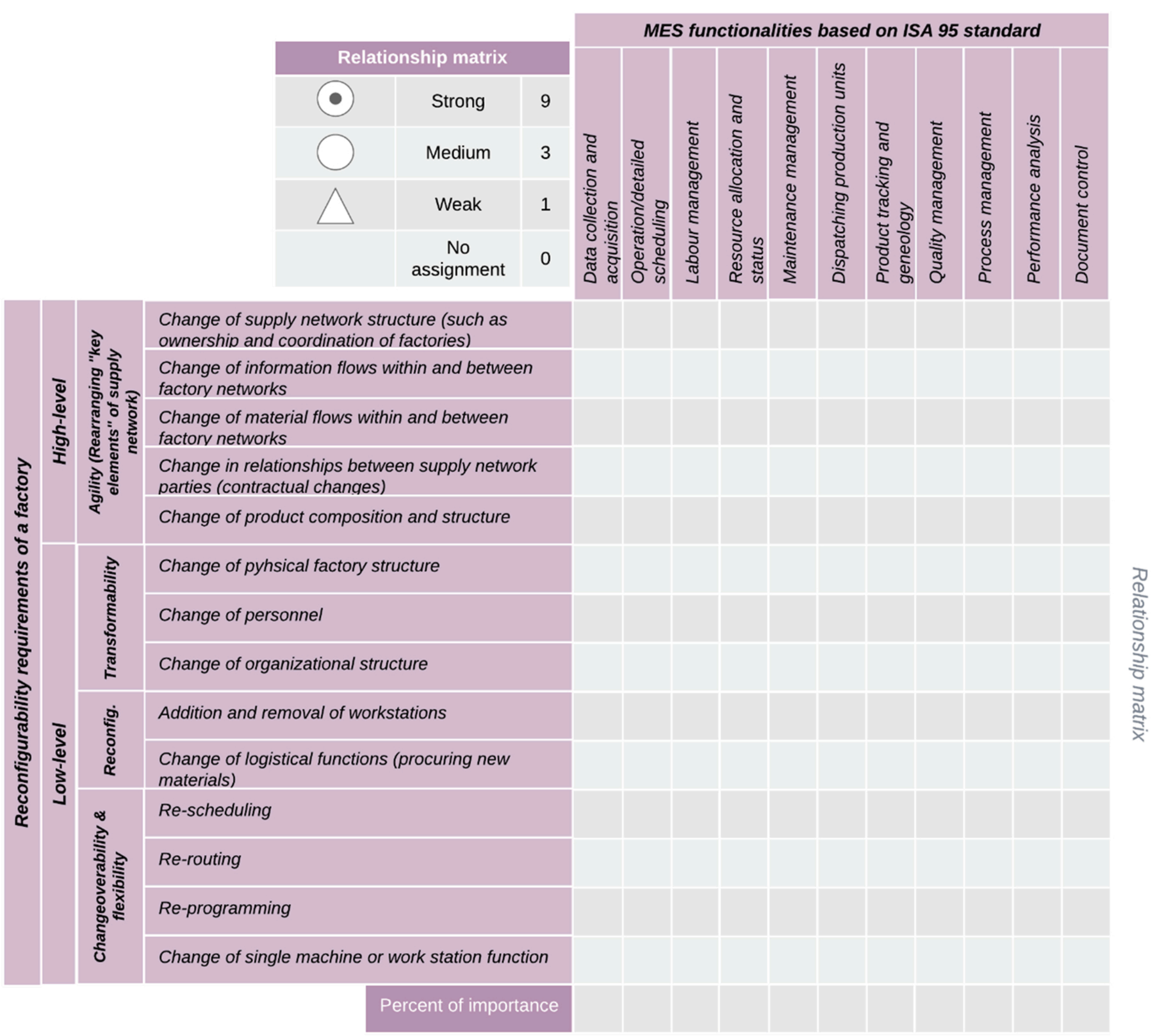

Fig. 4. House of Quality matrix to link reconfigurability requirements and MES/MOM functionalities (Mantravadi et al., Dec. 2020).

Table 1
Literature related to MES/MOM implementation challenges for Industry 4.0 supply chains.

Author (s)	Aim of the paper	Key takeaway	Method	Challenges identified
Pan, 2021(Pan et al., 2021)	To investigate how digital interoperability can help interconnect logistics and supply networks	Digital twins and autonomous self-organizing logistic systems presented as solutions	Review	Challenges for digital interoperability: Lack of adequate and open inter-organizational data sharing format, communications, privacy and security issues, and product and order-oriented data
Helo, 2021(Helo and Hao, 2021)	To provide critical analysis of AI-driven supply chain research and applications	Confirms the advantages of the adoption of AI for supply chain management through case study findings	Case studies	Further empirical investigations are needed to understand the AI application in supply chain management
Jasko, 2020(Jaskó et al., Dec. 2020)	To review ontology-based methodologies for MES/MOM development in Industry 4.0	Formal models and ontologies will play an essential role in Industry 4.0 systems	Review	The MES should interconnect all components of cyber-physical systems, and there are research opportunities to study MES for collaborative production management
Lobo, 2015(Almada-Lobo, Jan. 2016)	To analyze the role of MES/MOM in Industry 4.0	MES/MOM in Industry 4.0 will use decentralized control	Industry letter	Decentralized control is needed for Industry 4.0 systems, and research needs to investigate the logical decentralization of computing resources for horizontal integration
Candido, 2009(Cândido et al., 2009)	To present research challenges and applications of service-oriented architectures (SOAs) into reconfigurable supply chains	Low-level adoption of SOAs (e.g., OPC-UA) in production is beneficial for reconfigurable supply chains	Review	Seamless and effective IT integration is challenging for effortless access and management of distributed data

RQ1). What are the objectives of MES/MOM implementation projects to achieve Industry 4.0 supply chains in brownfield manufacturing companies?

RQ2). How can the design of MES/MOM be improved and effectively applied to support reconfigurability in manufacturing?

To answer these questions, we perform requirements analysis for MES/MOM by gathering information on Industry 4.0 needs from our six case companies. Then, we specifically analyze the data on MES/MOM implementation for Industry 4.0 to draw conclusions that support its development in the direction of reconfigurability. To achieve this goal, we develop a framework for *smart factory capabilities* using Industry 4.0 design principles (Hermann et al., 2016) to guide our requirements-gathering process based on interview research. Finally, through cross-case analysis of case data, we generate themes that determine the problem areas that can become the building blocks to enable Industry 4.0 supply chains.

2.4. Research framework

Fig. 5 illustrates an initial conceptual framework for smart factory capabilities grounded in theory. It is based on the four Industry 4.0 design principles proposed by Hermann el al. (Hermann et al., 2016), which are (a) interconnection, (b) information transparency, (c) decentralized decision making, and (d) technical assistance. The coding dimensions of interest are displayed in the grey boxes. The framework explains how the Industry 4.0 technologies can be applied to meet supply chain requirements and shows the synergies between business needs and technological capabilities. The integrative framework starts with smart factory capabilities that require ISA-95-based MES/MOM and includes four major design criteria of Industry 4.0 (Hermann et al., 2016) that presents four technological capabilities: ***digital twin, digital modularity, distributed control, and IIoT interconnectivity***. We argue that these technological capabilities must work together to fulfill a company's business requirements, with IIoT interconnectivity being a central technological enabler. The framework focuses on manufacturing flexibility as the business capability studied in this paper and highlights its connection with reconfigurability, as explained in Sections 2.1 and 2.3.

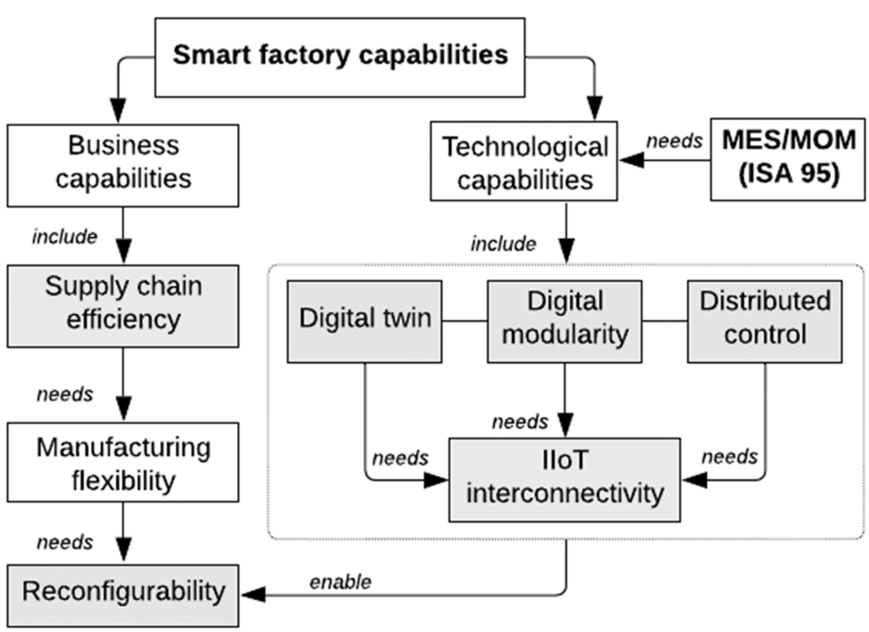

Fig. 5. Framework for smart factory capabilities (Mantravadi, 2022).

3. Methodology

3.1. Case study research

This study was part of a broader engagement with the companies from the Manufacturing Academy of Denmark (MADE) and involved interviews as the primary method of data collection. Additional data were collected from MADE workshops and design demonstrator events. We followed the seven stages of interview research, which include Thematizing, Designing, Interviewing, Transcribing, Analyzing, Verifying, and Reporting (Kvale, 2008). We selected interviewees from five very large (>10,000) and one large (around 2000 employees) global manufacturing companies, based on our case selection criteria, which required the companies to be actively involved in Industry 4.0 projects and working toward digitalization efforts with MES/MOM. Further details about the case company section is available in Table 2 (column 4).

We selected interviewees who were actively involved in the MES/MOM implementation projects in their respective companies and had a thorough knowledge of Industry 4.0-based innovation. We used the cross-case synthesis method of the case study research as it enables the researcher to draw robust cross-case conclusions on the phenomenon (Yin, 2014). We thematically analyzed the data and obtained second-order themes. The research process involved different phases, as presented in Fig. 6 below.

3.2. Data collection

The data collection approach is listed in Table 2.

3.3. Data analysis process

The data collection was performed in cooperation with the case companies. Because of commercial confidentiality, we anonymized the company names and referred to them with case numbers and by their industry type. The responses from the interviewees were electronically recorded as video files because the interviews were conducted using Skype (in 2018 and 2019) and MS Teams (in 2020 and 2021). These recordings largely consisted of the respondents' unstructured textual commentaries and PowerPoint presentations. The first author conducted all the interviews with active participation from the third author in the first three interviews. Each interview lasted 60–90 min, and the first author manually transcribed the audio files and analyzed the data in Nvivo. We found that the six cases we selected provided us with sufficient data to make substantial generalizations to answer our research questions and to develop meaningful themes. Our in-depth cases benefitted from rich data not only from interviews but also through workshops and secondary sources such as company reports. We used a purposive sampling approach and theoretical saturation criteria to guide our decision to select and analyze the six cases in our study.

The crucial data from the respondents were triangulated using the company documents and internal project files. Please refer to the rightmost column of Table 2 for further details on data analysis protocols. We followed the Miles and Huberman framework (Miles and Huberman, 1994) and used Nvivo R1 for thematic analysis (Bazeley and Jackson, 2013), for which we place case data along the coding dimensions (see Table 3). First-order themes are the coding dimensions (see Fig. 5, grey boxes), and the emerging second-order themes are presented in Table 4. Following are the coding dimensions:

1) **Data sharing and information flow in the supply chain**: The company's objectives regarding supply chain management through digital solutions.
2) **Reconfigurability**: The company's objectives regarding tactical and structural changes it intends to make in its factory.
3) **Process digital twin**: The company's objectives regarding real-time insight into the production process.
4) **Distributed control**: The company's objectives regarding decentralization of manufacturing control (e.g., multi-agent architecture).
5) **Digital modularity**: The company's objectives regarding the ability to allow easy addition and exchange of system components (e.g., microservice architectures).
6) **IIoT connectivity**: The company's objective to connect production assets and other devices in the supply chain to a network.

4. Analysis and findings

4.1. Case study narratives on smart factory journeys (exemplar cases)

In this section, we describe two exemplar case studies that serve as representative examples of successfully driving MES/MOM implementation projects and are illustrative of our research questions. These two companies with international manufacturing footprints have successfully implemented Industry 4.0 technologies and offer vastly different scenarios.

4.1.1. Case 1: Dairy products—IoT platform for food supply chain

This case study focuses on commissioning an IoT platform for the company's food supply chain. Case company 1 is a 100-year-old world-leading dairy manufacturing company from Scandinavia. It is a farmer-owned cooperative and the world's largest manufacturer of organic dairy products, with thousands of product variants sold in the market either under its brand name or with a private label.

The dairy industry is highly consumer driven, and there is an increasing demand from consumers for information on the product origins and operations—for example, how animals are treated or how hygienic the farm conditions are. To meet these demands, the company recognized the potential of data collection and information transparency among the company, farm owners, and consumers. Therefore, the company embraced Industry 4.0 as its agenda to digitalize its supply chain with an IIoT ecosystem. Its goals include improving logistics, food quality, flexibility, and scalability and establishing a foundation for data management and digital services.

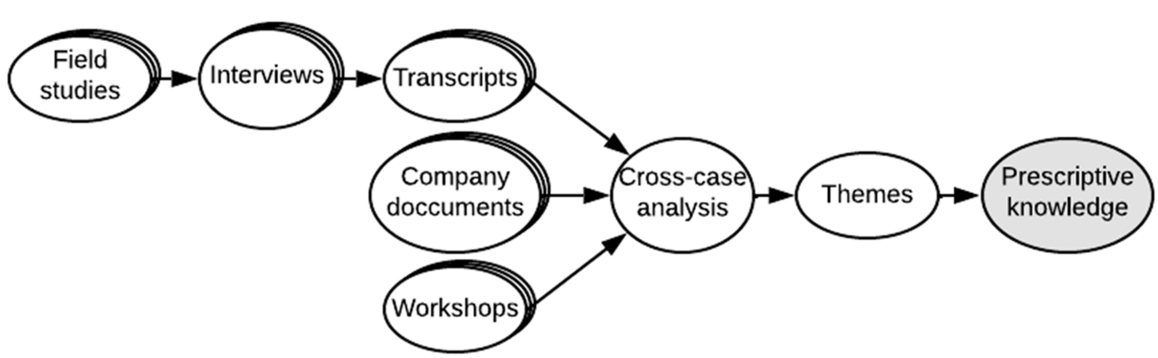

Fig. 6. Research process involving six case companies.

Table 2
Case study details and data collection approach (Mantravadi, 2022).

	Industry 4.0 vision	Interests in MES/MOM	Case selection criteria	Respondent (s) details	Data collection approach	Data collection protocol and triangulation
Case 1: Dairy products	To digitalize supply chains to create value from the IIoT data(Mantravadi and Møller, 2019)	The need to use enterprise systems to achieve an Industrial IoT ecosystem in the company	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(Mantravadi and Møller, 2019)	The demand from manufacturing projects to obtain manufacturing intelligence	Strategy for MOM and a core MES platform rollout	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	To be a knowledge-driven enterprise by discovering, articulating, and effectively utilizing the data(Mantravadi and Møller, 2019)	The need to improve competitiveness through streamlining processes	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 in Horsens, Denmark	- 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	To utilize IoT data for better decision making in design, supply chain, training, logistics, and equipment monitoring	ISA-95 standardization, end-to-end digital data handling, and traceability	Business unit with a full mass customized production platform and the goal 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 h 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	To have a Digital twin infrastructure for automatic data collection from products in the market	Enterprise systems for data generation, processing, and presentation to have the right quality of information	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 h interview on skype for business in December 2019 - Two one-day workshops in 2019 and 2020 involving formal presentations on 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	To become a data-driven company, mainly to optimize	Extracting data out of machines and making it discoverable	Building logic into systems to handle the synchronization of orders,	Two senior solution architects	Interviews, follow-up interview, Virtual factory visit, design	- Agile approach open innovation project in 2020 for 6 months with monthly

(*continued on next page*)

Table 2 (*continued*)

	Industry 4.0 vision	Interests in MES/MOM	Case selection criteria	Respondent (s) details	Data collection approach	Data collection protocol and triangulation
	production equipment and maintenance		edge analytics for machine-level automation, and better supply chain management by reducing supplier complexities and distribution networks		demonstrator in autumn 2021	design sprints and weekly status discussions - Two 1 h 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

The company chose the ISA-95 approach and promptly kickstarted its MES rollout program to address data silos and prevent low-level data from being held up with its suppliers. To improve IIoT connectivity, the company also decided to follow carrier and semantic protocols such as MQTT and OPC UA. It embraced open industry standards and actively participated in RAMI 4.0 discussions to push for open standards. On a strategic level, its MES implementation goals were to standardize and establish a stronger connection between its factory (and farms) networks and the central IT department.

4.1.2. Case 6: Plastic toys—AI-driven prepackaging with digital twins for mass customization

This case study focuses on digitalizing the prepackaging process in plastic product manufacturing by introducing digital twins and production line–level innovations to improve line productivity. Case company 6 is a world-leading plastic toy manufacturing company with an iconic product. The company is almost a century old and has a vast international manufacturing network with five manufacturing sites on three continents. It has flexible supply chains and an e-commerce platform to meet the global market demands for customized products. Its product has several variants, with toys of more than 3000 shapes available in various configurations. The company also collaborates with Disney to manufacture toys based on its film franchises.

The toy market is facing intense competition with decreased profit margins due to the increasing presence of new companies offering products at lower price ranges. With the increased internet-based e-commerce in recent years, consumers expect customized products with short delivery times. To mitigate the supply and delivery issues, the company has embraced Business-to-Consumer (B2C) strategies and invested in research and development of consumer-centric products. In addition, the company has adopted an Industry 4.0 strategy, such as developing digital twins to improve its operations.

The company has concentrated on prepackaging and implemented several initiatives to enhance productivity, such as reducing the workload of prepack machine operators through artificial intelligence (AI) driven automation to eliminate failures and reduce machine downtimes. To achieve automation, the company aims to adhere to established industry standards such as ISA-95 for data storage and exchange. In addition, it is focusing on defining an appropriate IT/OT architecture using a modular MES/MOM layer that can interoperate seamlessly. The company acknowledges that from a system standpoint, a MES/MOM overlaps with IT and OT.

Table 3 summarizes the relevant details of all the cases.

Table 3
Structuring cases along the coding dimensions of smart factory capabilities.

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
Data sharing and information flow in the supply chain (from secondary evidence)	The company is investing in CAPEX to improve production capacity and footprint, focusing on digital supply chains by increasing value from the data. However, it has challenges around data being held with vendors on disconnected clouds. The company wants to own the data and be able to analyze and change vendors.	The company needs to make improvements in warehouse management systems. To become digital leaders, it wants to roll out digital solutions for predictive and descriptive maintenance on the end-user side. It also wants to strengthen partnerships with suppliers that can produce larger volumes.	The company is interested in real-time scheduling and making a daily plan for each factory on what to produce. Being a cooperative of over 5000 farmers, it cannot have suppliers outside this pool.	The company is highly dependent on its vendors and what they can deliver. Its vision includes increased integration by optimizing that part of the value chain. It wants to gain greater visibility for coordinating logistics. In addition, it wants to analyze relevant data sets, which can impact the extended value chain.	The company's main supply chain interest is to deliver faster. It also wants to improve stock management because it does mass customization. It would like to decrease its stock with better forecasting tools. It also wants to make better use of advanced shipping notifications.	The company can shuffle its orders among factories in different countries because it has the same manufacturing setup in every factory globally. It seeks improvements around planning orders and optimizing the use of resources. It also wants to implement traceability on lower levels.
Reconfigurability	The company aims to achieve stronger relations between factories and central IT. It intends to gain	Replacing legacy equipment is not economically feasible; therefore, existing equipment	Unlike the poultry and fish industries, which are relatively more automated, the company depends more	Because the company specializes in one-piece flow, many business processes have had to be	The company has invested in a solution for day-to-day production planning to remove	The company is creating software solutions based on data that can enable faster changeovers. Although it has only one

(continued on next page)

Table 3 (*continued*)

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
	flexibility but still follow the ISA-95 model. Vendor lock-in and silo solutions need to be avoided.	needs to be updated. It is implementing IoT and sensors, but this requires much effort across the company's 23 factories.	on manual labor. Because a sales order for one type of meat necessitates processing an entire animal, the animal must be used to the best extent possible. This includes assigning a single sales order to multiple sites for manufacturing wherever it fits.	automated. It wants to make the IT architecture modular so that it can be adapted to different sites globally.	the need for the "water spider" to plan the next day manually, moving away from Excel sheets. The main key performance indicator (KPI) it is interested in is changeover time, ranging from minutes to hours, depending on the actuator.	process, molding, it often needs to change different parameters—and the goal is to provide the user with the information required to perform the changeover. It is not prepared for transformability, i.e., introducing a new product or process.
Process digital twin	MES served as a process digital twin. A use case example in which real-time data from MES were used to identify a flaw in cheese as a storage problem, which was previously thought to be a production problem when data were manually acquired. The company aims to have dashboards on the MES level to give more flexibility and visibility to operators using real-time information. Therefore, it aims to gather more data at the MES level. It is investing in a cloud-based solution for factory process digital twins to know what is happening on site.	The company wants to have a visual factory providing real-time information on production status. It has been exploring augmented reality for visualizing information on the status of machines and production but found no business case.	The company has developed a dashboard for farmers that tracks their livestock's weight and other indicators, allowing it to respond to any issues and increase productivity. Over half of the cooperative's 1600 pig farmers have used the dashboard. In meat processing factories, the quality of the meat is of utmost importance. Therefore, it envisions to enable MES/MOM to track temperature, processing time, cleanliness of machines, etc., to improve the quality. Data visualization may also be instructive to operators, explaining the needed operations.	Only an overview of the production status is available in the MES. The company aims to extract and visualize the real-time process and manufacturing data and enable alerts, predictive maintenance, augmented reality for maintenance and manufacturing, and track OEE.	The company cannot currently extract the needed data from its machines. It aims to gain this capability to improve production planning and help find the causes of errors in production. It is also exploring AI to predict the behavior and lifetime of the actuators it produces; however, this also depends on shop floor data.	The company is deploying ThingWorx and linking it with the Azure IoT platform. The factory will be modeled in ThingWorx, and this model can be accessed through a Mendix front end from a webpage or phone app. Production is standardized, which enables comparing these data across factories—for example, to compare production between factories in Mexico and China. Because molding machines are frequently moved around on the shop floor, there is also interest in installing sensors that track their position in real time.
Distributed control	The MES layer is the point of contact for all the factory PLCs. Master data are managed per factory by MES to allow local variation. Some data are not transparent to other locations. The company is committed to the ISA-95 structure to build its future MOM platform. It is trying to include level 1 and 2 activities in the ISA-95 activity model.	On-premise control is desired against a centralized IT to avoid high latency and disruption in production in network issues. The aim is to run production without connecting to ERP for at least 3 days.	The SAP ERP is not involved in production scheduling. Instead, it is done locally on the shop floor. The company hopes to automate its slaughterhouses' most expensive manual work to reduce manual labor.	The company is working on migrating to a single global SAP ERP instance. Each factory has its own MES instance, and each production line has its controller.	The company currently does not have a dedicated MES solution, but it is exploring the ISA-95 structure as a guideline to move away from its "spaghetti" IT system landscape. It is interested in using IIoT platforms to control production machines.	Because of the concerns of MES being a monolithic application, the company has moved to an agile microservice architecture to cover its MOM layer. Its MOM solutions are not cloud based. It wants to push all production data to an IIoT platform called "Crystal Ball," running on Azure. The goal is machine learning on an edge device that optimizes the machine. Artificial intelligence–based control is already being implemented in one of the company's processes dominated by legacy machines to achieve speed and automatic control.
Digital modularity	MES implementation is in progress to allow communication between the business and the shop floor. The	The company's ERP solution provides an interface to MOM systems. Different MOM systems can	The company has one SAP ERP instance globally for production planning. Currently, it has more than 30 MES	The MES systems are built around ISA-95. The company is using SAP ME on half of its sites and is moving	The company is working toward an IT architecture that simplifies integrating new	The company uses a microservice-based architecture, which allows a relatively easy replacement of software

(*continued on next page*)

Table 3 (*continued*)

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
	Wonderware ArchestrA platform provides unified communication to all the PLCs and devices of the factory. The company demands suppliers' PLCs to comply with the communication standards of Wonderware.	connect to these interfaces and give a unified view of ERP. The company invested in multiple industries and wants to use different MOM solutions suitable to the individual sector. To reduce the complexity of IT maintenance, it aims to have all the MOM solutions connect to the ERP through the same interface (e.g., REST API).	solutions across 72 factory locations. It aims to have one unified MES solution for the MOM layer per factory.	toward using it globally. It is also working on standardizing its maintenance tool package.	functions and systems.	components. It purchases different solutions to cover the MOM layer, each best suited for a given function, and integrates them into its architecture through microservices.
IIoT interconnectivity	Data collection from machines that was previously performed manually has now been automated through connection with MES. The company wants to connect current MES and PLCs to new edge solutions and smart devices using open industry standards.	The company is promoting OPC UA to connect devices, but legacy systems have customized interfaces. Adding IoT sensors to legacy systems may help extract their data because the equipment is more reliable than humans. But standards are needed.	Adding sensors may be helpful to assist the labor. Vertical and horizontal integration is desired for traceability at the unit level and production path.	OPC UA and PackML were recently chosen as integration and package description standards, respectively. The company is working on standardizing the data structure at ERP and CRM levels.	Extracting data from machines is difficult because many machines are old and not designed for connectivity. Connectivity from ERP to MES to the machine is desired. The current MOM has redundancies in data storage that should be removed.	The company is in the process of connecting machines to enable data collection and traceability. Some old machines are deemed not worth updating. ThingWorx and Kepware connect machines in the parking area with a custom converter to connect ThingWorx to the other systems. ERP has not yet connected adequately to manufacturing systems.

4.2. Cross-case analysis and emerging themes

Table 4 summarizes the analysis of six cases across six coding dimensions. Its last column presents the second-order themes that emerged (highlighted in bold) as outstanding features of MES/MOM and manufacturing flexibility. The first-order themes resulted from coding the thematic observations from the six case studies (see Table 4) and the Table illustrates how the case companies aim to follow Industry 4.0 principles through MES/MOM design and application. For instance, case company 6 aims to have digital modularity by employing microservice-

Table 4
Summary of cross-case analysis of six cases using Nvivo R1 (Mantravadi, 2022).

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
Data sharing and information flow in the supply chain	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 the material & component level* (2,3,4,6) *Real-time information sharing* (3,4,5)
Reconfigurability	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 workstations and **factory structure**; therefore,	They want a backend MES solution to improve scheduling efficiency on the shop floor. They want increased **data visibility** to support the	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	The company aims to empower human users and have operator assistance for **changing** colors, shapes, molds, and ancillary	*Reduce changeover time and increase delivery speed* (4, 5) *Supply network coordination using IT* (1,2, 4,6)

(*continued on next page*)

Table 4 (*continued*)

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
		they want to enhance machine connectivity/	distribution of orders to sites for better use of slaughtered animals.		investing in better shop floor planning software.	equipment in their process. They have a good level of **supply network coordination** due to a globally harmonized IT infrastructure.	
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 a visual factory at the MES layer. **Establish a 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)
Distributed 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	*Process analytics technology* *Edge analytics* (3,6)
Digital modularity	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 interconnectivity	Batch data acquisition through MES Use of **open standards/ protocols** for interconnection (such as OPC UA, MQTT)	Looking to extract data from **legacy machines** by **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 is in process, but some **legacy systems** are 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)

based architecture for MOM. The numbers next to the second-order themes in the parentheses of the last column represent cross-references from the case study numbers. These themes are supported by the evidence from at least two case studies.

4.3. Summary of findings and interview insights

We identified seven common themes emerging from the cross-case analysis (see Table 4, column 8), namely: ***traceability, real-time information sharing and retrieval, reduction of changeover time, supply network coordination, edge analytics, ISA-95 and open standards and open APIs, integration of legacy machines*** (e.g. adding sensors). Among them, traceability, real-time information sharing and retrieval, and edge analytics concern the company goals regarding Industry 4.0, which can be directly achieved by implementing IIoT-connected MES/MOM. One of the striking observations was that many respondents identified legacy systems as the main hurdle to Industry 4.0 implemenation.

We present brief summaries of each theme, along with representative quotes from the interviews. To maintain the authenticity of the interviewees' expression, we preserved their habitual language in the passages (Kvale, 2008).

4.3.1. Theme 1: traceability

Four out of the six interview respondents emphasized the need for traceability and have taken intiatives to track the origins and flow of products in the supply chain.

> *"For example, to follow a [piece] throughout the production line is not possible in [our company] yet. We don't yet have connectivity to all the machines, and we don't have the scanner on all the machines to scan it. We currently can do traceability only at a very high level. But there are other challenges to implementing traceability; for example, we might not want to put a QR code on the packet because it might not look nice. We can then use RFID tags inside the bags. Our status of Industry 4.0 is we are still connecting machines." (Sr. Solution architect, Plastic toys)*

4.3.2. Theme 2: real-time information sharing and retrieval

Four companies have expressed a belief that retrieving shop floor information in real-time is essential to gain insight into the production processes and have expressed confidence that MES/MOM can achieve this. Aditionally, three companies have expressed a desire to enhance their planning and forecasting capabilities through real-time information sharing.

> *"Every item on the shop floor would have an ID that refers to a batch, grouped as per the product. The batch is known in the MES layer and every time they needed analysis of the packaging details of 270 types of cheeses, they asked the operator to register the product so that the data enters the MES database. This system made it easy to examine problematic cheese at the shop floor level, where the technicians believed that the flaw was due to a production problem but the day-to-day analysis of the real-time data* via *the MES layer helped them identify the issue to be a storage problem." (Sr. IT architect and product owner, Dairy products)*

4.3.3. Theme 3: reduction of changeover time

Two respondents mention reducing changeover time as their companies' primary target, and they believe that better shop floor planning software is a way to achieve this.

> *"The main KPI we are interested in is the change over time. Every order is specific to each customer. Orders can be from 2 actuators to 100 actuators (or more). However, changing to a new order, the changeover takes a lot of time. If we can reduce that, we can increase our productivity." (Project engineer, digital production, Electric actuator equipment)*

4.3.4. Theme 4: supply network coordination

Four out of the six companies focus on coordination among supply chain partners through the integration of business processes with vendors and harmonization of IT infrastructure across different locations.

> *"We are highly dependent on our vendors and the things they can deliver to us – the quality and speed that they deliver to us. Integrating more and skipping some of the traditional business processes by optimizing that part of the value chain has been seen as part of the [Industry 4.0] vision." (Director for global smart automation systems, Energy equipment)*

4.3.5. Theme 5: edge analytics

Two of the interviewees have mentioned having initiatives to optimize manufacturing performance by using machine learning on edge devices to analyze data from their equipment.

> *"Currently, we are enabling ourselves to talk to the molding machines by hooking in ethernet cables into them. But the next step is to get the data out of our machines and enable people to work with the data. We have an IIoT platform Crystal Ball running on Azure, where we want to hook in all the data sources. The next step could be to utilize some of this data to create machine learning. Push the machine learning into an edge device next to the machine to optimize the machine." (Sr. Solution architect, Plastic toys)*

4.3.6. Theme 6: ISA-95, open standards, and open APIs

Standardization of interfaces and data formats is a central issue for all our case companies. Five of the six companies reported attempting to use ISA-95 and five of them mentioned the importance of open standards to their Industry 4.0 projects, and two mentioned the importance of open APIs.

> *"We started the standardization journey, and on the components side, we have been specific with the standards. In one segment, we were not so standardized, but we recently specified OPC UA as the standard for integration and PackML to describe the packages that go back and forth. We are considering HMI layouts. We might standardize further." (Director for global smart automation systems, Energy equipment)*

4.3.7. Theme 7: integration of legacy machines

Integrating legacy equipment into IIoT is a concern for most of our case companies. Four of our interviewees expressed difficulties in extracting data from legacy systems, while three other described plans to add sensors to existing equipment to obtain the necessary data.

> *"Our company has equipment that costs millions of dollars which is going to last for the next 15 years. Exchanging that for anything new is just not feasible. But IoT might help us with legacy systems [.] To get the data out of legacy systems I need the right hardware so I might buy some IoT sensors and make an interface to Aprisso. An RC232 cable might not be the right hardware to extract the data. That's not a good interface." (Head of global IT, Wind turbine and electric equipment)*

5. Discussion

Although previous research examined reconfigurability needs and proposed Industry 4.0–related solutions, empirical studies on MES/MOM implementation for reconfigurability are lacking in the literature. Despite several attempts to use Industry 4.0 methods for supply chain problems, the lack of comprehensive empirical studies in this area has prompted us to adopt a systems thinking approach. This approach allowed us to examine the MES/MOM implementation problem within the broader context of Industry 4.0 systems. We believe that the systems thinking approach can provide long-term strategic benefits to develop Industry 4.0 supply chains. The identified themes capture the problem areas that require attention for successful MES/MOM implementation to achieve Industry 4.0 supply chains.

5.1. Enabling Industry 4.0 supply chains with MES/MOM

International manufacturing networks have complex supply chains, and it can be challenging to manage heterogeneous systems in factories across different geographical locations. The problem becomes even more acute with mergers and acquisitions because newly acquired plant facilities may not have similar systems to their parent enterprise, further adding complexity to the heterogeneity. In such situations, implementing standards can be beneficial to link the newly acquired systems to their distribution channels and achieve optimal coordination within the manufacturing network.

Optimization of physical distribution is crucial during supply chain disruptions. However, previous studies in the field of supply networks suggest that there is a need for further research on methods and tools to optimize international manufacturing networks (Cheng et al., Nov. 2011). Efficient handling of physical (product) distribution is essential to ensure product delivery to the customer. This falls under the domains of logistics management, materials management, demand management, order fulfillment, etc. (Lambert and Cooper, 2000) and requires support from IT systems such as MES/MOM.

Industry 4.0 is expected to bring mobile and modular factories (Fountaine, 2020), leading to more heterogeneous systems. To manage the resulting complexity, industry is increasingly turning to RAMI 4.0, a reference framework for Industry 4.0–based digitalization. As RAMI 4.0 framework (Hankel and Rexroth, 2015) incorporates the functional hierarchy of ISA-95, implementing MES/MOM becomes crucial to enabling Industry 4.0 supply chains. However, the industry is currently uncertain about how to use MES/MOM effectively. Our findings on MES/MOM implementation project objectives provide insights into how it could be developed and used for Industry 4.0. The interview data reveal companies approaches to reconfigurability, offering clues on how information systems could be used more effectively. We address **RQ1** in Table 3 and summarize the MES/MOM implementation project objectives for reconfigurability using the following excerpts from the interviews.

System design for reconfigurability is a challenging task (Morgan et al., 2021), especially when it comes to cost-effectively introducing reconfigurability principles in existing systems (Bortolini et al., 2018). However, our study reveals that investing in a high-quality information system can have long-term benefits for future scalability and reconfigurability. This was highlighted by the head of global IT at case company 3, who stated:

> *The current MES system that we have is not cheap, but it is cheaper in the long run. We wanted a Rolls Royce of MES because we looked at the company's requirements ten years from now and understood what we need in the future. We did that using ISA-95 model. There is a very structured process around ISA-95 model. (Head of global IT, Wind turbine and electric equipment)*

A centralized and monolithic information system is not suitable for Industry 4.0 data management (Almada-Lobo, Jan. 2016). Our study sheds light on the importance of interoperability for MES/MOM in manufacturing companies. For instance, the senior solution architect at case company 6 emphasized the need for open APIs:

> *I don't mind what model my machine is or where in the world it's situated; the data looks the same because it's been unified in my MES layer by the MES standard software. But what I require for my MES software is that it's easy to integrate. It must have open APIs. We prefer rest APIs and that, which is both readable and writeable so that I can communicate with my machines through MES. (Sr. Solution architect, Plastic toys)*

5.2. Recommendations for applying IIoT-connected MES/MOM for reconfigurability

Using abductive reasoning, we answer **RQ2** by presenting Fig. 7, which proposes how MES/MOM can be designed and applied for Industry 4.0 supply chains. The levels in the pyramid represent the steps toward achieving these goals; each level contains propositions for building reconfigurability based on the themes that emerged from Table 4.

To achieve end-to-end integration of Industry 4.0 supply chains, it is necessary to adopt both top-down and bottom-up strategies. This requires the top management of a manufacturing enterprise to have a vision for a smart factory and develop its enterprise architecture accordingly. For example, a robust digital business architecture centered around MES/MOM can be a starting step for AI applications in the supply chain and a prerequisite for traceability (Helo and Hao, 2021). At the same time, bottom-up approaches require several shop floor initiatives to aggregate real-time production data to be shared with MES/MOM. This will enable MES/MOM to interconnect with cyber-physical systems (Jaskó et al., Dec. 2020). Only with high-quality production data can traceability be achieved in the supply chain and value be gained from AI analytics.

Fig. 7 illustrates the importance of IIoT interconnectivity in a factory as a foundation for Industry 4.0 supply chains. We stress that companies should focus on reusing existing legacy production assets by upgrading them, for example, by adding sensors to obtain data from the low-level production activities. In addition, companies should actively work on standardizing the interfaces between IT and OT in their factories. This requires them to demand that production equipment and software suppliers adhere to open standards such as OPC UA. By doing so, companies can address the problems of interoperability and inter-organizational data sharing and enable modularity within an organization's IT systems (Pan et al., 2021), (Cândido et al., 2009).

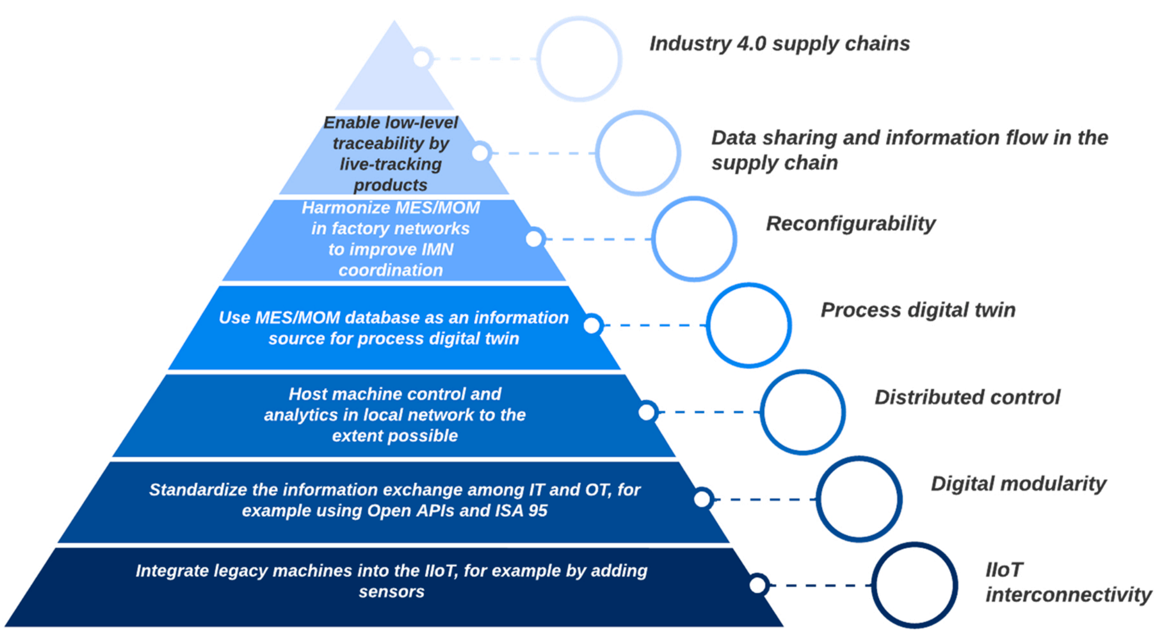

Fig. 7. Steps to enable Industry 4.0 supply chains with IIoT-connected MES/MOM (Mantravadi, 2022).

6. Conclusions

In this paper, we conducted a cross-case analysis to investigate the expectations from MES/MOM to achieve smart factories of Industry 4.0. We collected case data mainly using semi-structured interviews from six large manufacturing companies with ongoing Industry 4.0 initiatives and MES/MOM implementation projects. The aim was to provide guidance for the future design and application of MES/MOM in Industry 4.0 supply chains that are end-to-end integrated and responsive to market demands. Our findings suggest that data management initiatives using MES/MOM can contribute to reducing lead times and inventory; improving product variety, quality, and performance; and enabling manufacturing flexibility. Seven themes were identified through the cross-case analysis: ***traceability, real-time information sharing and retrieval, reduction of changeover time, supply network coordination, edge analytics, ISA-95 and open standards and open APIs, and the integration of legacy machines***. Based on these themes, we proposed design recommendations to achieve reconfigurability (see Fig. 7).

Our study reveals that IT/OT integration plays a crucial role in enhancing manufacturing flexibility. However, the lack of consensus on MES/MOM's use for manufacturing flexibility has hindered IT/OT convergence in manufacturing enterprises. Despite this, our findings suggest that MES/MOM implementation projects are driving the convergence, and one of the significant hurdles to achieving the smart factory is extracting data from the legacy machines. Our study indicates that many companies—including the leading global manufacturers—are in the first phase of the journey toward the smart factory, which involves connecting machines on the shop floor to IT (e.g., MES/MOM). The use of open standards and open APIs can enhance interoperability between the systems of different suppliers and enable IIoT interconnectivity, improving supply chain efficiency. MES/MOM can also be leveraged to create digital twins, enabling optimization of the supply chain through effective inventory management, quality control, and seamless collaboration among supply chain parties.

Our work has generated prescriptive knowledge on improving the high-level design and usability of MES/MOM for future industry needs. However, this study's limitation is that it does not cover the development and evaluation of such a system in a company. Future research might use an action research approach to investigate the real-world implementation of the MES/MOM and generate knowledge on its low-level design. In addition, further research could validate the design recommendations proposed in this study in other case companies to yield a generalizable architecture.

In conclusion, our study illuminates the critical role of MES/MOM in achieving reconfigurability and enhancing manufacturing flexibility. The findings provide useful insights for practitioners and academics to improve the design and application of MES/MOM in Industry 4.0 supply chains.

CRediT authorship contribution statement

Soujanya Mantravadi: Writing – original draft, Writing – review & editing, Conceptualization, Investigation, Formal analysis, Data curation, Visualization, Validation, Project administration. **Jagjit Singh Srai:** Writing – review & editing, Conceptualization. **Charles Møller:** Funding acquisition, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

Acknowledgements

This work was fully supported by the Manufacturing Academy of Denmark (MADE Digital and MADE FAST projects), financed by the Innovation Fund Denmark. The authors thank interviewees from the case companies for sharing their knowledge.

Appendix. : Semi-structured interview guides

- The preliminary interview guide (Mar 2018 – Dec 2019)

1. Can you briefly introduce your company, your role, and the MES implementation project?
2. Industry 4.0 vision

– What is your idea of a modern factory?
– What are your plans for ISA-95? Will you integrate all the nine functionalities of ISA-95 MOM?
– What are your future production requirements?
– How vital is smart manufacturing to you? Do you plan to achieve operational transparency and vertical integration?

3. MES implementation and benefits

– What is your current state of automation in your factory?
– Can you describe your MES journey? Which production control functionality has been integrated?
– What did MES deliver, and how valuable is it to you? Any case studies?
– Do you have web-enabled technologies on your shop floor?

4. Implications

– Are you planning to manufacture individualized products?
– What level of *digital maturity* do you intend to achieve?
– What are your ''Industry 4.0'' initiatives?

- The revised interview guide (after Dec 2019)

1. Can you briefly introduce your company, your role, and the MES implementation project?
2. Industry 4.0 vision

– What is your idea of a modern factory? What do you expect from it?
– What are your future production requirements?
– How vital is smart manufacturing to you (transparency, control, interoperability, systems integration, analytics, etc.)?
– What type of process improvement are you interested in? How?
– What is your manufacturing IT strategy automation strategy, and what are the business challenges?
– What is your vision and current state for IIoT?

3. Manufacturing flexibility specific

– How well are you doing in terms of flexibility? What makes flexibility difficult?
– How do you use MES for flexibility? Does MES support/limit it?
– Do you plan to expand MES/MOM to a broader range of applications for flexibility?
– Which MES/MOM functionalities help the flexibility? Your expectations and challenges?
– How do you measure the performance of MES for flexibility in your organization?
– Based on your experiences, what are the potential applications of MES/MOM for flexibility?

4. MES implementation and the benefits

– Are you looking into ISA-95? Why? Why not?
– What is your state of machines and production line automation?
– What other 'manufacturing operations management systems would you choose in place of MES?
– What did MES deliver, and how valuable is it to you? Any case studies?
– What are the technical and practical challenges around MES/MOM implementation?

5. Implications

– Do you have real-time process visibility? How?
– How is the data exchanged between MES and other systems?
– What data visualization and analytics tools do you use, and how do the devices interface?
– What kind of AI applications are you interested in?
– How do you plan to mitigate your most pressing supply chain issue using manufacturing IT tools?
– What can MES do for supply chains (e.g., collaborative e-sourcing)? How to achieve that in practice?
– How do you coordinate with your supply networks?
– How would you use the data from MES/MOM and IIoT to respond to market needs?
– Why are standards important to you, and what's missing for Industry 4.0?

References

Almada-Lobo, F., 2016. The industry 4.0 revolution and the future of manufacturing execution systems (MES). J. Innov. Manag. 3 (4), 17. https://doi.org/10.24840/2183-0606_003.004_0003.

P. Bazeley and K. Jackson, "Qualitative data analysis with NVivo," 2013.

Bortolini, M., Galizia, F.G., Mora, C., 2018. Reconfigurable manufacturing systems: literature review and research trend. J. Manuf. Syst. 49 (September), 93–106. https://doi.org/10.1016/j.jmsy.2018.09.005.

Cândido, G., Barata, J., Colombo, A.W., Jammes, F., 2009. SOA in reconfigurable supply chains: a research roadmap. Eng. Appl. Artif. Intell. 22 (6), 939–949.

Cheng, Y., Farooq, S., Johansen, J., 2011. Manufacturing network evolution: a manufacturing plant perspective. Int. J. Oper. Prod. Manag. 31 (12), 1311–1331. https://doi.org/10.1108/01443571111187466.

Dolgui, A., Ivanov, D., Sokolov, B., 2020. Reconfigurable supply chain: the X-network. Int J. Prod. Res 58 (13), 4138–4163. https://doi.org/10.1080/00207543.2020.1774679.

Fountaine, L., 2020. Smart manufacturing: It's a journey, not a destination. Smart Manuf. 1–25. https://doi.org/10.1016/B978-0-12-820027-8.00001-0.

Garbie, I.H., Parsaei, H.R., 2021. Reconfigurable Manufacturing Enterprises for Industry 4.0. CRC Press.

M. Hankel and B. Rexroth, "The Reference Architectural Model Industrie 4.0 (RAMI 4.0)," 2015.

Helo, P., Hao, Y., 2021. Artificial intelligence in operations management and supply chain management: an exploratory case study. Prod. Plan. Control 1–18.

Helo, P., Suorsa, M., Hao, Y., Anussornnitisarn, P., 2014. Toward a cloud-based manufacturing execution system for distributed manufacturing. Comput. Ind. 65 (4), 646–656. https://doi.org/10.1016/J.COMPIND.2014.01.015.

M. Hermann, T. Pentek, and B. Otto, "Design Principles for Industrie 4.0 Scenarios," in *2016 49th Hawaii International Conference on System Sciences (HICSS)*, Jan. 2016, vol. 2016-March, pp. 3928–3937. doi:10.1109/HICSS.2016.488.

Jaskó, S., Skrop, A., Holczinger, T., Chován, T., Abonyi, J., 2020. Development of manufacturing execution systems in accordance with Industry 4.0 requirements: a review of standard- and ontology-based methodologies and tools. Comput. Ind. 123, 103300 https://doi.org/10.1016/j.compind.2020.103300.

H. Kagermann, W. Wahlster, and J. Helbig, "Recommendations for implementing the strategic initiative INDUSTRIE 4.0: Final report of the Industrie 4.0 Working Group," April, p. 82, 2013.

Koren, Y., et al., 1999. Reconfigurable manufacturing systems. CIRP Ann. Manuf. Technol. 48 (2), 527–540. https://doi.org/10.1016/S0007-8506(07)63232-6.

Kvale, S., 2008. Doing interviews. Sage.

Lambert, D., Cooper, M., 2000. Issues in Supply Chain Management. Ind. Mark. Manag. 29 (1), 65–83. https://doi.org/10.1016/S0019-8501(99)00113-3.

Mantravadi, S., 2022. Enabling the Smart Factory with Industrial Internet of Things-Connected MES/MOM.. Aalborg Universitetsforlag., Aalborg University, Denmark https://doi.org/10.54337/aau468604062 (PhD dissertation).

Mantravadi, S., Møller, C., 2019. An overview of next-generation manufacturing execution systems: how important is MES for industry 4.0? Procedia Manuf. 30 https://doi.org/10.1016/j.promfg.2019.02.083.

Mantravadi, S., Srai, J.S., Brunoe, T.D., Møller, C., 2020. Exploring reconfigurability in manufacturing through IIoT connected MES/MOM. 2020 IEEE Int. Conf. Ind. Eng. Eng. Manag. (IEEM) 161–165. https://doi.org/10.1109/IEEM45057.2020.9309989.

McFarlane, D., Giannikas, V., Lu, W., 2016. Intelligent logistics: involving the customer. Comput. Ind. 81, 105–115.

Miles, M.B., Huberman, A.M., 1994. Qualitative data analysis: an expanded sourcebook. sage.

Morgan, J., Halton, M., Qiao, Y., Breslin, J.G., 2021. Industry 4.0 smart reconfigurable manufacturing machines. J. Manuf. Syst. 59 (April), 481–506. https://doi.org/10.1016/j.jmsy.2021.03.001.

Pan, S., Trentesaux, D., McFarlane, D., Montreuil, B., Ballot, E., Huang, G.Q., 2021. Digital interoperability in logistics and supply chain management: state-of-the-art and research avenues towards Physical Internet. Comput. Ind. 128, 103435.

Pansare, R., Yadav, G., Nagare, M.R., Jani, S., 2022. Mapping the competencies of reconfigurable manufacturing system with the requirements of industry 4.0. J. Remanuf. 12 (3), 385–409.

Sauer, O., 2014. Information technology for the factory of the future - state of the art and need for action. Procedia CIRP 25 (C), 293–296. https://doi.org/10.1016/j.procir.2014.10.041.

B. Scholten, The Road to Integration: A Guide to Applying the ISA-95 Standard in Manufacturing. ISA, 2007.

Schuh, G., Anderl, R., Gausemeier, J., ten Hompel, M., Wahlster, W., 2017. Industrie 4.0 Maturity Index. Managing the Digital Transformation of Companies (acatech STUDY). Herbert Utz Verlag, Munich.

Srai, J.S., Gregory, M., 2008. A supply network configuration perspective on international supply chain development. Int. J. Oper. Prod. Manag. 28 (5), 386–411. https://doi.org/10.1108/01443570810867178.

Ustinova, A., 2020. In the thick of the 'herculean' vaccine push. SME. https://www.sme.org/technologies/articles/2020/september/vaccine-placeholder/.

Wiendahl, H.P., et al., 2007. Changeable manufacturing - classification, design and operation. CIRP Ann. Manuf. Technol. 56 (2), 783–809. https://doi.org/10.1016/j.cirp.2007.10.003.

Yin, R.K., 2014. Case Study Research: Design and Methods, 5th ed. SAGE Publications Inc, California.

Zhang, Q., Vonderembse, M.A., Lim, J.-S., 2003. Manufacturing flexibility: defining and analyzing relationships among competence, capability, and customer satisfaction. J. Oper. Manag. 21 (2), 173–191.

Zhou, K., Liu, T., Zhou, L., 2015. Industry 4.0: towards future industrial opportunities and challenges. 2015 12th Int. Conf. Fuzzy Syst. Knowl. Discov. (FSKD) 2147–2152.