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

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ABSTRACT

The role of enterprise information systems is becoming increasingly crucial for improving customer responsiveness in the manufacturing industry. However, manufacturers engaged in mass customization are currently facing challenges related to implementing Industrial Internet of Things (IIoT) concepts of Industry 4.0 in order to increase responsiveness. In this article, we apply the findings from a two-year design science study to establish the role of manufacturing execution systems/manufacturing operations management (MES/MOM) in an IIoT-enabled brownfield manufacturing enterprise. We also present design recommendations for developing next-generation MES/MOM as a strong core to make factories smart and responsive.

First, we analyze the architectural design challenges of MES/MOM in IIoT through a selective literature review. We then present an exploratory case study in which we implement our homegrown MES/MOM data model design based on ISA 95 in Aalborg University's Smart Production Lab, which is a reconfigurable cyber-physical production system. This was achieved through the use of a custom module for the open-source Odoo ERP platform (mainly version 14). Finally, we enrich our case study with three industrial design demonstrators and combine the findings with a quality function deployment (QFD) method to determine design requirements for next-generation IIoT-connected MES/MOM. The results from our QFD analysis indicate that interoperability is the most important characteristic when designing a responsive smart factory, with the highest relative importance of 31% of the eight characteristics we studied.

1. Introduction

The ongoing COVID-19 pandemic has prompted manufacturers to reform their manufacturing operations management to face market disruptions. In view of the importance of digital technologies in terms of managing operations, the "Smart Factory" of the Industry 4.0 paradigm has gained momentum, with manufacturers looking to make their manufacturing systems responsive enough to deal with market uncertainties. By supporting flexible and agile manufacturing, smart factories can play an important role in driving innovation.

Responsiveness in manufacturing is a concept that has been widely studied since the 1990s, when agent-based distributed manufacturing control approaches were considered. McFarlane and Matson [1] define responsiveness as follows:

> "Responsiveness is the ability of a production system to respond to disturbances (originating inside or outside the manufacturing organisation) which impact upon production goals."

Here, a production system is seen as a combination of the functions of material supply, planning, scheduling, control, and the physical process

Abbreviations: AAU, Aalborg University; AI, Artificial intelligence; API, Application programming interface; BOM, Bill of materials; EIS, Enterprise information system; ERP, Enterprise resource planning; IIoT, Industrial Internet of Things; ISA, International Society of Automation; ISA 95, An international standard; IT, Information technology; IoT, Internet of Things; LTE, Long-Term Evolution; MADE, Manufacturing Academy of Denmark; MAS, Multi-agent systems; MDD, Model-Driven Development; MES, Manufacturing execution system; MOM, Manufacturing operations management; MQTT, Message Queuing Telemetry Transport (a communication protocol); OPC UA, OPC Unified Architecture (a communication protocol); OT, Operational technology; PCB, Printed circuit board; PLC, Programmable logic controller; QA, Quality assurance; QFD, Quality function deployment; RAMI 4.0, Reference Architecture Model Industrie 4.0; RFID, Radio-frequency identification; TLS, Transport Layer Security; UML, Unified Modeling Language; XML, Extensible Markup Language.

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itself. Disturbances may refer to unexpected events in the supply chain (such as rush orders or changes in material availability) or internal events such as the malfunctioning of machines [1].

A smart factory uses advanced digital technologies for interoperable systems, and is guided by the design principles of (a) interconnection; (b) information transparency; (c) de-centralized decision-making; and (d) technical assistance [2]. Smart factories are data-driven and self-organized, and the Industrial Internet of Things (IIoT) serves to optimize the overall production value and boost productivity. Smart factory design offers reconfigurability for a manufacturing enterprise and has the potential to improve responsiveness. However, industry use cases in this area are still limited, due to the baggage of legacy systems. We therefore focus in this paper on the development of smart factory capabilities in a brownfield manufacturing enterprise.

Many manufacturing companies around the world are striving to exploit the opportunities of enterprise information systems (EIS) in IIoT in order to improve their supply chain efficiency, particularly in terms of the competing priorities of delivery speed and the variety of products offered. EIS, such as manufacturing execution systems (MES), have formed an integral part of the computer-based automation of manufacturing operations. However, the automation pyramid of the Purdue model [3] of an enterprise is under challenge due to the introduction of IIoT, since IIoT devices, such as smart sensors and actuators, which belong to level 1 of the Purdue model, can directly connect to information technology (IT) systems such as MES in level 3, thus circumventing level 2 and leading to a convergence of IT and operational technology (OT). Furthermore, due to the large amount of data that is created by IIoT devices, a big data infrastructure may need to be in place to process, store and analyze the data before it can be useful to MES [4].

The most popular industrial standard, ISA 95 [5], also needs to be re-evaluated for the age of digital platform architectures due to its inflexibilities and compartmentalization of systems [6]. With its models and terminologies, ISA 95 remains the most effective method for integrating business-level systems with the shop floor; it also defines the place of MES in an enterprise and how information exchange should be structured around MES. However, new design challenges are arising in the Industry 4.0 era of IIoT, and we believe that next-generation MES/manufacturing operations management (MOM) is faced with the following problems:

- **Standardization**: The full or partial standardization of MES/MOM architecture, data models, and interfaces through the use of standards such as ISA 95 remains a challenge for industrial companies. This results in high costs for system integration both within the factory and between the supplier and manufacturer.
- **Interoperability**: A high level of interoperability is difficult to achieve when it comes to integrating MES/MOM with various systems and platforms (e.g., enterprise resource planning (ERP), IIoT platforms). In addition to using common data formats, these different systems need to have a common understanding of the data in order to interoperate effectively [7]. Plug-and-play, that is, the ability to integrate new devices and software functionalities without configuration by the user, is still a long-term goal, even though there is ongoing research in this direction [8].
- **Software customization level**: Although buy-and-use is an easy strategy that allows companies to integrate popular MES software into their production lines, most vendor MES are highly encapsulated, leaving limited scope for companies to customize them for their own purposes. Open-source solutions have a high degree of reliability [9], and an open solution can help a company to gain control and improve the customization level of their MES/MOM system. For example, a company may wish to extend the MES/MOM to interoperate with previously unsupported software and devices, or to comply with regulations that are specific to its location.
- **Modularity**: Since MES is a database application, most MES are monolithic and include most or all MOM functionalities defined by ISA 95, leading to vendor lock-in. A modular system, for example based on microservices, allows the most suitable software solution to be selected for each functionality [8,10].

The re-design of MES/MOM is crucial in terms of supporting the future information needs of factories. Level 3 of ISA 95 must be re-designed in a secure and distributed way to allow for the integration of IIoT and IT/OT. Motivated by this need, we aim in this work to re-design MES/MOM using existing ISA 95 models to achieve standardization, interoperability, and software customization of information systems, in order to support responsiveness in manufacturing. In the following, we refer to MES and MOM together, since we are not treating MES as a software product but as an implementation of the MOM functionalities of ISA 95.

1.1. Approach and outline

In this paper, we explore design choices for next-generation MES/MOM in order to develop smart factory capabilities. We use a real-world case from a reconfigurable cyber-physical factory (Aalborg University's Smart Production Lab), and we explore a scenario involving order management for mass customization, mimicking real examples from our project companies. These companies are large multi-national manufacturing enterprises, based in Denmark, that have an international manufacturing footprint with active smart factory development projects. We believe that the contributions made in this study are also relevant to small-scale manufacturing companies working within a brownfield environment. The Venn diagram in Fig. 1 illustrates our research focus; the intersection represents the application of enterprise information systems for the development of a responsive smart factory.

Our methodology is inspired by the three-cycle design view of Hevner [11], which provides an iterative process that can ground design science research with both theoretical rigor and practical relevance. In Section 2 we conduct a selective literature review of MES/MOM design development for Industry 4.0, and based on this, we identify a gap related to IT/OT interconnectivity in MES/MOM design. We address this gap by presenting a design for a system architecture and a MES/MOM data model based on ISA 95, which is applicable in the smart factory, in Section 3. We then evaluate the applicability of our system architecture and data model design through an exploratory case study on mass customization carried out in Aalborg University's Smart Production Lab, and three design demonstrators at three international manufacturing companies in Section 4. In Section 5.1 we use our findings from the case study and the demonstrators to propose design requirements for a next-generation MES/MOM in a smart factory, and we use quality function deployment (QFD) to correlate these with the design characteristics of MES/MOM in Section 5.2. In Section 5.3, we present design recommendations for next-generation MES/MOM and propose a high-level architecture for IT systems in a smart factory centered on MES/MOM. We describe the instantiation of this architecture in the case study in the Smart Lab in Section 5.4. Our conclusions are presented in

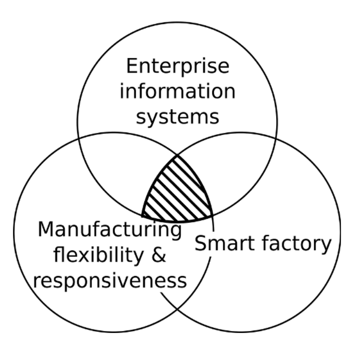

Fig. 1. Research focus

Section 6.

1.2. Contributions

The following is a summary of the main contributions of our work, both theoretical and practical.

- **ISA 95-based data model design:** We identify the core object and activity models of ISA 95 related to product definition, production scheduling, and production control. Based on the selected data models and information flows of ISA 95, we propose a data architecture for IIoT-connected MES/MOM. These data models will provide a consistent basis allowing manufacturers to build a more standardized MES/MOM.
- **Implementation with IIoT for mass customization demonstrators:** We implement and iterate our data model through three industrial design demonstrators at Aalborg University's Smart Production 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.
- **Secure distributed architecture:** We combine an analysis of the findings of our case study with a QFD assessment in order to present design recommendations for an architecture for next-generation IIoT-connected MES/MOM that can enable responsive smart factories.

2. Background and related work

2.1. Development of smart factory capabilities for responsiveness

Smart factories need several capabilities to allow them to work together to be responsive and flexible, and this poses not only a technological challenge but also an organizational one. We present the idea behind our MES/MOM design choices using the sketch in Fig. 2.

For a smart factory to achieve the goals of manufacturing flexibility and increased productivity, the following four capabilities need to be achieved:

IIoT interconnectivity means that the components of the smart factory, including smart devices (programmable logic controllers (PLCs), smart sensors), smart products, and servers (MES/MOM, ERP, analytics, etc.), should be able to interconnect easily and securely in order to exchange information and instructions in real time. Interconnectivity is a basic requirement for the other capabilities of the smart factory.

Distributed control is a long-standing concept from the field of holonic manufacturing. On the software side, this idea is supported by agent-based architectures. Although agent-based distributed control has been around for more than two decades, the level of adoption in industry has been rather low [12]. This concept is also central to the development of smart factories, since centralized control systems are unable to handle future market uncertainties and demands. In agent-based distributed control, the production flow in a smart factory is no longer orchestrated by a central, monolithic entity; instead, the products and workstations negotiate operations that are to be performed autonomously. In this case, information about the operations to be applied to a product is logically stored with the product itself, although in a physical sense, it may still be stored in a central MES/MOM database [13].

Digital modularity refers to the capability to connect a variety of devices and services from different vendors in a plug-and-play fashion, allowing for the easy addition, modification, and replacement of components without having to make changes throughout the system. Modularity enables a manufacturer to make changes to their products and to introduce new products much more rapidly and at a lower cost than would be the case for static assembly lines.

A process **digital twin** is a virtual real-time representation of all the components of the smart factory (here we consider "real-time" to mean a timeframe of within approximately one minute). The use of digital twin is valuable in terms of gaining an overview of the current state of the production process, retrieving information about the state and performance of the components, and simulating its behavior in the near future. This allows for easier detection of inefficiencies in production and the predictive maintenance of equipment.

In the view of these requirements for the capabilities of a smart factory, the Reference Architecture Model Industrie 4.0 (RAMI 4.0), developed by ZVEI [14], can be useful. It aims to represent the entire space of Industry 4.0 using a three-dimensional model (see Fig. 3). The *layers* along the vertical axis represent the different aspects of the machines, products, factories, etc. being mapped, from a given physical asset to its integration with IT, the dimensions of data and communication and the business processes associated with it. Another axis

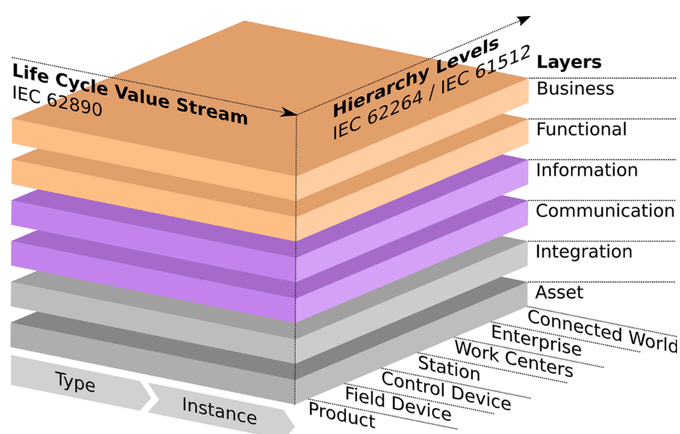

Fig. 3. RAMI 4.0 standard, showing the ISA 95 hierarchy along one axis [14]

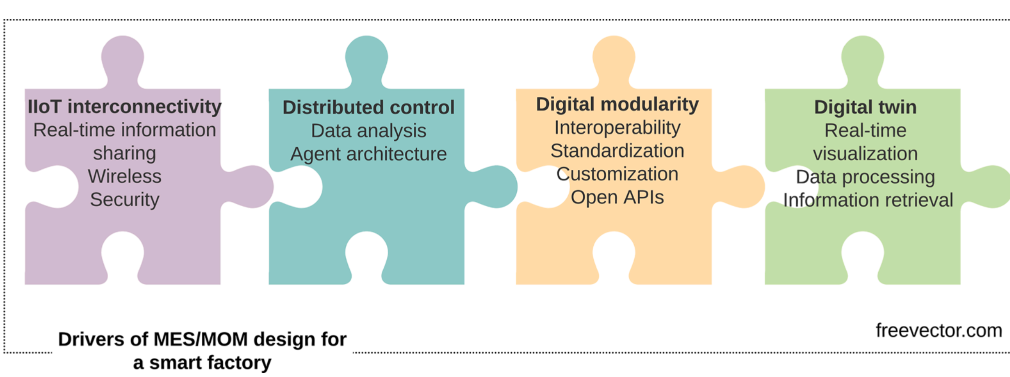

Fig. 2. Building blocks for a responsive smart factory

represents the *hierarchy levels* of the system; these correspond to the functional hierarchy of ISA 95, with the additions of the product itself and the connected world. The third axis shows the *lifecycle and value stream*, which represents the lifecycle of products, machines, etc. throughout the processes of development, production, and maintenance.

The goal of RAMI 4.0 is to provide a common framework for the discussion of Industry 4.0, of which the hierarchy of ISA 95 forms a significant part. Mapping existing standards onto the RAMI 4.0 model makes it possible to identify and close gaps in standardization, and to find overlaps, in which case a preferred standard can be chosen [14]. RAMI 4.0 offers a clear understanding of the requirements for communication and systems for a smart factory, although it is not possible to realize a smart factory without implementing MES/MOM to support these requirements.

2.2. Needs of smart factories for next-generation MES/MOM

According to a McKinsey study [15], much of the manufacturing IT infrastructure in IIoT-enabled smart factories will be integrated into digital manufacturing platforms, which can be hosted in the cloud and provide the infrastructure needed to support the functionalities of ERP, MOM, etc. in the form of apps. According to ISA 95, the functionalities of MOM include: (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 [16]. To reduce the complexity of implementation of MOM, these functionalities can also be implemented as separate apps on a digital platform.

IIoT platforms will be connected to a variety of shop floor devices and information systems to enable the exchange of production data along the supply chain. This highlights the need for MES/MOM and the associated infrastructure to support interconnectivity and modularity, mainly by providing open application programming interfaces (APIs), adhering to standards (such as ISA 95), and supporting wireless communication. Many manufacturing companies already implement ISA 95 at least partially, and hence basing the design of MES/MOM on ISA 95 simplifies brownfield implementations.

Wireless technologies are important enablers for interconnectivity, especially in view of the use of mobile components such as smart products or mobile industrial robots. They also aid modularity, as they reduce the need for rewiring when elements of the shop floor are rearranged. Wireless technologies that are commonly in use or have been suggested for the shop floor include Long-Term Evolution (LTE) Advanced, 5G, Wi-Fi, Bluetooth Low Energy, ZigBee, and LoRaWan, which differ in their effective ranges, data rates, and latencies. The nascent technologies 5G and Wi-Fi 6 (IEEE 802.11ax) promise to deliver higher throughput and lower latency than their predecessors, which will be essential for real-time, large-scale data collection. Although the use of wireless technologies on the shop floor is mostly a matter of network infrastructure, MES/MOM needs to be able to make use of the newly gained ability to obtain data from sensors and devices throughout the factory, and be able to handle potentially unreliable wireless connections.

Furthermore, security needs, especially in wireless networks, have not been addressed sufficiently in last generation MES/MOM, and there is a gap in the academic literature [17]. The higher need for interconnection leads to an increased surface for cyber-attacks, and protective strategies against these attacks, such as the use of cryptographic protocols and intrusion detection systems, are therefore required.

2.3. Related work on design challenges of MES/MOM

In this section, we carry out a selective literature review using Google Scholar, with an emphasis on studies from the last five years. The objective of this survey was to understand the state of the art in MES/MOM design challenges in Industry 4.0 and in particular, we looked for work that addressed ISA 95 based studies. The key studies we identified in this way are listed in Table 1.

We found several recent studies that discussed the use of MES/MOM for novel applications through design enhancements. One aspect that was common to most of these studies was the identification of a need for decentralized control in the Industry 4.0 era. For example, Almada-Lobo [13] wrote that traditional centralized MES may be incompatible with the concept of Industry 4.0, and suggests that future MES should evolve accordingly into a fully (logically) decentralized system. He envisions that the shop floor of Industry 4.0 will become a "marketplace", where smart products and workstations negotiate operations to be conducted autonomously without any central control. Wunck [10] also proposed a decentralized MES architecture in which the current monolithic MES is broken down into microservices. Similarly, Jeon et al. [19] designed an architecture for a "Smart MES" that supports collection and analysis of

Table 1
Literature on MES/MOM design challenges.

Author(s)	Aim of paper	Key takeaway	Method	Challenges identified
Jaskó et al., 2020 [7]	To review standard and ontology-based methodologies for MES/MOM development	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
Almada-Lobo, 2015 [13]	To examine the role of MES/MOM in Industry 4.0	MES/MOM in smart factories will utilize decentralized control	No method identified	Decentralized control is needed to achieve the best possible efficiency
Wunck, 2019 [10]	To study the microservice architecture of MOM	Splitting MOM functionalities into separate microservices aids software maintenance and flexibility	Review	Most MES are monolithic, leading to vendor lock-in
Koerber et al., 2018 [15]	To study the impact of implementing IIoT and to provide recommendations	A platform-based infrastructure for manufacturing IT systems	Industry white paper	IIoT increases the complexity of integration IIoT needs to have a clear business case
Novák et al., 2019 [18]	To present Plan Executor MES/MOM, a manufacturing execution system combined with a planner for Industry 4.0 production systems	A new MES architecture for enabling flexibility in products, processes, and available production resources	No method identified	The MES should be able to plan and schedule production in a dynamic way with regard to the current status of production systems and customer needs
Jeon et al., 2017 [19]	To study the shortcomings of MES with regard to data analysis and to design an architecture to address these	A MES architecture that enables data collection and analysis and collaboration of functionalities	Design	Current MES lacks sufficient interconnection with devices to make effective use of data
Kannan et al., 2017 [20]	To analyze the requirements for MES in Industry 4.0, and to provide a gap analysis for existing automotive MES	Vendor MES systems are analyzed and scored based on Industry 4.0 requirements	Model-based requirement engineering	Misalignment between ISA 95 and the compliance of the existing software tools

device data, and which is modular, with MES functionalities being separate, collaborating applications. However, these studies are mostly theoretical, do not test their architectures with real-world case studies and do not work with empirical data.

On the other hand, Kannan et al. [20] performed a comparative study on different vendor MES (in automotive industry), and they realized that for many MES there is a lack of compliance with the industry standards such as ISA 95. This gap makes our study even more relevant as one of our research objectives is to best use ISA 95 for Industry 4.0 based heterogeneous systems in IIoT. However, their study is limited to the automotive industry, whereas MES/MOM also has a significance in process industry.

A few industry white papers discussed enterprise information systems with an emphasis on IIoT platforms. Of these, a McKinsey study [15] suggested that the implementation of IIoT with a cloud-based platform infrastructure could boost revenue and performance in manufacturing enterprises. Jaskó et al. [7] carried out a review of standard- and ontology-based methods and discussed how MES should be implemented in Industry 4.0, suggesting that due to the importance of interoperability, formal models and ontologies will be central to MES design in Industry 4.0. Zeid et al. [21] reviewed different types of interoperability in smart manufacturing, as well as reference architectures for interoperable manufacturing. They mention the absence of implementations of these architectures, and particularly the lack of semantic interoperability between manufacturing IT systems. Novák et al. [18] proposed an architecture for MES that enables the dynamic planning and scheduling of production, and which allows for re-planning via a digital twin in case of failure. Similarly, Negri et al. [22] designed and implemented a digital twin model that is integrated with MES to allow for bilateral communication. Unlike most existing digital twins, which merely represent the state of the field devices, the device in this case can be controlled from the digital twin. The digital twin-based approach of Leng et al. [23] supports reconfigurability and modularity through an open architecture of machine tools and a reconfigurable IIoT system. Zhong et al. [24] presented a radio-frequency identification (RFID)-enabled real-time MES with the aim of reducing scheduling inefficiencies in mass customization by tracking manufacturing resources in a factory. We note that many of these studies do not focus on the integration of MES/MOM with both ERP systems and shop floor devices, and do not discuss the use of IIoT platforms for connecting to devices.

Much of the literature reviewed here focused on the concepts of distributed control, modularity, and digital twins associated with MES/MOM. We note that as a prerequisite, all these concepts depend on IIoT interconnectivity to a level that is far above what most manufacturers currently have access to. Developing this interconnectivity requires a design for MES/MOM that is integrated with an IIoT platform, and which can manage and control a heterogeneous set of shop floor devices. We have not found sufficient empirical evidence for such an IIoT-connected MES/MOM design in the literature, and this is the main gap that we aim to address in our paper.

2.4. Summary

ISA 95 was defined at a time where sales, manufacturing, etc. were separate departments and data silos existed, and its developers did not envision the degree of interconnectivity that would become possible with the emerging IIoT technologies. The degree to which ISA 95 is still useful is therefore unclear, given the goal of vertical and horizontal integration in manufacturing enterprises in Industry 4.0. This integration is necessary to achieve the level of responsiveness required to meet rapidly changing market demands [1].

We note, however, that RAMI 4.0 includes the system hierarchy of ISA 95 along one of its axes, meaning that this hierarchy is still relevant for smart factories. We therefore pose the following questions in this study:

Q1) How is ISA 95 relevant to the IIoT paradigm for designing responsive smart factories?

Q2) What design choices are necessary for a next-generation MES/MOM that is compatible with IIoT?

In order to address these questions, there is a need to redesign MES/MOM data models to accommodate IIoT in a smart factory. The various systems of a smart factory, such as the IIoT platform, MES/MOM, and ERP, need to work with a shared data model. By defining how the entities and concepts in a smart factory are represented in the databases and software, and how they relate to each other, data models can provide a common language that allows the systems in the factory to exchange information. We elaborate our approach to this design in the next section.

3. Design of a MES/MOM data model for a smart factory

Model-Driven Development (MDD) [25,26], one of the most popular software development paradigms, shifts the focus from the complicated details at a low level of code development to the high abstraction level of system design.

In general, MDD uses models as the main artifacts, which raises the abstraction level and hides the complexity of an application. This helps the stakeholder to gain a global view of the proposed system at an early stage, and closes the gap between the IT and manufacturing domain by introducing system design principles into specific manufacturing applications that deliver value [27]. Furthermore, the use of MDD with Unified Modeling Language (UML) is widely accepted and applied within industry [28], as this offers a formal, easy way to visualize the system and data model and reduces complexity.

In this section, we apply the MDD approach to illustrate the high-level architecture of a smart factory, e.g., ERP, MES/MOM, and IIoT platform, in terms of their core components and the interactions between them. We then present a data architecture for the desired MES/MOM using UML. The data architecture provides the logical relationships between the data models (e.g., the product definition model and production schedule model) based on the activities and objects defined in ISA 95. The data models for MES/MOM form the basis for provision of the smart factory capabilities listed in Section 2.1. We aim to determine how and how well ISA 95 can serve as a basis for the data architecture of a smart factory, given the increased need for connectivity between MES/MOM and shop floor devices.

3.1. System description

We design a system for a smart factory that complies with the ISA 95 systems hierarchy. The aims are to:

- Easily interconnect devices, assets, and IT systems and smoothly integrate them with MES/MOM;
- Empower workers to perform better; and
- Quickly build a solution by leveraging existing software, physical equipment, and products.

Overview of system integration:

The successful integration of MES/MOM with a manufacturing system involves identifying the related systems (e.g., an ERP system), the platform (e.g., the IIoT platform), and the exchange of information between the enterprise business level, the manufacturing level, and the control level. Fig. 4 shows where the proposed MES/MOM could be positioned in the integrated systems. The top level is the ERP system (which defines the business-related activities such as planning, sales, and logistics). The MES/MOM is located at level 3, where the main functions are production scheduling, production definition, production execution management, and resource management. The IIoT platform is introduced into these systems due to its standout performance in production control, monitoring, and resource management. Sensors and shop floor devices are located at the bottom level.

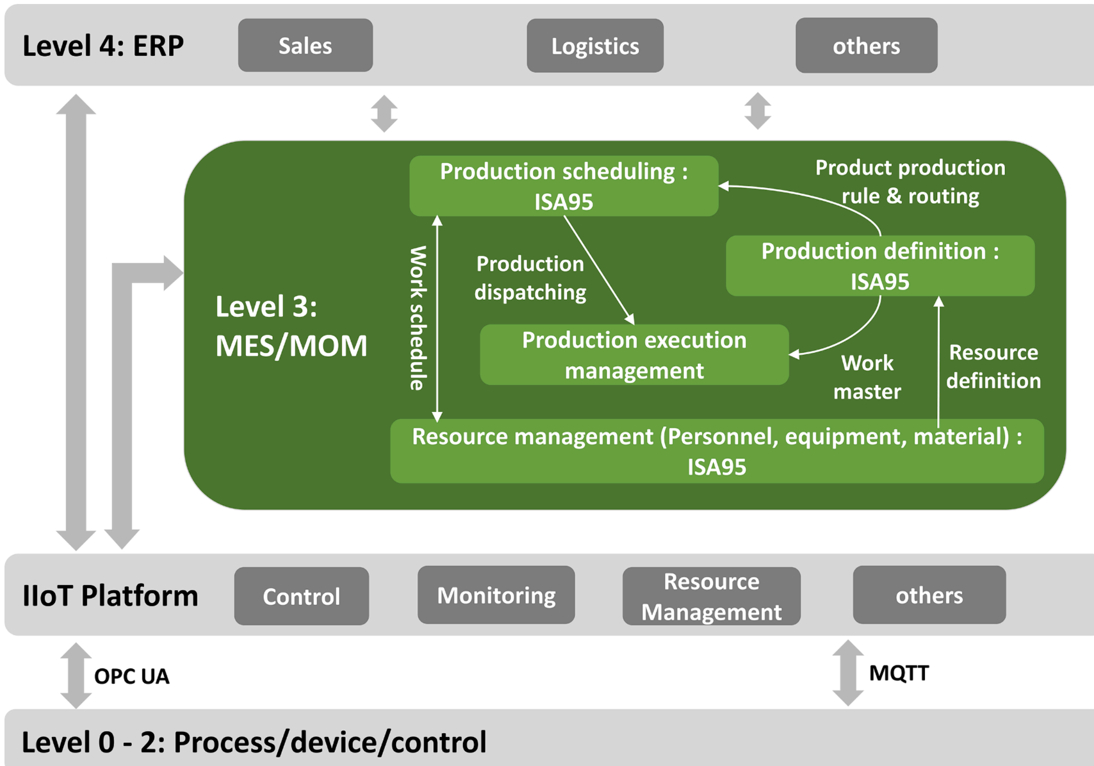

Fig. 4. Proposal for a system architecture for a responsive smart factory based on an IIoT platform

3.2. Data model design

To understand the functions associated with manufacturing operations, control systems, and enterprise systems and the integration between them, we examined the ISA 95 industrial standard [5]. ISA 95 covers the activities and business processes of MOM in terms of production, quality, maintenance, and inventory. We investigated parts 3 and 4 of ISA 95, with a particular focus on the activity and object models of MOM, and identified core activities and object-related data models most relevant to production. Those data models provide an overview of the functional and data flows that exist within the manufacturing organization.

Although these data models can be used to guide MES/MOM implementations, manufacturers can easily become lost when applying such massive pre-defined data models and their relationships. Hence, to design a more standardized MES and to ensure a low level of complexity in terms of integration with legacy systems or interfaces provided by third-party vendors, we selected only the core activities and object models and categorized them into two groups: master data and transaction data [29]. The master data models, also called resource models, describe core data related to the entities of the manufacturing processes, whereas transaction data are mainly associated with events related to production scheduling and execution. Fig. 5 illustrates the data model. It has three main parts: **production scheduling, product definition**, and **resource models**. The gray boxes on the bottom left show an example of the equipment master data model. Previous designs for MES data models, such as that of Zhou et al. [30], were not created with IIoT and smart factories in mind, and their main focus is therefore on execution rather than using MES/MOM for data management.

The purpose of creating a data architecture is to provide a unified data model for standardization and formalization of the production data generated from the ERP, MES/MOM, and devices. The data structures we considered in our work are resource and operation data models.

3.2.1. Resource models

The three resource models (i.e., master data) considered here are the personnel model, equipment model, and material model [31] (see the lower part of Fig. 5).

- The personnel model contains information about the classes, properties, and qualifications of personnel. According to the ISA 95 standard, the personnel class is a high-level abstraction of a particular type of person in the enterprise, such as a production manager or operator. The properties of the person also need to be defined, e.g., their gender, age, or position. The qualification test results were selected as a special class that specifies the qualifications of an employee, such as certification for a special task or position.
- The equipment model contains information about the classes and properties of equipment, and equipment capability tests. In a similar way to the personnel class, the equipment class categorizes the types of equipment that enable production, such as a mobile industrial robot or drilling machine. The properties of the equipment are strongly related to its physical attributes, e.g., its weight and size. One of the most important attributes that must be defined is the result of a capability test, which describes capability specifications for a specific piece of equipment, such as the speed of a conveyor belt.
- The material model defines the classes and properties of materials, and quality assurance (QA) tests of materials. The material class defines the type of material used in a product or to support production, such as a printed circuit board (PCB). The material property class defines the attributes of the material, such as its color or size. To verify that the material satisfies the quality requirements, a class representing the result of a QA test is needed, for example of the thickness of the PCB.

3.2.2. Operation model

The operation model is also called the transaction model. As mentioned above, to reduce the complexity of the MES design, we only

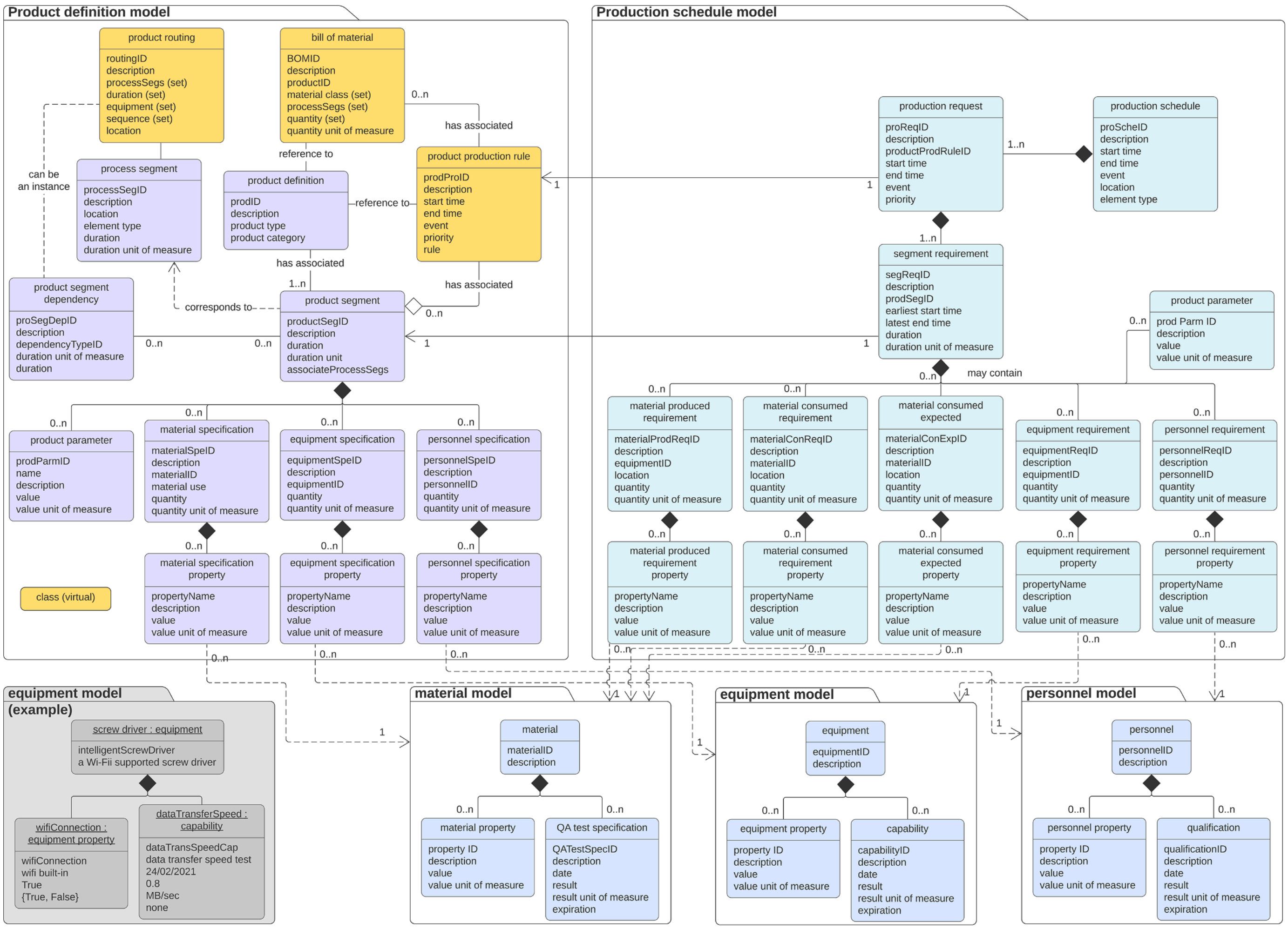

Fig. 5. UML class diagram of the proposed data model design based on ISA 95

use the most relevant data models of production scheduling and execution. The production schedule model can be mapped to a corresponding work request, which defines the information required by the manufacturing department to fulfil the scheduled work. Each work request should specify the production order, production state, and the quantity that needs to be produced and may be composed of multiple job lists that consist of job orders. A job order mainly relates to an atomic operation and includes the name of the operation and the requirements, e.g., drilling a hole in a PCB, and the maximum speed of drilling. The production rule is used as a guide for the detailed job order in terms of the related requirements, including personnel, equipment, and material. Fig. 6 illustrates the operation model.

3.3. Summary

In this section, we have presented a system architecture and data model for MES/MOM in a smart factory. However, it is not sufficient to only have a design and a concept; we need to test it in practice using industrial demonstrators, as required by Hevner's relevance cycle for design science study, which demands input from the contextual environment into the research [11]. The next section describes how we tested our approach and the experimental setup used for the mass customization case.

4. A case study on mass customization

As a concrete case example of mass customization, we studied the

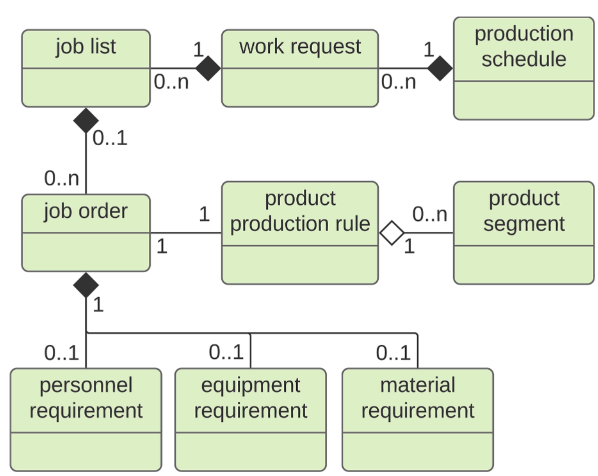

Fig. 6. UML class diagram for the operation model

design challenges of MES/MOM in reconfigurable cyber-physical production systems at Aalborg University's Smart Production Lab (henceforth referred to as the Smart Lab) in Denmark. The purpose of using the Smart Lab was to understand the challenges and operation of a smart factory supporting low-volume and high-variety production. The lab also allowed us to test ideas related to the concept of IIoT, since it is a reconfigurable manufacturing system that supports changeability requirements [32]. Multiple projects were carried out with companies to test their ideas for enterprise architectures in the Smart Lab. We use design demonstrators from three of these projects in this study. In this section, we describe our ongoing project that involves testing and improving our IIoT-connected MES/MOM design in a lab environment.

4.1. Experimental setup at Aalborg University's Smart Lab

The Smart Lab (see Fig. 7) is a *Festo CP Factory* and is a learning cyber-physical production line. It produces dummy smartphones consisting of a bottom cover, a circuit board, a variable number of fuses, and a top cover. The lab consists of multiple production modules, each with two workstations. Each workstation is controlled by a programmable logic controller (PLC) and executes a single step, such as providing the bottom cover, a mock drilling step, or the addition of fuses. These PLCs are managed by a custom Python script, hosted on-premise, which takes the role of an IIoT platform. This script is in turn connected to an Odoo instance, which is hosted in the cloud and fulfills the roles of both ERP and MES/MOM.

The production line in the Smart Lab consists of a conveyor belt, which forms a closed loop passing by each workstation. There are several carriers (see Fig. 8) on the conveyor belt, and the individual products are assembled on these as they pass through the workstations. The workstations identify the carriers using RFID and retrieve the operations they need to execute from the MES/MOM. The carriers are constantly cycling through the production line, even when they are not being used.

ERP and MES/MOM (Odoo):

The ERP software is responsible for managing a variety of business processes, such as logistics, sales, and human resources. The process most relevant to this paper is the management of sales orders and manufacturing orders. A MES/MOM keeps track of various aspects of the manufacturing process, and manages among other things resources, product definitions, production scheduling, execution of production, and collection of production data. In the Smart Lab, the open-source enterprise software Odoo (currently version 14), developed by Belgian company Odoo S.A., fulfils the roles of the ERP and MES/MOM (see Fig. 9). Odoo is an open-source collection of business applications that can be integrated to offer a complete ERP. In our installation, MES/MOM functionalities are offered by Odoo via both the built-in manufacturing module and a custom module called AAU MES.

IIoT platform (ThingWorx or custom script):

An IIoT platform is responsible for connecting to and monitoring a plethora of IIoT devices, and serves as an intermediary to connect them with information systems in a unified way. IIoT platforms such as ThingWorx (developed by the US company PTC) are expected to take over some of the traditional MES/MOM functionalities. IIoT platforms can be hosted on-premise or in the cloud. However, we have learned from interviews and field studies that most manufacturers prefer to run IIoT platforms on-premise due to lower latency and to avoid production being interrupted in the case of internet connectivity issues. Although ThingWorx has been used in the Smart Lab in the past, the role of the IIoT platform in this study was taken by a custom middle layer script written in Python and running on a local machine.

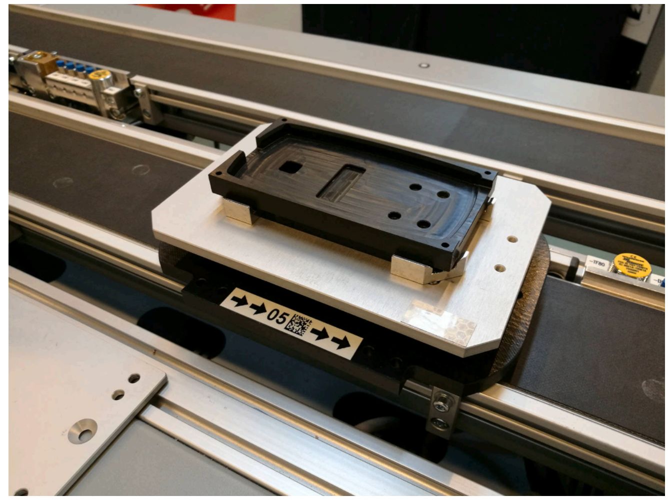

Fig. 8. A carrier containing the bottom cover of a mock mobile phone

IIoT device (PLC):

An IIoT device is connected to the IIoT platform and interfaces with the physical process of manufacturing. It retrieves instructions from the IIoT platform and supplies status information and measurement data. In our case, we used Festo CECC-LK PLCs in the Smart Lab, which are low-power controllers that control sensors and actuators and which were connected to the custom middle-layer machine via ethernet.

Communication during order execution:

Fig. 10 shows a sequence diagram of the simplified exchange of information between the ERP, MES/MOM, the middle layer, and the PLCs during production execution in the Smart Lab.

Fig. 7. Aalborg University's Smart Production Lab

Fig. 9. Home screen of the open-source Odoo business platform in the Smart Lab

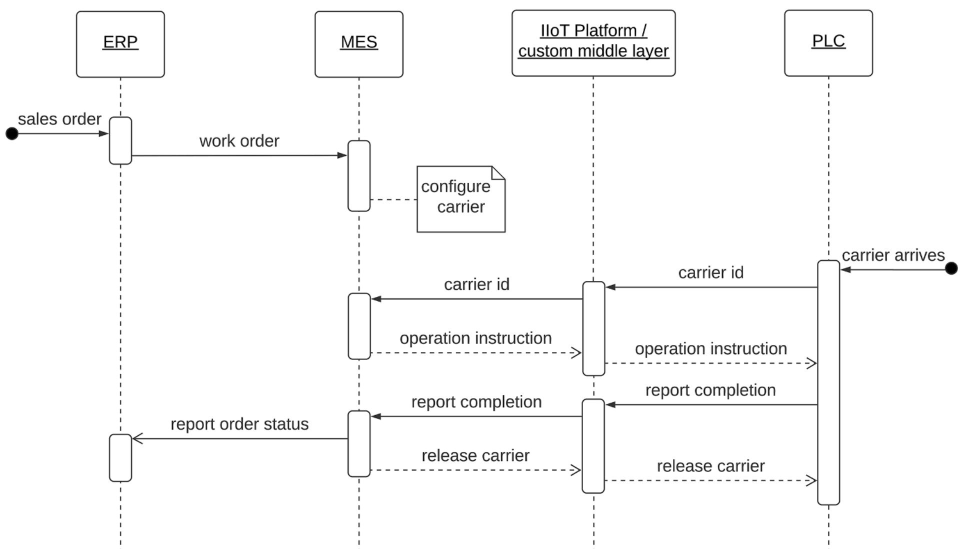

Fig. 10. UML sequence diagram for simplified production execution in the Smart Lab

- When a sales order has been created at the ERP and its feasibility has been checked, it is translated into a set of manufacturing work orders, which are sent to the MES/MOM.
- For each work order, the MES/MOM then selects a free carrier from the production line and assigns the order to it.
- When a carrier arrives at a workstation, the PLC reads its identifier via RFID and sends it to the MES/MOM via the middle layer, which responds with the operations that the workstation needs to execute on that particular workpiece, if any. In some cases, the middle layer can bypass this process if it knows that no operation is to be executed.
- When the operations are complete, the PLC reports this to the MES/MOM, which updates the ERP on the status and, when ready, tells the PLC to send the carrier on its way.

The carrier selected for a given work order will eventually pass through all the workstations needed to execute the order.

4.2. Demonstrators with industrial applications

The procedure used to check the feasibility of the design presented in Section 3 is to implement it in the form of industrial demonstrators (in collaboration with the project companies), which apply the design solutions to solve real industrial problems. Below, we describe a partial implementation of our approach to standardization, IIoT interconnectivity, modularity, and software customization.

Demonstrator 1 onvertical integration:

In many manufacturing companies, vertical integration is still a challenge, where enterprise information systems cannot be seamlessly connected to shop floor devices. In the first iteration of our MES/MOM design, the goal was only to demonstrate how an open-source business platform with MES/MOM functionality could send instructions to IIoT devices. At the “Robotbrag 2018” event in Odense, Denmark, we demonstrated how our customized Odoo module “AAU MES” could receive production orders from the Odoo sales module and execute them by controlling mobile robots (see Fig. 11) on the shop floor using the OPC Unified Architecture (OPC UA) protocol [31]. For this demonstrator, we used Odoo version 11.

Demonstrator 2 on **interoperability:**

Interoperability is an issue in many manufacturing companies that are aiming to introduce end-to-end supply chain integration to improve flexibility and speed. Here, the challenge is to smoothly aggregate and standardize data from various systems, such as the MES/MOM and the IIoT platform. The data should be represented in a unified manner in terms of both data format (e.g., Extensible Markup Language (XML)), and of data types (e.g., integer, string). In the autumn of 2019, we demonstrated the design of a middle data layer between MES/MOM and

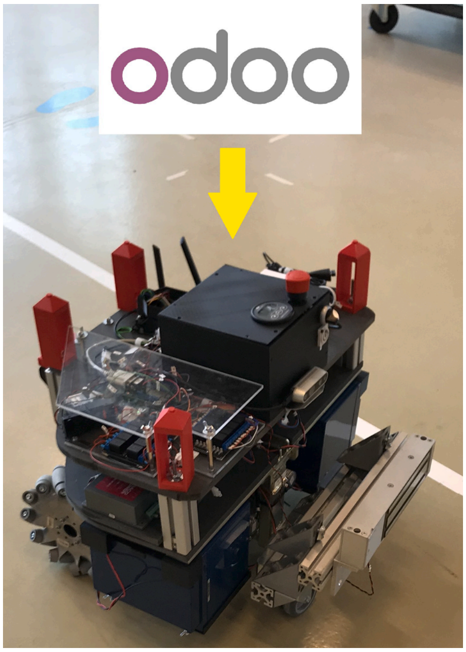

Fig. 11. Customized Odoo MES/MOM connecting to mobile robots at Robotbrag 2018 event in Odense, Denmark

the IIoT platform based on the ISA 95 standard. Fig. 12 shows the system architecture in the form of a UML component diagram. Our design was tested on a workstation in the Smart Lab. The middle data layer served as an intermediary between the Odoo MES (version 12) and the ThingWorx IIoT platform (version 8.4), mapping the data from both systems to a standard representation based on ISA 95. The middle layer was implemented in Python and used MySQL 8.0 for local data storage. The ThingWorx IIoT platform communicated with the IIoT devices through the PTC KEPServerEX connectivity platform (version 6.7), via OPC UA or Message Queuing Telemetry Transport (MQTT) [33].

Demonstrator 3 on o**rder customization:**

Mass customization is an important strategy for solving problems with customer responsiveness in manufacturing companies. The issues of reducing the time-to-market and increasing the variety of products remain challenging for manufacturers. The goal of this ongoing demonstrator is to use enterprise information systems to illustrate the easy execution of a customized order. Fig. 13 shows the order execution workflow in Odoo (version 14), from the reception of the sales order to delivery of the product. Due to the platform architecture of Odoo, which contains modules for sales, manufacturing, purchase, and inventory, conversion from sales order to manufacturing order happens as soon as the sales order is confirmed. Likewise, the creation of manufacturing orders or requests for quotations for missing materials is automatic. If the sales order contains customization options (e.g., colors), this will be reflected in the bill of materials (BOM) of the manufacturing order. During order execution, workstations will receive the correct instructions from the Odoo manufacturing module (through the IIoT platform) and in turn report the completion of each manufacturing step. Due to this integration of IT and OT, the correct variant will be produced, and since each order is tracked individually, the finished product can be delivered to the customer.

4.3. Summary

These demonstrators allowed us to put into practice our concepts for the design of a data model based on ISA 95 and to prove their industrial relevance to IIoT. Our design choices such as standardization based on ISA 95 and the use of open-source software for modularity and interoperability were also proven to be valid through demonstration to industry peers for their approval. Our findings suggest that IIoT and ISA 95 can not only coexist but also complement each other. The three design demonstrators also showed that ISA 95 can offer support for future design challenges related to the use of MES/MOM in IIoT. This answers our research question **Q1**.

We analyze the findings from the case study in the following section,

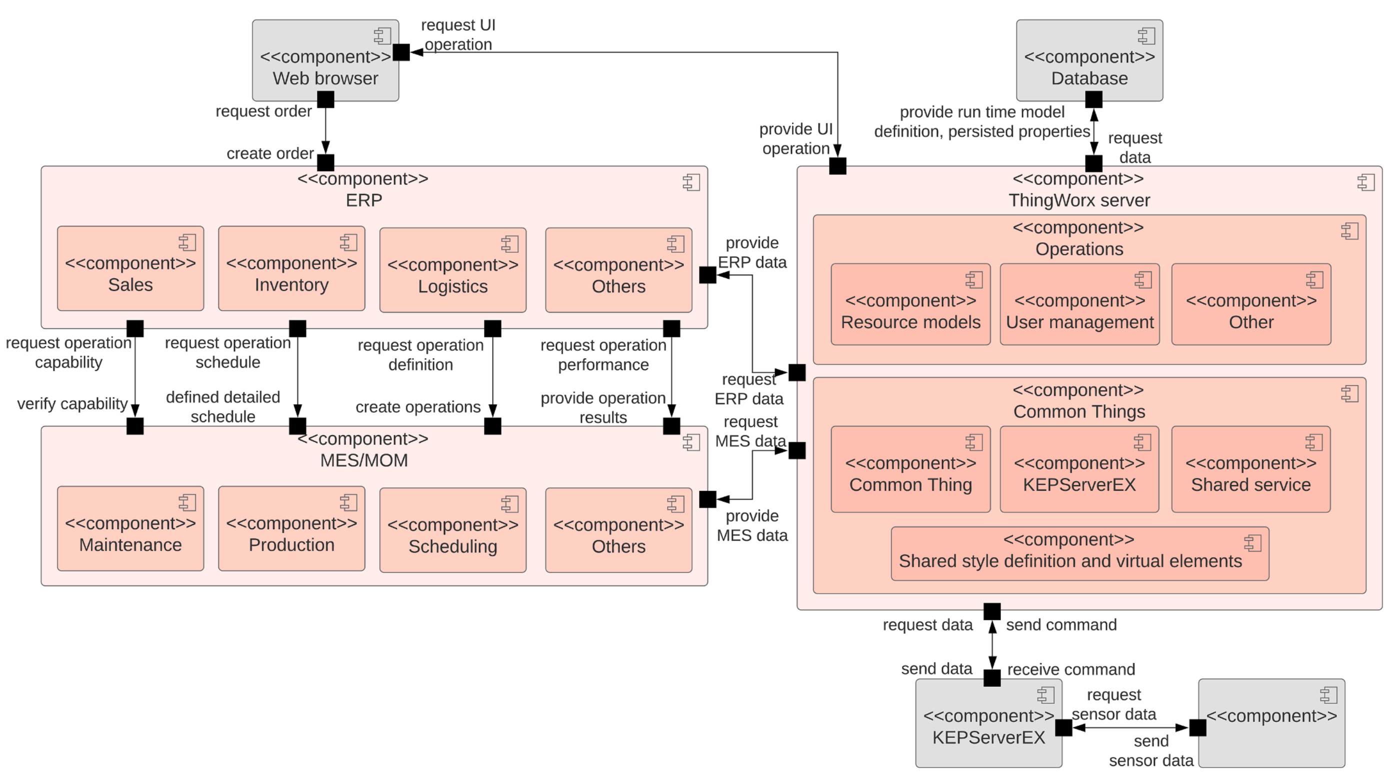

Fig. 12. UML component diagram showing the system architecture design

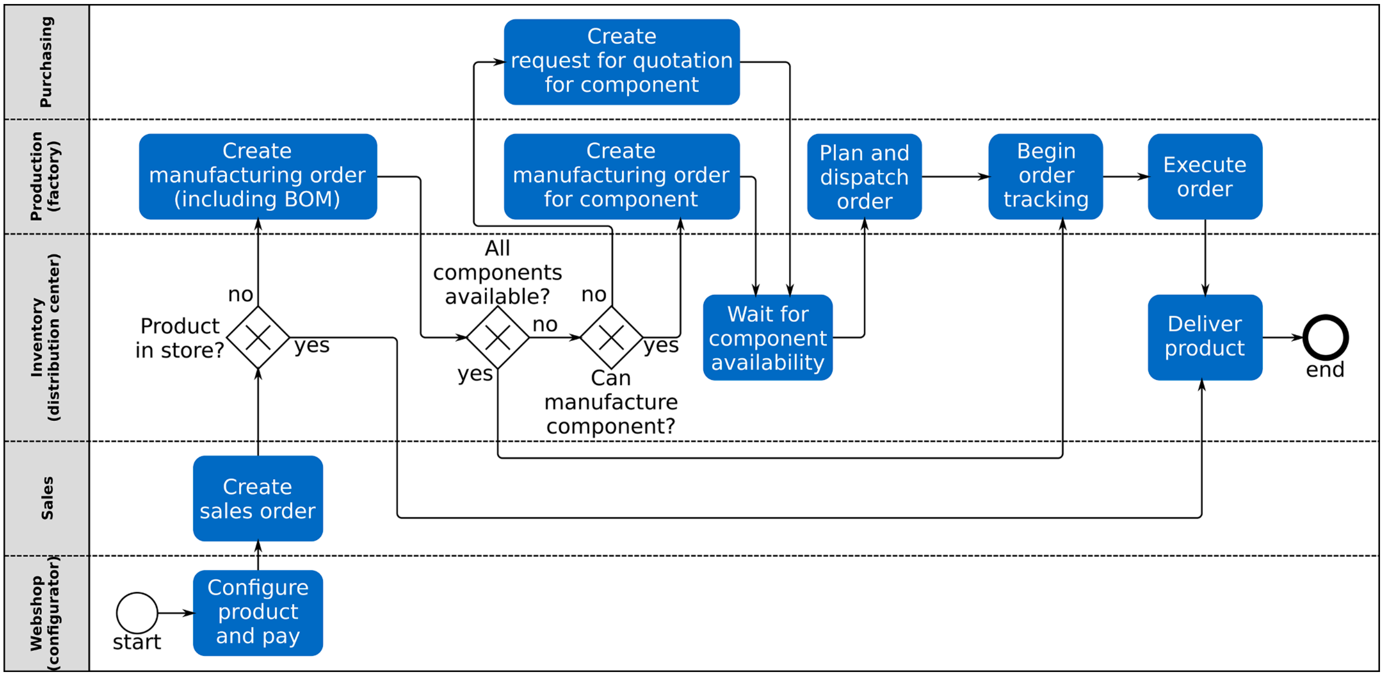

Fig. 13. Order execution workflow for a demonstrator (inspired by a real-world case)

and formalize the design requirements for a next-generation IIoT-connected MES/MOM for a responsive smart factory.

5. Analysis & discussion of findings

Although previous studies have discussed MES/MOM design in the context of IIoT and Industry 4.0, there are no concrete examples of how ISA 95 models can be adapted to the IIoT paradigm. In spite of the literature identifying the importance of interconnectivity and interoperability, and several conceptual architectures to address these issues, there are still only few concrete implementations [21]. We believe that they have not addressed the ways in which MES/MOM should be implemented to allow for connectivity to a plethora of IIoT devices. In light of this, we follow the design science approach, in which the problem is explored in its natural environment through iterative design cycles. We therefore conducted this study in the form of industrial design demonstrators to ensure its applicability in a real-world setting. In this section, we analyze our findings.

5.1. Design requirements for a responsive smart factory

The smart factories of Industry 4.0 will offer greater flexibility in manufacturing operations, enabling companies to respond to changing market demands much more readily, with shorter product life cycles and higher product variety. The increased visibility of data can also help increase the efficiency of manufacturing supply chains due to better traceability. To achieve these goals, the MES/MOM of a smart factory should be designed to exploit the opportunities provided by IIoT. We will focus on the following design requirements for responsive smart factories:

1) Increased manufacturing flexibility through increases in new product flexibility, mix flexibility, and volume flexibility [34]
2) Exploitation of the opportunities of IIoT, in order to increase both product variety and production efficiency
3) Low-cost implementation
4) Low-complexity implementation

5.2. Determining the requirements for MES/MOM using QFD on Smart Lab's IT

To determine the design requirements for MES/MOM for responsive smart factories, we used the QFD method [35]. QFD is based on a tool called the House of Quality (first used in Japan by industrial engineers) that allows the high-level design requirements for a system to be correlated with lower-level design characteristics, meaning that the relative importance of different design characteristics can be assessed.

For our QFD analysis, we chose the following theoretically grounded technical design requirements for a smart factory (see Section 2): user-friendly interfaces, easy information retrieval, real-time information sharing, modularity of hardware and software, autonomous systems, secure interconnection, and secure data storage. The non-technical requirements were: manufacturing flexibility, low implementation complexity, and low-cost implementation. The design characteristics for MES/MOM were data visualization, interoperability, ISA 95 structure, use of open-source software, distributed control, data analysis, use of cryptography, and reuse of existing systems. In the House of Quality shown in Fig. 14, the relationship matrix represents our estimate of the importance of each design characteristic (column) in terms of achieving each design requirement (row). Our estimates are based on our experience from the case study and demonstrators. The correlation matrix (the "roof") represents synergies and conflicts between the design characteristics. We note, however, that the method of QFD analysis is limited in terms of being mainly a qualitative method, and the assignment of relative importance can be imprecise [36].

Below, we describe each row of the House of Quality:

1) **User-friendly interfaces**: With data visualization, dashboards can be created to display the state of production to the user. Data analysis also enables the use of smart assistants such as chatbots. An open-source interface allows for the customization and implementation of the features requested by users.
2) **Easy information retrieval**: Interoperability is essential to allow information to be retrieved from different systems and devices. A standardized data model such as that of ISA 95 can help in this regard. The use of open-source systems allows the deployer to add code to extract the necessary data.

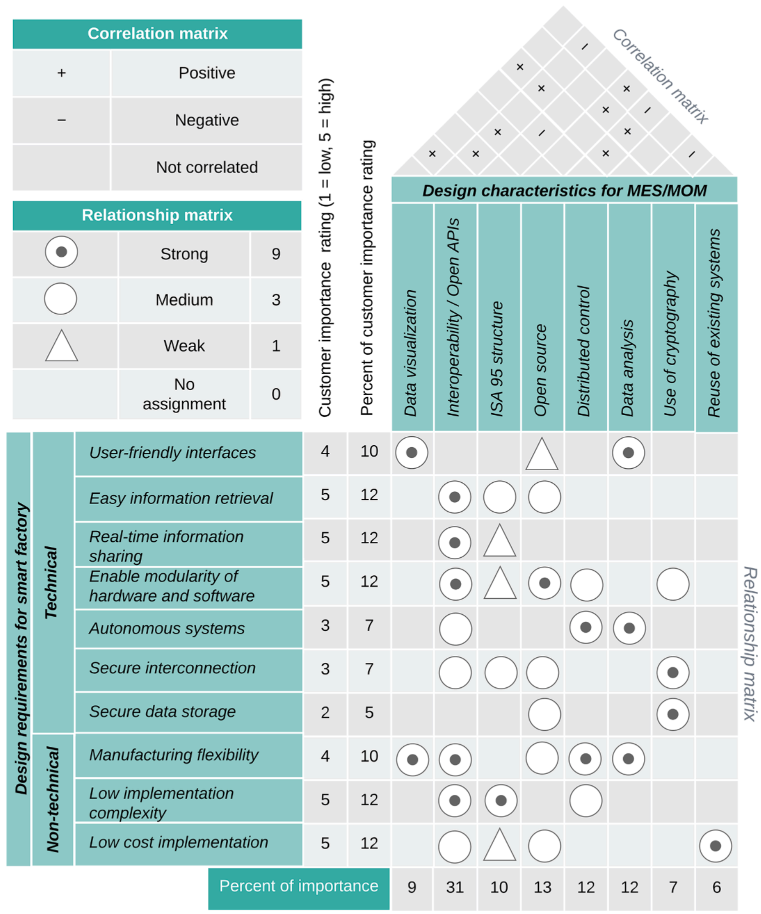

Fig. 14. The House of Quality – linking the design characteristics of MES/MOM with the design requirements for a smart factory

3) **Real-time information sharing**: Again, interoperability is essential for information sharing, and a standardized data model is helpful.
4) **Enable modularity of hardware and software**: The interoperability of different components is necessary to enable modularity. The use of open-source software allows for the creation of interfaces to connect components that are not already compatible. Distributed control means that different devices in the factory can have their control systems, which can then be added as a module to the modular architecture. The use of cryptographic authentication schemes ensures that only legitimate modules are included in the system.
5) **Autonomous systems**: Interoperability is necessary to allow for autonomous systems to communicate with their environment, and to form part of a decentralized control system. Autonomous systems also rely on data analysis to adapt to their environment.
6) **Secure interconnection**: Cryptographic protocols for encryption and authentication are essential for secure interconnection. The use of these protocols needs to be defined as part of the interoperability standards, as ad hoc solutions are likely to be less well thought out. The use of open-source software means that the security of the software can be audited, leading to quicker discovery and fixing of vulnerabilities. It also enables the use of cryptographic protocols in software that does natively support them. ISA 95 can aid security through its division of IT systems into levels; for example this can prevent a compromise of the ERP systems from affecting the shop floor if the connections between levels are controlled sufficiently well.
7) **Secure data storage**: The encryption and signing of stored data can help prevent theft and the unauthorized modification of data. The arguments for the use of open-source software for secure data storage are the same as those for secure interconnection.
8) **Manufacturing flexibility**: Data visualization and data analysis allow the company to determine changes in demand and capabilities more readily, thus increasing efficiency. Interoperability enables the reconfiguration of components to respond to such changes. Open-source software can also more easily be modified when changes are needed. The use of distributed control enables flexibility, since self-organized agents are more capable of adjusting to dynamic environments [37].
9) **Low-complexity implementation**: The use of interoperability standards and standard data models reduces the complexity of the implementation, since different components naturally speak the same language and less additional code is needed to connect them. Decentralized control also reduces the need for a complex central control.
10) **Low-cost implementation**: Clearly, the reuse of existing systems reduces the need to purchase new systems. Interoperability standards provide more flexibility in terms of choosing different solutions for the components of the IT infrastructure and shop floor, rather than of being dependent on certain vendors. This may lead to the selection of lower-cost solutions. Open-source software is usually free to acquire, although there is often a requirement to pay for support. Some open-source solutions such as Odoo are “open core”, meaning that only a base set of functionalities are open-source, and the extended functionalities must be paid for.

The “percentage of importance” calculated for each design characteristic shows that interoperability is by far the most important design characteristic for MES/MOM in smart factories. This means that when designing smart factories, priority should be placed on defining standardized protocols and interfaces for the IIoT devices and IT systems that will be interconnected.

5.3. Recommendations for designing a brownfield smart factory

To achieve modularity, it is necessary to develop standardized protocols for the interconnection of components. Standardized data models (such as those provided by ISA 95) are also needed to ensure that the different components speak the same language [7]. To be able to include heterogeneous components from different vendors in a given setup, it is further important that open APIs are used, so that custom code can call their functions. Open-source components mean that functionality can be extended or adapted to the needs of a specific situation [9]. Modular and open-source software platforms such as Odoo allow for the creation of custom modules to integrate new functionalities and services, and easy connectivity to other systems. This is an advantage compared to closed alternatives in which solutions from one vendor often cannot interoperate with products from other vendors, thus leading to vendor lock-in [38]. In our case study, the modularity of Odoo allowed us to create the custom AAU MES module that allowed us to connect to the IIoT platform, which would have been difficult with a closed system. This platform-based approach is also in line with the integrated industrial automation stack suggested by Koerber et al. [15]. We note, however, that restricting oneself to open components limits the available choices, and may not be realistic in some cases as no suitable open solutions are available.

Standardized interfaces and data models are particularly important for enterprises looking to develop smart factory capabilities in a brownfield environment. IIoT technologies need to be integrated with legacy systems and devices, since rip-and-replace can be too expensive. Companies aiming to develop smart factory capabilities can use the communication and information layers of RAMI 4.0 to ensure coverage of their data and communication architecture with standards [14].

Due to the increased interconnectivity in a smart factory, it is becoming increasingly important to secure the communication between devices and servers through the use of cryptographic protocols, to ensure the confidentiality, authenticity, and integrity of the data being transferred. The confidentiality and integrity of data in storage also need to be ensured. A secure authentication and authorization scheme for both users and devices needs to be in place that ensures that data can only be accessed, and operations can only be executed, by those who are authorized to do so. Another important security issue is availability, which means that data and services must be available at any time they are requested. This requires protection against denial-of-service attacks, the aim of which is to interrupt the functioning of the manufacturing systems. A system should also be in place that allows for the detection of anomalous behavior if a cyber-attack does take place, as well as the protocols necessary to respond to a detected attack in progress and to recover from a successful attack. The feasibility of a certain protocol for secure IT/OT connection in the Smart Lab was evaluated in [17], and it was also shown that the ISA 95 structure can help to secure IIoT interconnection in a factory.

5.4. Design choices for a smart factory with MES/MOM as a core

The core element of our architecture is an IIoT-connected MES/MOM, based on Odoo. Fig. 15 shows the redesign of a MES/MOM to establish secure interconnection in a distributed way. The figure

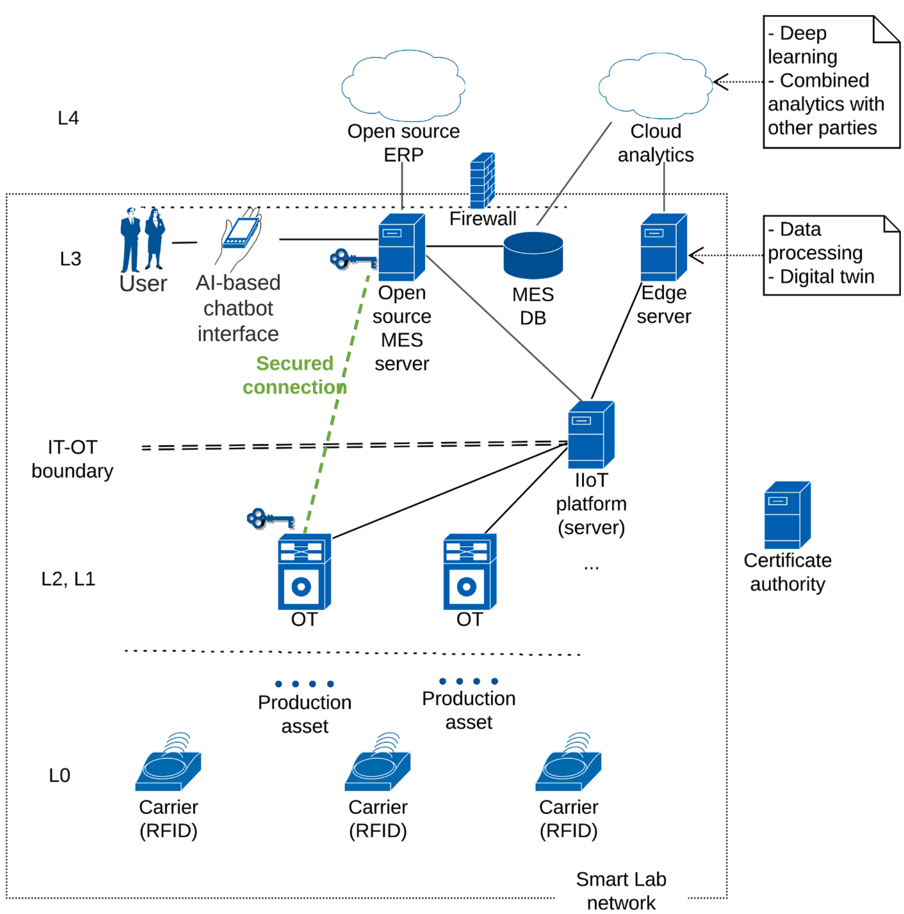

Fig. 15. Proposed high-level architecture for an IIoT-connected MES/MOM (based on the Smart Lab)

represents a securely distributed and digitalized architecture for systems in the Smart Lab. The objective of this design is to enhance digital modularity and interoperability.

The IIoT platform manages a variety of OT devices and provides a unified way for MES/MOM and edge servers to communicate with them. Production data from OT devices are transferred via the IIoT platform to an on-premises edge server, which processes the data and uploads them to a cloud analytics server. The production data are then harvested on the server using deep learning models. The IIoT platform, edge server and cloud analytics server are all part of the factory's big data infrastructure, and MES/MOM is both a data source and consumer [4]. The data analysis can aid in optimizing production and automating decision making, for example by implementing multi-agent systems (MAS) on the shop floor or designing a decision support mechanism for MES/MOM using machine learning techniques. The design and implementation of MAS is outside of the scope of this study, in spite of their promising approach of using decentralized control in solving complex decision and routing problems more efficiently.

As a platform-based system with different apps, Odoo appears to be capable of supporting our goals for mass customization, since it allows for the seamless translation of product customization options in a sales order into a manufacturing order and BOM. Its modular architecture and open-source nature also allow for the addition and modification of functionalities to accommodate the individual and changing needs of an enterprise. This is especially useful for manufacturing enterprises with an international manufacturing footprint, as it means they can adapt their systems to different cultural and legal requirements.

In the Smart Lab, interconnection is a key requirement for implementing distributed control as the products need to communicate with the workstations, which then need to communicate with the MES/MOM to retrieve and update information on the relevant order. In our architecture, the production assets are therefore equipped with RFID readers that read the tags attached to each carrier. In this way, the OT device can identify the carrier/product and query the IIoT platform for operation instructions, which are retrieved from the MES/MOM. Since each workstation acts independently and negotiates the operations to be executed with the product, our IIoT-connected MES/MOM design to a certain extent supports the distributed control needed in Industry 4.0 [13]. It is feasible to implement this as part of a MAS, in which the control for each workstation is implemented in the form of an agent. These agents could be embedded in a MAS platform or deployed independently as separate (containerized) applications. The latter option has several advantages in terms of flexibility and vendor independence, as different agents need not comply with the same platform as long as they can communicate using a common protocol [39]. Containerized agents may however be less efficient in terms of computational resource usage, and less well suited to real-time applications [39].

The connections between devices and servers are secured using standard protocols such as Transport Layer Security (TLS), with certificates provided by a certificate authority that is not connected to the network. The factory network is further protected against unauthorized access by a firewall.

An artificial intelligence (AI) based chatbot interface with a prediction system serves as an interface layer for MES/MOM, and can be used for easy information retrieval from the MES/MOM database. This interface can also be combined with a prediction system that can provide live updates on production to the MES/MOM user. The chatbot interface can be implemented using open-source software such as Artificial Intelligence Markup Language. This feature demonstrates the potential of human-AI collaboration in a factory and supports an important concept of smart factories in which technology empowers human workers. An open-source enterprise solution such as Odoo is also an advantage to the implementation of virtual intelligent assistant systems on the shop floor for operator assistance.

In summary, the MES/MOM forms the central piece of our architecture, and directly or indirectly connects all the components of the smart factory [7]. In Fig. 16, we generalize the architecture of Fig. 15 to a model of the systems comprising a smart factory with MES/MOM as its core. To allow for the possibility of the kind of microservice-based MOM architecture described in [10], we model the MOM functionalities individually, connecting them to each other and the surrounding systems as needed. An example instantiation of this model based on the Smart Lab is shown in Fig. 17.

By designing a MES/MOM that is better prepared for interconnection with all the elements of the cyber-physical systems [7] in a manufacturing enterprise, we have contributed to improving the responsiveness of production systems, making them better able to respond to disturbances [1]. Our design represents an attempt to improve MES/MOM for data acquisition and presentation of information in IIoT.

We have addressed research question **Q1** by verifying the relevance of ISA 95 models to IIoT in this study through the use of industrial demonstrators. By analyzing the findings from the case study, we have also addressed **Q2** by presenting architectural and design recommendations for a next-generation MES/MOM that is compatible with IIoT.

5.5. Future work

We plan to evaluate the proposed model by involving industry peers. We intend to conduct a focus group study with representation from manufacturing companies, both discrete and continuous, from the Manufacturing Academy of Denmark (MADE) network. We also plan to ensure that the participants are an appropriate mix of both IT and OT

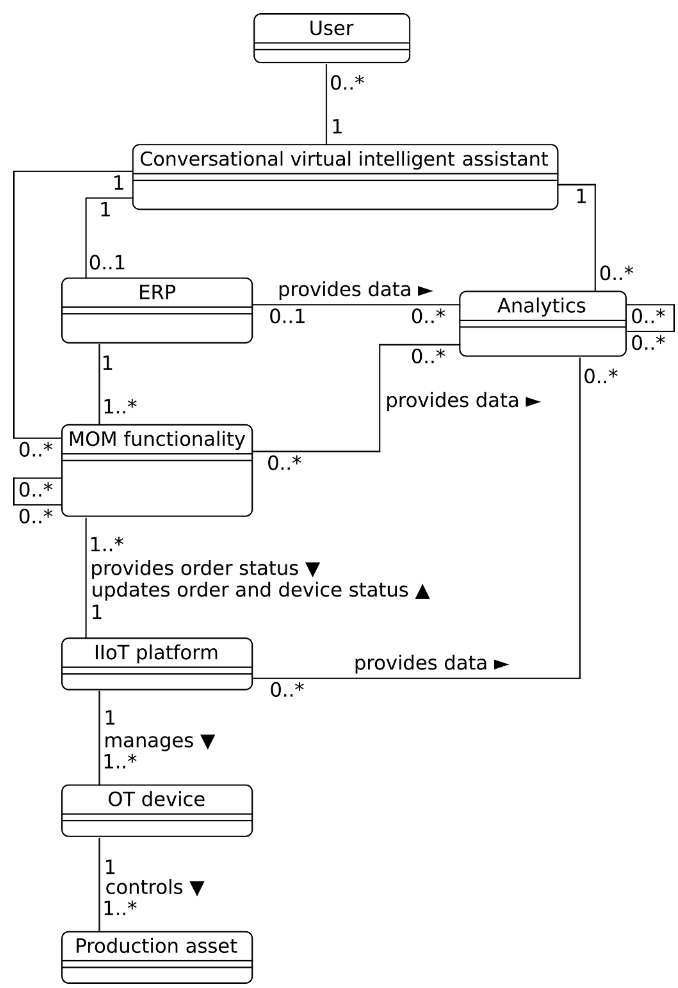

Fig. 16. UML class diagram of the proposed next-generation IIoT-connected MES/MOM in a smart factory

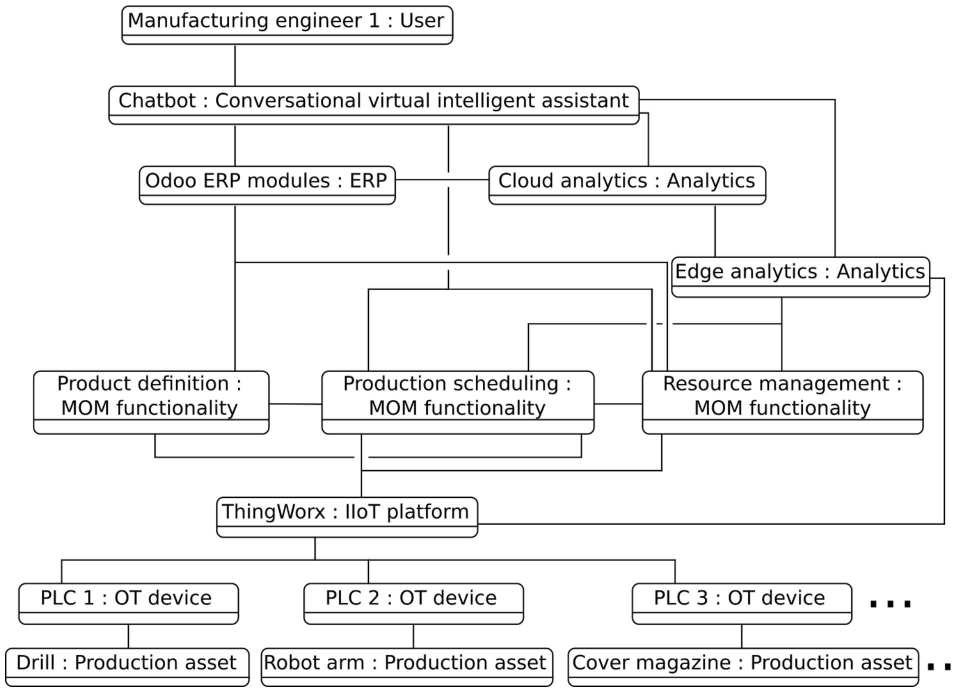

Fig. 17. UML object diagram showing the instantiation of the architecture (Fig. 14) for the Smart Lab

professionals. Future work will aim to investigate the applicability of the models in order to determine whether they are operationally realistic and cost-effective. It would also be worthwhile to develop metrics that allow quantitative evaluation of approaches to integrate MES/MOM with IIoT platforms.

Our data model shows how ISA 95 can be adapted to a smart factory setting; although this was sufficient for our case study, it may not apply to all situations. Our work covers only four of the MOM functionalities defined in ISA 95, which we judged to be within the scope of this work in terms of studying the problem of responsiveness. Future research can study how functionalities such as maintenance or quality control need to be re-designed to benefit from IIoT connectivity. Furthermore, rather than implementing MES/MOM as an app for a platform, as in our case study, a microservice-based system could be set up in which MOM functionalities are run as separate but interconnected services. The latest research also suggests that an architecture based on containerized microservices is better than a platform-based one in terms of cost and the flexibility to implement MAS [39].

5.6. Developing design principles for next-generation IIoT-connected MES/MOM

As discussed in Section 5.4, the traditional inflexibilities of MES/MOM need to be addressed, and it should be redesigned to accommodate the data management needs of Industry 4.0. In practice, modernizing legacy MES will remain a huge challenge for companies due to the high costs and the complexity of implementation, but this will be necessary to improve the responsiveness in order to face future market uncertainties. Since data management needs in IIoT should drive the next-generation of MES/MOM design, we propose three design principles based on our research work:

i. **Principle of reconfigurability**: To allow smart factories to become capable of manufacturing flexibility, an IIoT-connected MES/MOM should support the reconfigurability needs at both a low-level (e.g., operative-level change objects such as software and hardware components) and a high-level (e.g., strategic firm-level change objects such as supply network structure and ownership) [40].
ii. **Principle of user-assistance**: Data collected from IIoT should be accessible to MES/MOM users in real-time through user-friendly interfaces, preferably using AI-based intuitive virtual assistant systems [41].
iii. **Principle of security**: Data exchange between IIoT devices and MES/MOM needs to be protected from theft and falsification by cryptographic encryption and authentication protocols, which should form part of the communication standards [17].

6. Conclusions

We have presented a system architecture and a MES/MOM data model based on ISA 95 that integrates MES/MOM with an IIoT platform, thus enabling interconnectivity and interoperability between IIoT devices, MES/MOM, and ERP. We implemented our design as part of a case study at Aalborg University's Smart Production Lab, in which we replicated industry scenarios. The open-source Odoo business platform served as an ERP and MES/MOM. The relevance of our design was further tested through a series of industrial demonstrators, in which our approach was partly implemented and evaluated. Our approach also considered the systems analysis and design perspective to explore the related Industry 4.0 standards (e.g., ISA 95), investigate the traditional industrial automation hierarchy, analyze the requirements from both high-level business and low-level production, and design the data models based on the available resources (e.g., material, equipment). The findings from a case study and a QFD analysis lead us to conclude the following:

- ISA 95 can be useful in an IIoT context to systematize and standardize the data models and data flows for enterprise information systems. Responsive smart factories can benefit from MES/MOM design adapted from ISA 95 models to integrate with IIoT platforms using standard interfaces. This approach is particularly beneficial for connecting to IIoT in brownfield implementations, where companies have already adopted some of the principles of ISA 95.

- Interoperability is an essential design choice for responsive smart factories, and can best be addressed through the use of open standards and open APIs. However, the goals of interoperability are made more difficult by the use of legacy systems in factories designed in the pre-IIoT era that are hard to integrate.
- **The concept behind next-generation IIoT-connected MES/MOM**: IIoT-connected MES/MOM can be designed as a core in a smart factory. Rather than the monolithic form of MES that is currently widespread, future MES/MOM systems should be agile and modular. A modular MES/MOM architecture can be built as a collection of apps on top of a platform such as Odoo, each of which provides a MOM functionality. Alternatively, a microservice-based MES/MOM architecture can be employed in which each MOM functionality is offered as an independent service, thus enabling even greater modularity. MES/MOM needs to be able to interconnect and communicate with the factory's field devices, including legacy devices, through an IIoT platform. When enriched by sensor data from production machines, MES/MOM can serve as a candidate for implementing process digital twins. Furthermore, the MES/MOM should to be able to connect to the ERP system to support vertical and horizontal integration. The latter allows for improved coordination in the supply network, leading to both greater responsiveness and end-to-end traceability.

We propose an architecture model of a smart factory information system centered around MES/MOM, which takes into account the goals of modularity, customizability, security, and operator assistance. We have instantiated this architecture in the Smart Lab using a platform-based approach. Cyber-security is often not considered in designs of MES/MOM for smart factories with IIoT, even though it is crucial to protect against malicious interference with the factory's operations and information theft. Instead of being an afterthought, security needs to form part of the smart factory design from the beginning, and we have therefore considered it as a part of our analysis.

For theoreticians, our paper serves as a concrete example of how to use ISA 95 to develop standardized solutions for smart factories. We provide insights into designing next-generation MES/MOM by contributing to the research on responsive smart factories and IIoT within the domains of industrial engineering and operations management. Practitioners can benefit from this work by learning how to best apply ISA 95 models to integrate the IIoT platform into their ongoing system landscape and how to develop smart factory capabilities in a brownfield environment. From our experience with industrial demonstrators, we note that many companies interested in Industry 4.0 currently fall short in the areas of interconnection and interoperability, and improving this aspect is seen as the main agenda in their journey toward Industry 4.0.

CRediT authorship contribution statement

Soujanya Mantravadi: Writing – original draft, Writing – review & editing, Conceptualization, Software. **Charles Møller:** Supervision, Funding acquisition. **Chen LI:** Writing – review & editing, Software. **Reto Schnyder:** Writing – review & editing.

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.

References

[1] D. McFarlane, J. Matson, Assessing and improving the responsiveness of manufacturing production systems, IEE Seminar Customer Focused Manufacturing: Survival of the Fittest 1999 (166) (1999), pp. 2–2.
[2] M. Hermann, T. Pentek, B. Otto, Design Principles for Industrie 4.0 Scenarios, in: *2016 49th Hawaii International Conference on System Sciences (HICSS)*, 2016, pp. 3928–3937, vol. 2016-March.
[3] T.J. Williams, The Purdue enterprise reference architecture, Comput. Ind. 24 (2–3) (Sep. 1994) 141–158.
[4] Y. Cui, S. Kara, K.C. Chan, Manufacturing big data ecosystem: A systematic literature review, Robot. Comput. Integr. Manuf. 62 (Apr. 2020), 101861.
[5] ISA, *ANSI/ISA-95.00.03-2013 Enterprise-Control System Integration - Part 3: Activity Models of Manufacturing Operations Management.*
[6] A. Tiwana, Platform Ecosystems: Aligning Architecture, Governance, and Strategy, Elsevier, 2014.
[7] S. Jaskó, A. Skrop, T. Holczinger, T. Chován, J. Abonyi, 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 (Dec. 2020), 103300.
[8] J. Wang, C. Xu, J. Zhang, J. Bao, R. Zhong, A collaborative architecture of the industrial internet platform for manufacturing systems, Robot. Comput. Integr. Manuf. 61 (Feb. 2020), 101854.
[9] A. Bonaccorsi, C. Rossi, Why open source software can succeed, Res. Policy 32 (7) (2003) 1243–1258.
[10] C. Wunck, Towards a Microservice Architecture for the Manufacturing Operations Layer, EPiC Series in Computing 63 (2019), 241–230.
[11] A.R. Hevner, A Three Cycle View of Design Science Research, Scand. J. Inf. Syst. 19 (2) (2007) 87–92.
[12] P. Leitão, Agent-based distributed manufacturing control: A state-of-the-art survey, Eng. Appl. Artif. Intell. 22 (7) (2009) 979–991.
[13] F. Almada-Lobo, The Industry 4.0 revolution and the future of Manufacturing Execution Systems (MES), J. Innov. Manag. 3 (4) (Jan. 2016) 17.
[14] M. Hankel and B. Rexroth, "The Reference Architectural Model Industrie 4.0 (RAMI 4.0)," 2015.
[15] B. Koerber, H. Freund, T. Kasah, and L. Bolz, "Leveraging industrial software stack advancement for digital transformation," 2018.
[16] ISA, *ANSI/ISA-95.00.01-2000 Enterprise-Control System Integration - Part 1: Models and Terminology*.
[17] S. Mantravadi, R. Schnyder, C. Møller, T.D. Brunoe, Securing IT/OT Links for Low Power IIoT Devices: Design Considerations for Industry 4.0, IEEE Access 8 (2020), pp. 200305–200321.
[18] P. Novák, J. Vyskočil, and P. Kadera, "Plan Executor MES: Manufacturing Execution System Combined with a Planner for Industry 4.0 Production Systems," in Lecture Notes in Artificial Intelligence, vol. 11710 LNAI, 2019, pp. 67–80.
[19] B.W. Jeon, J. Um, S.C. Yoon, S. Suk-Hwan, An architecture design for smart manufacturing execution system, Comput. Aided. Des. Appl. 14 (4) (Jun. 2017) 472–485.
[20] S.M. Kannan, et al., Towards Industry 4.0: Gap Analysis between Current Automotive MES and Industry Standards Using Model-Based Requirement Engineering, in: 2017 IEEE International Conference on Software Architecture Workshops (ICSAW), 2017, pp. 29–35.
[21] A. Zeid, S. Sundaram, M. Moghaddam, S. Kamarthi, T. Marion, Interoperability in Smart Manufacturing: Research Challenges, Machines 7 (2) (Apr. 2019) 21.
[22] E. Negri, S. Berardi, L. Fumagalli, M. Macchi, MES-integrated digital twin frameworks, J. Manuf. Syst. 56 (April) (Jul. 2020) 58–71.
[23] J. Leng, et al., Digital twin-driven rapid reconfiguration of the automated manufacturing system via an open architecture model, Robot. Comput. Integr. Manuf. 63 (Jun. 2020), 101895.
[24] R.Y. Zhong, Q.Y. Dai, T. Qu, G.J. Hu, G.Q. Huang, RFID-enabled real-time manufacturing execution system for mass-customization production, Robot. Comput. Integr. Manuf. 29 (2) (Apr. 2013) 283–292.
[25] B. Selic, The pragmatics of model-driven development, IEEE Softw 20 (5) (Sep. 2003) 19–25.
[26] T. Kapteijns, S. Jansen, S. Brinkkemper, H. Houët, R. Barendse, A comparative case study of model driven development vs traditional development: The tortoise or the hare, From code centric to Model centric Softw. Eng. Pract. Implic. ROI 22 (2009) 22–33.
[27] J. Hutchinson, M. Rouncefield, J. Whittle, Model-Driven Engineering Practices in Industry, in: Proceedings of the 33rd International Conference on Software Engineering, 2011, pp. 633–642.
[28] G. Scanniello, C. Gravino, G. Tortora, Investigating the role of UML in the software modeling and maintenance - a preliminary industrial survey, in: Proceedings of the 12th International Conference on Enterprise Information Systems, 2010, pp. 141–148.
[29] Dama International, DAMA-DMBOK: Data Management Body of Knowledge, 2nd ed., Technics Publications, LLC, Denville, NJ, USA, 2017.
[30] B. Zhou, S. Wang, L. Xi, Data model design for manufacturing execution system, J. Manuf. Technol. Manag. 16 (8) (Dec. 2005) 909–935.
[31] C. LI, S. Mantravadi, C. Møller, AAU Open Source MES Architecture for Smart Factories – Exploiting ISA 95, in: IEEE International Conference on Industrial Informatics, IEEE, 2020, pp. 369–373.
[32] H.-P. Wiendahl, et al., Changeable Manufacturing - Classification, Design and Operation, CIRP Ann. 56 (2) (2007) 783–809.
[33] C. LI, S. Mantravadi, C. Schou, H. Nielsen, O. Madsen, C. Møller, An ISA-95 based Middle Data Layer for Data Standardization - Enhancing Systems Interoperability for Factory Automation, in: Stuttgart Conference on Automotive Production, 2020.
[34] J. Olhager, B.M. West, The house of flexibility: Using the QFD approach to deploy manufacturing flexibility, Int. J. Oper. Prod. Manag. 22 (1) (2002) 50–79.
[35] J.B. Revelle, J.W. Moran, C.A. Cox, The QFD Handbook, John Wiley & Sons, 1998.

[36] R. Wolniak, The use of QFD method advantages and limitation, Prod. Eng. Arch. 18 (18) (Mar. 2018) 14–17.
[37] S. Wang, J. Wan, D. Zhang, D. Li, C. Zhang, Towards smart factory for industry 4.0: a self-organized multi-agent system with big data based feedback and coordination, Comput. Networks 101 (Jun. 2016) 158–168.
[38] L. Nyman, J. Lindman, Code Forking, Governance, and Sustainability in Open Source Software, Technol. Innov. Manag. Rev. 3 (1) (Jan. 2013) 7–12.
[39] M.P. Hernández, D. Mcfarlane, A.K. Parlikad, M. Herrera, A.K. Jain, Relaxing Platform Dependencies in Agent-Based Control Systems, IEEE Access 9 (2021) 30511–30527.
[40] S. Mantravadi, J.S. Srai, T.D. Brunoe, C. Møller, Exploring Reconfigurability in Manufacturing Through IIoT Connected MES/MOM, in: 2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), 2020, pp. 161–165.
[41] S. Mantravadi, A.D. Jansson, 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, Lecture Notes in Artificial Intelligence, Springer, ACIIDS 2020, 2020, pp. 189–201.