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Exploring Reconfigurability in Manufacturing through IIoT Connected MES/MOM

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Abstract - **This paper explores the role of manufacturing execution systems (MES) with ISA 95 functionalities for the reconfigurability in a manufacturing enterprise. The work is aimed at supporting digitalization based on Industry 4.0 and the Industrial Internet of Things (IIoT) concepts. For this, we use the quality function deployment method to link ISA 95 MES functionalities and reconfigurability needs, based on a case example of a cyber-physical factory (AAU Smart Lab). Accordingly, we present a framework to assess reconfigurability for smart factory development. The paper identifies reconfigurability approaches using IIoT connected MES/MOM for tackling severe market disruptions (e.g. the one caused by the ongoing COVID-19 pandemic).**

Keywords - **Reconfigurability, Industry 4.0, MES, IIoT**

I. INTRODUCTION

A. The problem

Reconfigurability goals in companies' concern requirements on short product life cycles along with increased product variety to support changing market demands and a smart factory vision should support this need. A smart factory is a key component of Industry 4.0 and it predominantly focuses on acquiring digital capabilities [1]. Due to this, MES (a shop floor information system) is considered critical for a smart factory [2]. Most of the academic literature on smart factories focuses on gaining technical capabilities but research on the topic of its strategic capabilities is still limited.

MES is increasingly recognized as a key system for smart factory development. However, it is facing challenges that demand improvements in its current ways of usage and development. Some challenges are:

- Ambiguity around the role of MES in Industry 4.0 on whether it is the next level of automated control or shop-floor support for operations [3]
- IIoT disrupting the traditional ISA 95 hierarchy of systems in industrial automation [4]

B. Smart factory goals

In Industry 4.0, a smart factory concept of manufacturing enterprise (including its global manufacturing facilities) embraces automation and digitalization of production using cyber-physical systems [1]. It is an IT-driven enabler to solve future manufacturing problems, especially the customer responsiveness problem by reducing time to market and by increasing product variety. Therefore, below we focus on manufacturing flexibility and enterprise integration:

1) Manufacturing flexibility, the dynamic capability of a smart factory:

Manufacturing enterprises can have several types of competitive priorities ranging from quality, cost, sustainability, and flexibility. We consider information systems to have a special role to play in improving manufacturing flexibility. Manufacturing flexibility is a well-established field and has been identified as an important competitive priority lately. It covers a broad range of subjects such as machinery material etc. From a strategic perspective, we argue that a smart factory should have the capability of manufacturing flexibility for the below reasons [5]:

- It focuses on improving the business by increasing volume flexibility, mix flexibility, and new product flexibility.
- It deals with improving the robustness and efficiency of manufacturing systems as a means to improve flexibility, thus directly aligning with the reconfigurability needs, which we discuss in Section 2.

2) Enterprise integration for Industry 4.0:

Enterprise integration concerns both horizontal and vertical integration of IT systems across the organization [6] to achieve robust information management. ISA 95 standard addressed part of it (vertical integration) in a manufacturing enterprise but does not tackle the exercise of integrating IT systems of supply chain partners (horizontal integration, as per the industrial automation field). Since factories are undergoing reconceptualization, MES implementation needs both vertical as well as horizontal integration in Industry 4.0

Manufacturing flexibility and enterprise integration is not to be seen as stand-alone goals. They are interrelated because enterprise integration allows a seamless flow of information and positively influences manufacturing flexibility. IT is an enabling technology for the factory of the future, to match customer requirements on product variety and delivery speed [7]. Therefore we consider the goal of manufacturing flexibility as a customer requirement and the goal of reconfigurability (driven by information systems such as MES) as a user (manufacturer) requirement in this paper. Considering both customers as well as manufacturer's needs is essential for realizing the smart factory vision and to design a digital enterprise.

C. MES as an enabler in manufacturing enterprise operations

MES is an operations management system and a popular software tool amongst manufacturers that came into limelight in the 90s for its powerful ability to replace paper-based activities of manufacturing operations management (MOM). MES follows the operational model of ISA 95. Since the Industry 4.0 paradigm is IT-driven and exploits the advancements of modern computing technologies, MES can possess production data in real-time. Even though the recent literature on MES states that it has a promising future in Industry 4.0 and is a core technology for realizing smart factories [8], how it should be implemented as an enterprise initiative in Industry 4.0 is still unclear. One of the reasons behind this problem could be that the business and the shop floor speak different languages and do not have a similar action plan [9]. Moreover, systems can create flexibility and inflexibility. Motivated by this need, we study the new role of MES as an enabler in manufacturing enterprise operations both from low-level as well as high-level perspectives. Therefore, we ask the following question for this paper:
RQ) How does digitalization of shop floor operations limit or support manufacturing flexibility?

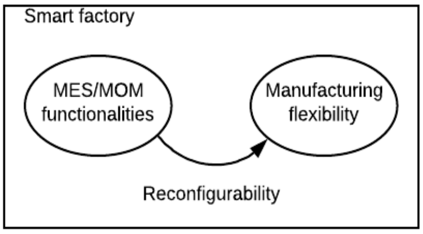

Fig. 1. Research focus.

Section 2 presents the theoretical framework for the topic of reconfigurability in the smart factory context. Section 3 presents the quality function deployment (QFD) method to assess reconfigurability requirements using the 'Smart Lab' case. Findings are discussed in Section 4 and conclusions on reconfigurability are drawn in Section 5.

II. RECONFIGURABILITY FOR A SMART FACTORY – A FRAMEWORK FOR ASSESSMENT

Smart factories can learn from mass customization strategies to become capable of manufacturing flexibility. Mass customization solves customer responsiveness problems using reconfigurable manufacturing systems as well as reconfigurable supply chain management methods [10]. Reconfigurability's definition is attaining a broader scope whereas in the past, it was mostly related to reconfigurable manufacturing systems where software and hardware components can be changed. The reconfigurable manufacturing systems view is still valid for low-level operative changes in a factory but an in-depth understanding of the change objects is required for high-level changes (strategic level). Therefore, we argue that the high-level reconfigurability needs can be understood with a supply network configuration lens.

We present the low-level and high-level reconfigurability from two different perspectives which will eventually drive digitalization in Industry 4.0 using MES. In other words, a next-generation MES system should be able to cater to both low-level and high-level reconfigurability needs. But before exploring the role of MES, below we define what reconfigurability entails.

A. Low-level reconfigurability at operative and tactical level - a factory changeability context

We derive the following low-level reconfigurability needs from the changeability classes in a factory [11] at an operative and tactical levels:

1) Changeoverability & flexibility class is the operative ability to change a single machine or workstation with minimal effort and delay.
2) Reconfigurability class is the operative ability to switch within a predefined family of workpieces or sub-assemblies by changing functional elements. (The reconfigurability class not to be confused with "reconfigurability" that we address as a larger issue in this paper)
3) Transformability class is the tactical ability to make structural changes in a factory (e.g.: adding a new production line)

B. High-level reconfigurability at a strategic level – a supply network context

Configuration of the supply network problem predominantly belongs to the domain of a firm strategy. It pertains to the organization's mission, markets, and resources, etc. Types of configurations can relate to the firm's span of control, types of decentralization, and planning systems [12]. On the other hand, "reconfiguration" can be a route to organizational coherence and is often used in the context of business transformation [13].

In this paper, we derive high-level reconfigurability needs from the attributes of supply networks [13] at a strategic level of manufacturing enterprise, in which the authors' present reconfigurability as the ability to rearrange the following "key elements":

1) Supply network structure (such as ownership and coordination of factories)
2) The flow of material and information within and between factory networks
3) The role, inter-relationships between supply network parties (e.g. contractual changes)
4) "Value-structure" of the product or service (e.g.: product composition and structure)

We developed the QFD assessment tool (see fig. 4) based on all the above reconfigurability requirements.

III. APPROACH

A. The case of "Smart Lab"

The AAU Smart production lab (Smart Lab) is a "small Industry 4.0 factory" and a learning laboratory that has an automated assembly line to manufacture mock mobile phones (see fig 2.). It is also a reconfigurable manufacturing system with IIoT devices that allow for a single piece flow (see fig 3). It has two stations (for drilling, inspection, etc.) on each of the five modules. The lab is situated in Aalborg University, Denmark, and has enabled many multi-disciplinary projects from various departments such as mechanical engineering, computer science, business, etc., since its establishment in 2016 [14]. Therefore, the lab supported researchers to co-create new knowledge of Industry 4.0. Since this lab is a replica of a smart factory, we used it to obtain requirement specifications.

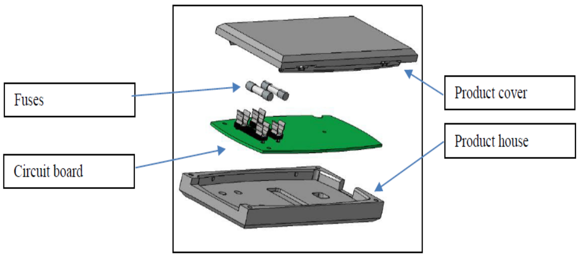

Fig. 2. The product manufactured in the Smart Lab [14].

The Festo cyber-physical automated production line is orchestrated by MES, which is loosely based on the MOM functionalities of ISA 95 standard. This MES already supports operative level reconfigurability, however, the tactical and strategic level reconfigurability requirements need further exploration. For requirements analysis, we used the QFD method on the Festo-CP factory of the Smart Lab.

Fig. 3. Set-up of the Smart Lab, a cyber-physical factory.

B. QFD method to assess reconfigurability in Industry 4.0

The House of quality tool of QFD enables engineers and designers to pinpoint requirements. This method was first used in Japan and ever since it has also gained popularity in the fields outside of industrial engineering. In our case, the tool (see fig. 4) enabled us to gauge which functionalities of MES can support the manufacturer's requirements on reconfigurability in a factory.

IV. ANALYSIS & DISCUSSION

Manufacturing flexibility can be achieved using the different levels of reconfigurability as presented in Section 2. Each level responds to different changes in products and volumes. Manufacturers must pick the right level of flexibility as too low and too high can have a cost. Therefore, determining the right amount of flexibility that is needed is extremely important, before starting digitalization.

A. User stories and features

We use "user stories" specification as per behavior-driven development (BDD) to provide examples of the features that MES needs to exhibit to support reconfigurability. BDD is an agile software development method used by business analysts and developers to document the behavior that is expected from software. It translates a complex business requirement in a domain-specific language, for example using English sentences.

An example of a user story in the Smart Lab on low-level reconfigurability (changeoverability and flexibility):

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

An example of a user story of MES to support the high-level reconfigurability:

```
As a Product architect
I want to check manufacturing recipes and product definitions of variants
So that I can support new product development and bring a new product to the market
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B. Assessment of reconfigurability

We used "changeability classes" to assess the role of MES functionalities for reconfigurability based on the Smart Lab case. Different classes of changeability serve different purposes in a factory. Below Fig. 4 is the house of quality matrix:

Relationship matrix		
◉	Strong	9
○	Medium	3
△	Weak	1
	No assignment	0

Reconfigurability requirements of a factory			Data collection and acquisition	Operation/detailed scheduling	Labour management	Resource allocation and status	Maintenance management	Dispatching production units	Product tracking and geneology	Quality management	Process management	Performance analysis	Document control
High-level	Agility (Rearranging "key elements" of supply network)	Change of supply network structure (such as ownership and coordination of factories)										◉	
High-level	Agility (Rearranging "key elements" of supply network)	Change of information flows within and between factory networks	○						◉				
High-level	Agility (Rearranging "key elements" of supply network)	Change of material flows within and between factory networks	○	◉						○		◉	
High-level	Agility (Rearranging "key elements" of supply network)	Change in relationships between supply network parties (contractual changes)								△		△	
High-level	Agility (Rearranging "key elements" of supply network)	Change of product composition and structure							◉	○		○	
Low-level	Transformability	Change of pyhsical factory structure						△		○		◉	
Low-level	Transformability	Change of personnel						△		○		◉	
Low-level	Transformability	Change of organizational structure								○			
Low-level	Reconfig.	Addition and removal of workstations			○	◉					○		△
Low-level	Reconfig.	Change of logistical functions (procuring new materials)				◉					○		△
Low-level	Changeoverability & flexibility	Re-scheduling		◉	○					○	○		
Low-level	Changeoverability & flexibility	Re-routing		◉				◉		○	○		
Low-level	Changeoverability & flexibility	Re-programming		△						○	○		△
Low-level	Changeoverability & flexibility	Change of single machine or work station function		◉						○	○		
		Percent of importance	3	20	3	10	0	6	10	15	10	22	2

MES functionalities based on ISA 95 standard — Relationship matrix

Fig. 4. House of quality (QFD) matrix - Linking reconfigurability requirements and MES functionalities.

Even though a QFD matrix is self-explanatory, some of the arguments for the relations (between MES functionality and reconfigurability), indicated in Figure 4 are:

1) Low-level reconfigurability:

MES was originally developed to serve this class. It supports most of the operative level changes with the help of its "Scheduling" functionality.

2) High-level reconfigurability:

"Scheduling" is also highly important to business level as it lets the manufacturing enterprise to update the schedules (assignment of resources, equipment, material) in the event of demand disruption. "Performace analysis" functionality can be used to make "informed" decisions to rearranging the supply network structure. The functionality of "product tracking and genealogy" can provide product-centric data to the other parties of the supply chain. The real-time data from MES can for example be related to the product shipments to the wholesaler, material, and human resource allocation. It is not possible to extract such thorough production details from ERP. Furthermore, MES digitalization with IIoT can enrich the data, which could then be used for tackling severe disruptions.

C. Recommendations

1) Next-generation MES is enabled by IIoT

Operations of a manufacturing enterprise can be enabled by an MES if it supports both operative/tactical and strategic needs of reconfigurability. IIoT interconnectivity is an enabler for MES to be used as a single information system for coordinating multiple supply networks. This vision aligns with the Industry 4.0 principles of interconnection and information transparency [1]. Many global manufacturing enterprises are already considering a firm level-MES with additional features, where shop floor data in real-time can be used in any location in the world. This can aid supply chain optimization.

2) MES as a factory process digital twin

Real-time production data is aggregated by MES, where ISA 95 standard defines the relevant MES functionality of "production data collection" as... [15]

'...the collection of activities that gather, compile and manage production data for specific work processes or specific production requests. Manufacturing control systems generally deal with process information such as quantities (weight, units, etc.) and associated properties (rates, temperatures, etc.) and with equipment information such as controller, sensor, and actuator statuses. The managed data may include sensor readings, equipment states, event data, operator-entered data, transaction data, operator actions, messages, calculation results from models, and other data of importance in the making of a product. The data collection is inherently time or event-based, with time or event data added to give context to the collected information.'

Cyber-physical factories such as the Smart Lab are equipped with IIoT devices that gather production data in real-time. The convergence of IT and OT enhances manufacturing flexibility through digitalization. Since the majority of standard MES solutions are web-based, MES functionalities can be hosted on the cloud. Having an MES server on the cloud enables combined analytics with other parties of the supply chain.

Previous studies presented the role of MES as a digital twin [3], however, to make it tangible, we suggest that manufacturers must develop their own MES system to cater to their individual reconfigurability needs. To support this cause, we presented a framework in Section 2 and Figure 2.

V. CONCLUSION

This paper develops reconfigurability approaches using MES functionalities in Industry 4.0. By providing a framework of assessment, we also attempted to identify the relative importance of each functionality for each reconfigurability goal. For the Smart Lab case, we attained high percentages of importance for MES functionalities, "Scheduling" and "performance analysis" with 20% and 22% respectively. Our QFD template (fig. 4) can be used as a reconfigurability assessment tool for smart factory development, where theoreticians and practitioners can use the template to get scores based on their state of information systems and priorities.

By analyzing the findings, we conclude that MES has prospects in supporting high-level reconfigurability, especially when used as a digital twin. The majority of MES functionalities support low-level reconfigurability with their support for shop floor operations. But MES functionalities also have the potential to support the business operations in a manufacturing enterprise. Challenges will be in the high-level reconfigurability as manufacturers must understand where and how to apply MES. Due to improved real-time production data collection in IIoT, MES functionalities present opportunities for supply network reconfiguration. We conclude that MES in IIoT can allow manufacturers to quickly respond to market demands with changes in product composition, material flows, and replenishment modes, thus enabling manufacturing flexibility. Hence, digitalization and a subsequent smart factory with MES in IIoT can support reconfigurability in manufacturing for severe market disruptions. This can also include the disruptions caused due to the ongoing COVID-19 pandemic.

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