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FUNCTION ANALYSIS OF MANUFACTURING EXECUTION SYSTEMS (MES) IN CYBER PHYSICAL PRODUCTION SYSTEMS (CPPS)

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ABSTRACT: *Cyber Physical Systems (CPSs) play a crucial role in the Industry 4.0 paradigm. The application of CPSs in production environments gave rise to the term Cyber Physical Production Systems (CPPSs). The emergence of CPPSs transforms the automation pyramid into a decentralized structure. Manufacturing Execution Systems (MES) are being highly influenced by this transformation. Currently, there remains a dispute on the role of MES in CPPSs, specifically with respect to the functions they support in CPPSs. This paper aims to shed light on the role of MES in CPPSs by analyzing the functional models of the two. Firstly, functional models of CPPSs and MES are proposed in the form of IDEF0 diagrams. Then, data flows between the functional models of CPPSs and MES are described and the functions of the two are compared. We find that MES will continue to play a significant role in CPPSs, but it will take new forms. The next-generation of MES requires greater flexibility, dynamism and improved functionality.*

KEYWORDS: *Cyber physical systems; Cyber physical production systems; Manufacturing execution systems; Functional modelling (IDEF0); 5C architecture; ANSI/ISA-95*

1 INTRODUCTION

In the era of Industry 4.0, Cyber Physical Systems (CPSs) play an essential role because they make the fusion of the physical and the virtual worlds (Kagermann et al., 2013). The application of CPSs in production environments leads to the development of Cyber Physical Production Systems (CPPSs). The first detailed description of a CPPS was given by Monostori et al. (2016), which has been widely cited and broadly accepted in recent years. As a complement to Monostori's description, Cardin (2019) added several missing points, including knowledge management, decision making and adaptability, and adapted it as following (the complementary part of Cardin's description has been highlighted in bold): “*CPPSs are systems of systems of autonomous and cooperative elements connecting with each other in situation dependent ways, on and across all levels of production, from processes through machines up to production and logistics networks, **enhancing decision-making processes in real-time, response to unforeseen conditions and evolution along time***”.

Monostori et al. (2016) claimed that CPPSs partly break with the traditional automation pyramid. Traditionally, the Manufacturing Execution Systems (MES) was positioned as a middle layer to bridge the shop-floor with the Enterprise Resource Planning (ERP) system (left side of Figure 1). Today, the automation pyramid will be transformed into a more decentralized structure (right side of Figure 1). However, this transformation leads to vague

on the role of MES in CPPSs: Does this decentralized structure of CPPSs make MES superfluous? If not, what is the role of MES in CPPSs? And how does MES need to change to fulfill this role? Some scholars attempted to answer these questions. For example, Rossit et al., (2018) claimed that current MES, which take care of scheduling and dispatching work orders, will be absorbed by CPPSs. This minimizes response times, increase the flexibility of the entire system, which is useful for decision making. However, Arica & Powell, (2017) and Mantravadi & Møller, (2019) outlined that with data collection, analysis, and communication functions across the value chains, MES should play a central role in Industry 4.0 manufacturing systems. ZVEI, (2017) working group also indicated that the significance of MES in Industry 4.0 will increase and not decrease. But the focus will shift away from simple execution management towards comprehensive coverage of all Manufacturing Operation Management (MOM) activities and away from the control of production towards optimization including the incorporation of events. Almada-Lobo, (2016) pointed out that MES is required to change to cope with the challenges created by Industry 4.0, especially considering the following four aspects: decentralization, vertical integration, connectivity and cloud computing and advanced analysis. We find that, in current academic research, there still remains a dispute on the role of MES in CPPSs, ranging from “no role because the hierarchical structure will be dissolved” and “fewer and fewer role because MES functions will be cannibalized by enhanced CPPSs and ERP functions” right up to “central role because MES will be the decision-making

center of an organization and create the optimal value chain”. The existing studies are either based on literature reviews or empirical methods, but no one builds functional models to elaborate and compare the functions between CPPSs and MES. Therefore, this paper aims to shed light on the role of MES in CPPSs, by proposing functional models of CPPSs and MES in the form of IDEF0 diagrams and thus comparing their functions.

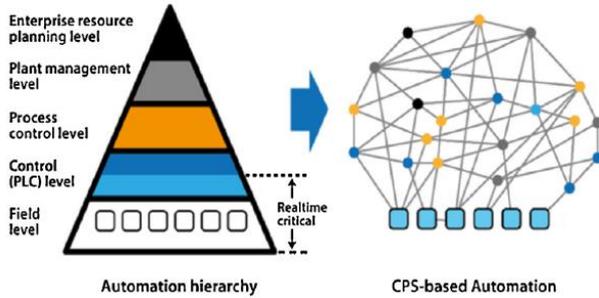


Figure 1: Decomposition of the automation hierarchy with distributed services (VDI/ VDE, 2013)

The rest of the paper is organized as follows. In Section 2, functional models of CPPSs and MES are proposed using IDEF0 diagrams. In Section 3, the data flows between the functional models of CPPSs and MES are described and then the functions of the two are compared. Section 4 concludes this paper and indicates future work.

2 FUNCTIONAL MODELS OF CPPS AND MES

IDEF0 (Integration DEFinition of function modelling) offers a functional modelling methodology for activity and information-flow analysis, focusing on the hierarchical decomposition of activities and the interaction flows between activities (IDEF0, 1993). In this section, using IDEF0 diagrams, the functional model of a CPPS based on the 5C architecture proposed in (Lee et al. 2015) and the functional model of an MES based on the ISA-95 standard (ISA-95 2005) are worked out.

2.1 Functional models of CPPSs

2.1.1 5C architecture

Lee et al. (2015) proposed a 5C architecture as a guideline for implementing CPSs. It defines the requirements and functions of what CPSs need to perform, through a sequential workflow manner. As shown in Figure 2, it consists of five levels: smart connection, data-to-information conversion, cyber, cognition and configuration levels. It can equally be extended to CPPSs. As the 5C architecture is a functional architecture, we propose to use it to build the functional model of a CPPS.

Level I (smart connection level) represents the physical space, where raw data are acquired from sensors and controllers and transferred to the network. At Level II (data-to-information level), raw data is processed to get meaningful data. Level III (Cyber level) is a central data

hub, where each CPPS can interact with other CPPS to enrich its own data. Level IV (cognition level) generates a thorough insight of the whole system, which supports expert users to make decisions. At Level V (configuration level), CPPSs can self-configure and self-adapt to return to normal behaviors. For each level, we can extract a major activity, which is “acquire raw data from the physical space”, “convert raw data to meaningful data”, “build the cyber space”, “make decisions”, and “self-configure and self-adapt”, respectively.

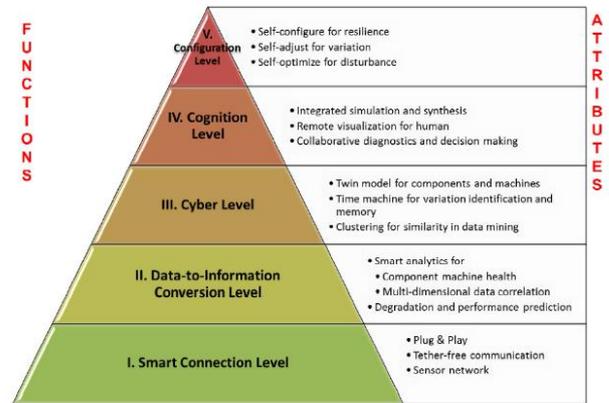


Figure 2: 5C architecture for the implementation of CPSs (Lee et al., 2015)

2.1.2 Functional model of CPPSs

According to the description of the 5C architecture, each level has a major activity. Therefore, the context diagram A0 “Implement a CPPS” can be decomposed into these five sub-activities, A1-A5, as shown in Figure 3, which shows the activities involved in the manufacturing process along with the information flows required to support these activities. A detailed description of the function modules and their relationship is given as follows.

A1—Acquire raw data from the physical space

This box describes the main activity in the Level I of the 5C architecture. The input is “operational commands”, which is transformed into “raw data”. The raw data refers to measurements data from plant instrumentation. The activity uses the mechanisms “data sources (such as sensors and controllers)”, “communication protocols (such as MTConnect)” and “data acquisition methods”, with the controls “production rules”, “production capability” and “production routing”.

A2—Convert raw data to meaningful data

This box describes the main activity in the Level II of the 5C architecture. The input that is linked to the prior output “raw data” of the activity A1 is transformed into “meaningful data”. The meaningful data refers to the data at a higher semantic level, such as movement events of resources and statuses data of resources. Data analysis technologies as the mechanism are needed for getting meaningful data. In addition to having the same controls as the activity A1, another control is the data format.

A3—Build the cyber space

This box describes the main activity in the Level III of the 5C architecture. It has one input which is linked to the prior output “meaningful data” of the activity A2, one output “simulation data on status and behaviors of CPPSs”, and the same controls as the activity A1. Simulation software and information systems are needed to support the activity and its function.

A4—Make decisions

This box describes the main activity in the Level IV of the 5C architecture. It has one input which is linked to the prior output “simulation data” of the activity A3, and

one output “corrective and preventive decisions”. Simulation software, information systems, proper presentation tools and expert users are needed to support the activity and this function. In addition to having the same controls as the activity A1, another control, the risk criterion, is needed to support the correct decisions to be taken.

A5—Self-configure and self-adapt

This box describes the main activity in the Level V of the 5C architecture. The input that is linked to the prior output “decisions” of the activity A5 is transformed into “adjusted production activities”. It has the same controls as the activity A1. Physical entities in shop floor are needed to support the activity and its function.

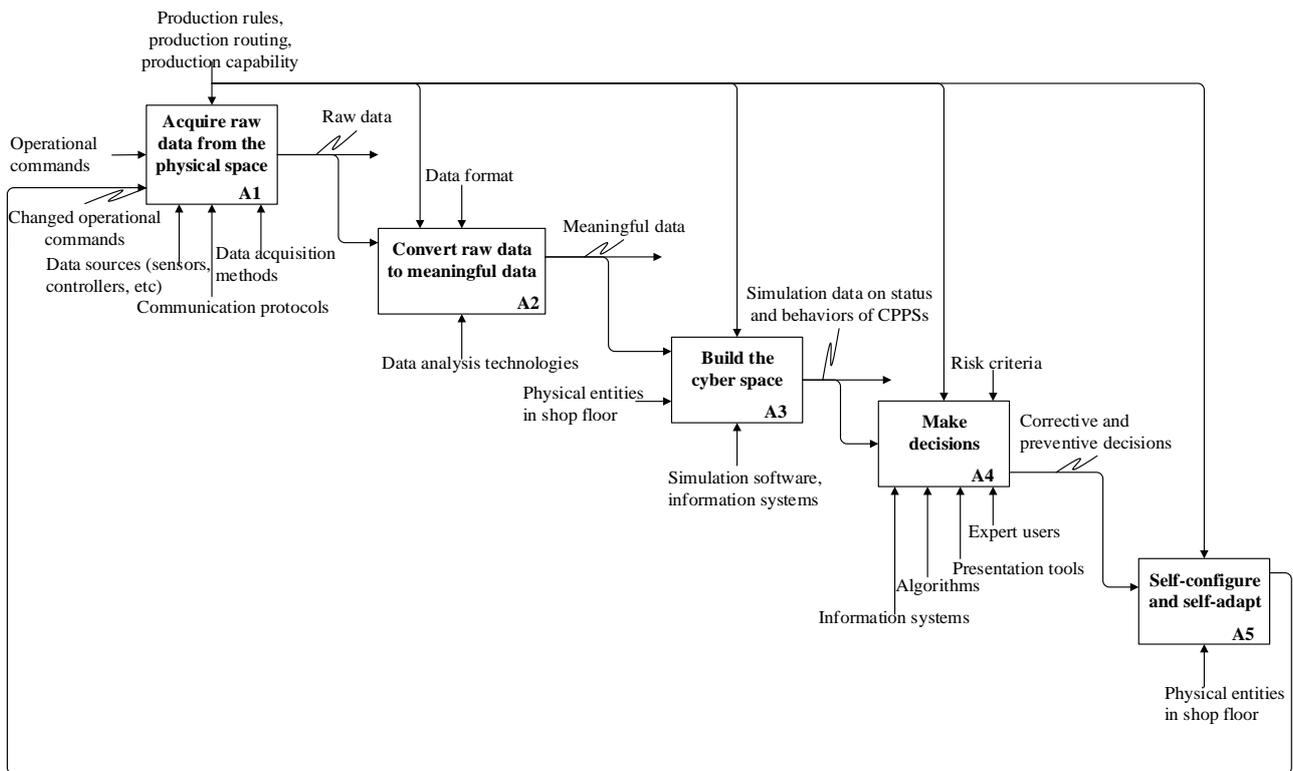


Figure 3: Activity A0 - Implement a CPPS.

2.2 Functional models of MES

2.2.1 ANSI/ISA-95 standard

The part 3 of the standard ISA-95 (2005) gives a detailed overview of all the activities and data flows of MOM in the area of production, inventory, maintenance and quality operational management. MOM could be regarded as the upper limited range of functions involved in MES applications. Generally speaking, the main focus of current MES applications is only on the production operations management. However, future MES functions will have to be developed towards MOM. Therefore, in this paper, MES refers to MOM, which covers all areas of operations management. One of the main advantages of ISA95 is the definition of the main functions and data

flows within MOM. Therefore, for this study, MES function's classification is based on the ISA-95.

2.2.2 Functional model of MES

The ISA-95 described the generic activities in MOM, as shown in Figure 4. Each of the four areas of operations management (production, inventory, maintenance and quality) is composed of these eight activities. According to this, the context diagram B0 “Implement an MES” was decomposed into eight sub-activities, B1-B8, as depicted in Figure 5.

Activity B1 (*Manage definitions of work*) manages the work information and develop work rules. Activity B2 (*Manage resource*) manages the information about the resources including machines, tools, labor, materials and

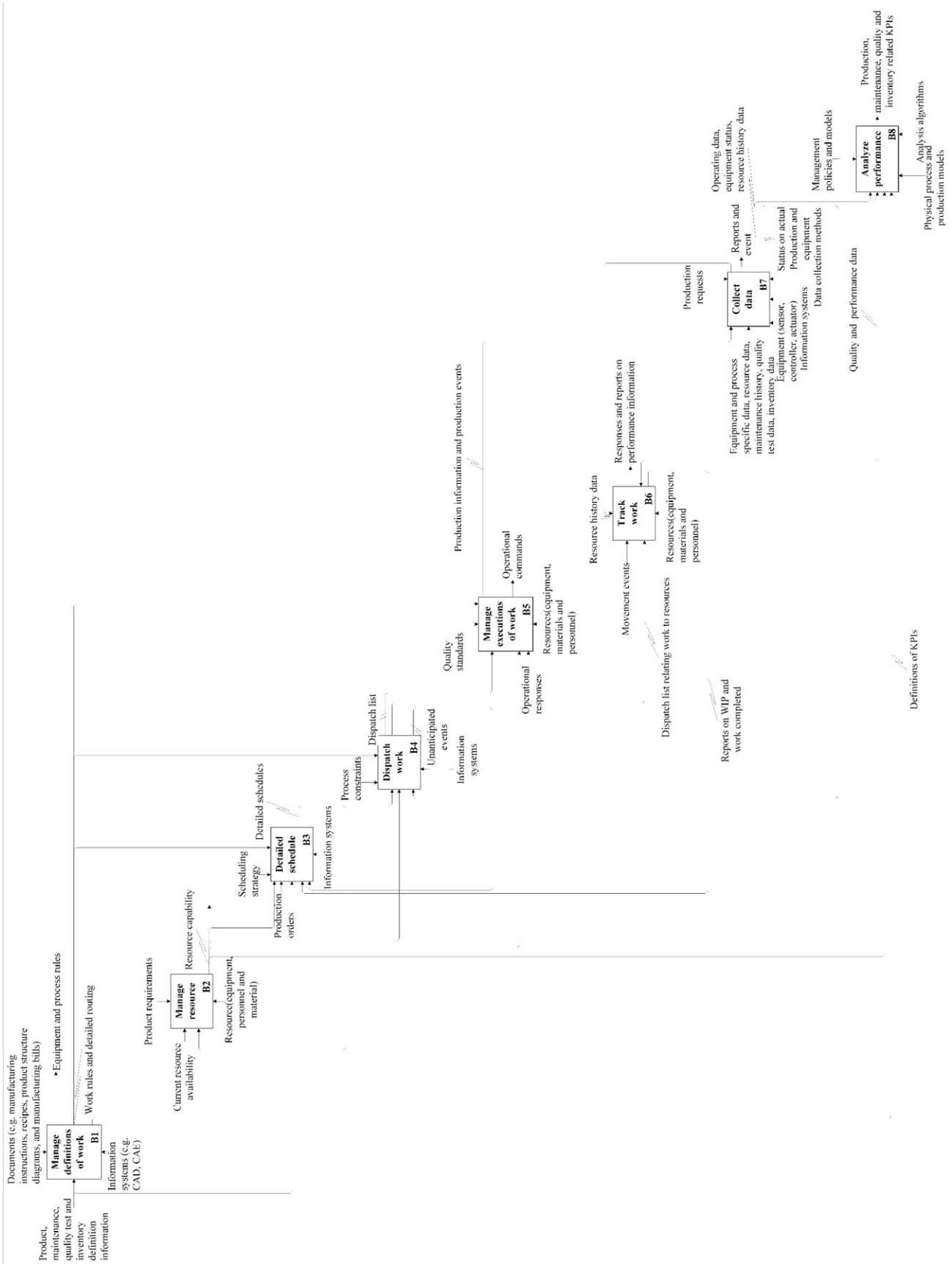


Figure 5: Activity B0 – Implement an MES

3 FUNCTION ANALYSIS OF MES IN CPPS

Based on the established functional model of CPPSs and MES, this section describes the data flows between CPPSs and MES, which represents the functional interfaces between them. Then based on the data flow, this section analyses which functions of MES are redundant in CPPSs and which functions are central.

There are two-way data flows in MES. On the one hand, MES deals with the top-down data flow: the requirements provided by the organizational level must be transformed into detailed operational commands to the production areas. On the other hand, it manages the bottom-up data flow. MES collects shop floor data, analyzes it, and extracts useful information to provide key performance indicators (KPIs) to the company for making commercial decisions and improving production performance. Therefore, the data flows between CPPSs and MES are described as follows.

- *Data flow 1: “equipment and process rules” from the output of the Activity B1 → mechanisms of the Activity A1 to A5.*

Equipment and process rules define the specific production/inventory/maintenance/quality test instructions that are executed in the shop floor based on the specific assigned tasks, such as programs for CNC machines.

- *Data flow 2: “operational commands” from the output of the Activity B5 → the input of the Activity A1.* Operational commands define the commands to start or complete elements of a work order in the shop floor, such as procedures for setting up machines or maintenance of machines.

- *Data flow 3: “operational responses” from the output of Activity A3 → the input of the Activity B5.* Operational responses define information received from the shop floor in response to commands, such as the completion or status of elements of work orders.

- *Data flow 4: “equipment and process specific data, resource data, maintenance history, quality test data, inventory data ” from the output of Activity A3 → the input of the Activity B7.*

Equipment and process specific data defines the data about the process being performed and the resources involved.

- *Data flow 5: “Production, maintenance, quality and inventory related KPIs” from the output of Activity B8 → the input of Activity A4*

The manufacturing operations management areas have different sets of performance indicators, which are used together to make decisions and to monitor the realization of enterprise business objectives.

- *Data flow 6: “current resource availability” from the output of Activity A3 → the input of Activity B2.*

Resources include machines, tools, labor (with specific skill sets), materials, and energy.

- *Data flow 7: “resource capability” from the output of Activity B2 → the input of A3*

Resource capability defines the committed available, or unattainable of resources. The information is based on the current statuses and future needs (as identified in Activity B3).

- *Data flow 8: “production and movement events” from the output of Activity A3 → the input of the Activity B6.*

Production and movement events include the movements of the path of materials and updates to lot locations.

For the data flow 1, 3, 4, 6, 7 and 8, MES mainly serves as an information platform that contains all information in the production, inventory, maintenance and quality test operations management and we find that the functions of MES are very similar to those of digital twin in terms of work definitions management, resource management, work track and data collection. For example, in terms of the MES’s function “data collection”, digital twins store all data from the field and other information systems in real-time, as in the MES. Digital twin refers to the virtualization of the physical resources in the cyber world and its main purpose is to facilitate the decision-making process through real-time simulation (Tao et al., 2018). Therefore, future MES can be used as a digital twin due to its ability to provide digital images and monitor manufacturing processes in real-time.

For the data flow 5, MES analyzes and reports performance information to expert users for decision-making. In the Industry 4.0 context, the function of performance analysis in MES becomes more complex and important. With the development of information and communication technology (ICT), the amount of data collected from the shop floor increases tremendously. MES should always be required to present the most relevant data to the humans for decision making.

For the data flow 2, MES sends the operational commands to the physical space of CPPSs. The function of executions management is equally important because it is not only necessary to have data coming from the shop floor to MES, but also to be able to act from the MES to the shop floor, by offering operational commands on the production control system. In the CPPSs context, it should be possible in the future to decentralize operational decisions and delegate a part of decisions made previously in MES to lower levels of production systems, such as smart machines and smart products. This reduces the number of tasks of this function in terms of the operational level decisions. Since MES covers all the areas of MOM, it can collect all data related to production, quality, inventory and maintenance. This endows MES with the holistic insights for the manufacturing processes and, which can make commands before any disruptions.

4 CONCLUSION AND FUTURE WORK

The paper studies the role of MES in CPPSs by analyzing the functional models of CPPSs and MES. MES’s functions are still required for CPPSs, but they need to

be presented in new and different forms, with some being incorporated into the CPPSs' functions, some expanding their horizons and some decentralizing to the local intelligent entities. For example, the MES's function "detailed schedule" will only have high level tasks, making rough planning of manufacturing orders, while flexible planning of partial orders will be made by local entities of CPPSs through taking into account local resource availabilities in real-time. Correspondingly, MES software will move from monolithic software systems towards functional modules that will be implemented in a highly distributed way. Therefore, the next-generation MES requires greater flexibility, dynamism and improved functionality than today's MES.

In the future work, validation in a real platform will be worked out to evaluate the quality of the proposed model. Besides, we will implement a "dynamic link" between CPPSs and MES from a functional perspective. In our view, the functional level is the best suited for this implementation as it enables to free of the underlying technical solutions. Indeed, the MES and CPPS interrelated functions cannot be engineered independently and then simply combined together. The idea is rather to coordinate the design of both systems to explore hidden functions and ensure that their interactions are mutually supportive. This "dynamic link" is twofold: one the one hand, if the configuration of CPPSs (e.g. the layout of CPPSs) changes, the organization and business processes will be changed automatically. One the other hand, if new functionalities of EISs are needed, CPPSs can configure themselves automatically to meet these new requirements. The digital twin could be a solution to implement such dynamic link as the change of state of the physical object will have impacts on the state of the cyber object automatically and vice versa in digital twins. Cimino et al., (2019) pointed out the future possibility of integrating the digital twin of the field devices with the MES in order that decision making could be made in a fully reactive way through the digital twin to the MES.

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