Status and Future of Manufacturing Execution Systems

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Abstract - **This paper proposes a taxonomy for characterizing manufacturing execution systems and discusses how they can benefit from the recent developments of Industry 4.0. The study is based on a literature review. The taxonomy contributes to theory and practice by providing a framework for benchmarking of manufacturing execution systems. The taxonomy can be utilized in the selection or design process of the manufacturing execution systems. Outlining the further opportunities provided by Industry 4.0 technologies, the paper also provides directions for future improvements of manufacturing execution systems.**

Keywords – **industry 4.0, manufacturing execution system, taxonomy**

I. INTRODUCTION

Manufacturing Execution Systems (MES) are primarily perceived to aid production monitoring, and control operations on the shop floor [1]. Conceptual standards such as developed by Manufacturing Execution System Association (MESA) expands this perception by the following main functionalities [1]: Resource allocation and status, Operations/ Detail scheduling, Dispatching Production Units, Document Control, Data Collection/Acquisition, Labor Management, Quality Management, Process Management, Maintenance Management, Product Tracking and Genealogy, Performance Analysis. The functionalities of MES cover the manufacturing monitoring and control tasks in an enterprise, making the shop floor data available and measuring the real time performance indicators such as equipment utilization, inventory availability, and quality status. Having emerged from the process industry [2], the application of MES has today become a very popular approach to the integration of manufacturing planning and control tasks, and has been applied in various types of industry. Recent vendor surveys show the significant increase in number of vendors and variety of industrial applications [3].

The manufacturing planning and control literature contain many studies on the implementation challenges of the manufacturing IT systems. Among others, Enterprise Resource Planning (ERP) systems gained the biggest interest in both academia and practice over the past decades; however still have many implementation challenges and high implementation failure rates [4]. As being the case with many other manufacturing IT systems, the practical implementation of MES is also not as straightforward and rewarding as it is theoretically claimed. Especially with the significant differences between shop floors, there is a need for a careful and comprehensive analysis of contextual and technological requirements for successful implementation of the MES systems.

This paper primarily aims to develop a taxonomy for initial benchmarking and selection of MES systems, describing the important factors of MES systems through a literature review. MES is a large system addressing many different processes on a company-specific shop floor. Therefore it is bound to have modification and specifications in the implementation process. Nevertheless, it is important to achieve a successful selection process to reduce the adjustment efforts (e.g. specification, further coding, etc.).

Furthermore, manufacturing industries stand in front of a new era, by what many refer to as the fourth industrial revolution or Industry 4.0. Characteristics of Industry 4.0 are high levels of automation, intelligent products and resources equipped with sensors and internet technologies, real time data exchange, and abilities to create new values and businesses from digitalization. Adaption to Industry 4.0 is crucial for manufacturing companies to sustain and improve their competitiveness. MES systems are also being highly influenced from this revolution. Characterizing the MES systems, this paper also outlines the opportunities of Industry 4.0 concepts for further developments of MES systems.

II. METHODOLOGY

This conceptual paper is based on a literature study. The primary source of literature is the academic studies conducted on MES. The academic literature on MES is however rather scarce with a single literature review which dates back to 2009 by de Ugarte, et al. [1]. This review study gives a great overview of the technological developments and shortcomings of MES. However, it has mainly focused on architectural and technological elements of MES. The study is very much technology oriented and gives a limited opportunity to characterize MES in terms of the business and manufacturing contexts. In addition to the MES literature, studies on Industry 4.0 technologies and manufacturing IT systems were included. Especially the learning and experiences from long studied and implemented ERP systems provide valuable insights for future MES studies. This is because ERP systems and MES complement each other and work together to support the manufacturing planning and control tasks. In fact, recent ERP systems also incorporate shop floor control functions.

III. RESULTS

A. A Taxonomy for MES

Based on the literature study, a taxonomy for characterizing MES was developed. The taxonomy is summarized in Table I and consists of two main categories of factors: i) business and manufacturing related factors and ii) technological factors. The technological factors should support the manufacturing and business factors. The vendor characteristics (e.g. size, market share), the environmental characteristics of the manufacturer (e.g. existing IT systems), and implementation factors (e.g. ease of implementation) may also influence the selection of the MES, as seen in the ERP literature [4]. However, these issues can be subjective being dependent on factors such as the interest of the company, urgency of the implementation project, financial strength, etc. The proposed model mainly focuses on the characterization and profiling of the systems themselves, to provide a preliminary idea for comparison of the existing systems. Further, the study does not primarily concern with providing a complete overview of hardware and software components and developments of MES such as databases, platforms, and networking technologies. de Ugarte, et al. [1] have largely elaborated on these issues. This paper rather focuses on overall characterization of MES.

Business and manufacturing related factors

These factors classify the MES systems in accordance with their *focus, scope,* and *functionality*.

Focus: Addressing the manufacturing monitoring and control tasks, MES show significant differences depending on the industry and production typologies. Manufacturing of products consists of unique processes, equipment, and data, which differentiates the requirements from MES systems. Such industry-specific differentiation of MES systems can be seen from recent MES surveys [3, 5]. The industrial fit is a critical factor for successful implementation of the MES system. Academic literature takes the issue of focus into account by varying business and manufacturing related factors. Wang, et al. [6] designed an MES system for pharmaceutical industry considering the special regulatory and governmental requirements of pharmaceutical manufacturing. Schmidt, et al. [7] suggests a functional reference model for MES in automotive industry. Naedele, et al. [8] proposes implementing the MES functionalities to software development projects. Besides the industry specific focus, production and logistics typology may distinguish the MES systems.

TABLE I
TAXONOMY FOR MES

Category	Factors	Main references
Business and manufacturing related factors		
Focus	Industry/ sector/ market/ product typology	[9], [6], [8], [5], [7]
	Production and logistics typology	[10], [11]
Scope	Enterprise level	[1], [6], [12], [13]
	Operational support	[1], [14], [6], [15]
Functionality	Functional configuration	[7], [12], [6]
	Functional role and integration	[7], [16], [14], [17], [18], [11]
	Functional structure	[1], [12], [19], [20], [21], [11]
Technological factors		
Data and communication management	Manufacturing data acquisition	[10], [9], [22], [6], [23]
	Data exchange between MES and other systems	[6], [12], [21], [18], [24], [25]
Decision support logic	Decision support type	[9], [20], [18], [11], [26]
	Decision support technique	[9], [14], [20], [18], [11]
User interface	Visualization	[12], [27]
	Mobile device interfaces	[2], [3]

Examples are MES for Make-to-Order and Engineer-to-Order production [10] and for short series production [11].

Scope: MES has two scope related factors; i) enterprise level and ii) operational support. Enterprise level refers to the coverage of MES system in the value chain. Most MES systems have focused on single plants [1]. However, recent literature contains MES systems with a wider focus on the value chain, such as MES designed by Helo, et al. [12] for collaborative manufacturing in a multi-company supply chain. Regarding the operational support factor, recent technical standards such as ISA95 suggests that MES should support the production, maintenance, quality, and inventory operations [14]. However, most MES systems are designed in accordance with the contextual requirements and partly cover these areas, see for example [6, 14, 15].

Functionality: Three factors can characterize the functionality of MES: i) functional configuration, ii) functional role and integration, and iii) structural design. Several standards have been developed for the functional configuration of MES such as ISA95, MESA, VDI, NAMUR, and NIST, see Schmidt, et al. [7] for detailed analysis of these standards. However most shop floors have favored custom-made or configured systems both before and after the introduction of the standardized MES concept. Analyzing the existing MES standards and characteristics of four automobile manufacturers, Schmidt, et al. [7]

configured a functional reference model for automotive industry. Helo, et al. [12] proposed an internet based MES concept with a configurable business logic, prioritizing the multi-site order flow functionality. Once the required functions are identified, there is need for choosing the right systems for functional roles and integration [17]. This is due to the functional overlaps and interfaces between MES and other information systems such as Enterprise Resource Planning (ERP), quality systems, and maintenance systems. ISA95 standard provides a remedy for this purpose by defining functional data flows and activity models between enterprise levels [14, 16], which makes ISA95 compliance a factor in selection or design of MES. For example, Cottyn, et al. [14] and Unver [16] utilized ISA95 to develop MES aligned with lean objectives. The last factor related to functionality is the functional structure that refers to the design and organization of the information flow and decision-making functions. Functional structure can be categorized into centralized/ hierarchical and decentralized /heterarchical structures [19]. Centralized/hierarchical systems are predominantly used due to the practicality and applicability concerns such as the existence of hierarchical legacy systems (e.g. ERP) in companies. However, recent academic studies on decentralized systems are increasing due to the drawbacks of centralized systems, such as the time and effort spent to react to dynamic changes [19]. Holonic and multi-agent MES systems such as proposed by [11, 20, 21] aim to close these gaps by distributing the decisional authorities.

Technological factors

MES is a decision support system (DSS) within the manufacturing planning and control domain. Hence, typical components of the decision support systems can be used as a framework for characterizing the technological aspects of the MES systems. A typical DSS consists of data and communication management components, model management component, and user interface components [28].

Data and communication management: Primary functionality of the MES is data collection and communication, both real time and aggregated forms. Regardless of the industry type, companies primarily employ MES for data collections. A primary factor for efficient data collection is to acquire the desired data about the tracked entities in manufacturing or supply chain and transmit the data efficiently and accurately into the MES system. For that purpose, Radio Frequency Identification Device (RFID) based MES systems are becoming more and more popular (see for example [6, 9, 22] due to RFID's significant advantages in tracking items of interest and obtaining necessary information such as identity, location, movement and states of them. To improve the accuracy of the information (e.g. localization) transferred into MES, Yang, et al. [23] proposes advanced localization algorithms. Nevertheless, communication and integration of MES with other systems is also an important factor, due to the functional overlaps, information exchange requirements, and interfaces. In this respect, technological improvements are aiming for better data storage, specification, and conceptualization to integrate and make shared sense of collected data from different systems. Cloud-based and web-based MES systems such as proposed by [6, 12, 21, 24] enable on-demand configuration of distributed applications and integration of distributed systems, with the help of Service-oriented Architecture (SOA) and Web-Service technologies for data integration among heterogeneous systems. Besides these technologies, other communication approaches also exist in literature, such as agent-based communication protocol between MES and a material flow simulation system, proposed by [25].

Decision support logic: As with other DSSs, MES contains decision support logic with varying types and techniques. The MES proposed by [9] employed an optimization-driven decision support type with rule-based techniques for real time scheduling. Cupek, et al. [11] proposed a simulation-driven scheduling in their multi-agent MES. Cottyn, et al. [14] designed lean-driven MES embedded with the CONWIP technique. Grauer, et al. [18] proposed a data-driven rule-based MES, employing data mining algorithm. The holonic MES of Rolón and Martínez [20] employed knowledge-driven decision support approach with learning agents that can predict future disruptions and react automatically.

User interface: A critical component of MES is the user interface for successful implementation and use of the system. Earlier studies on ERP systems suggests that one of the most important key factor for successful implementation of the ERP systems is ease of use [4]. MES is expected to be more vulnerable to this factor due to the target users (i.e. shop floor personnel with practical mind-set) and usage frequency (i.e. supporting real time operations). Visualization should therefore aim for keeping the operator's cognitive loads as low as possible. Most MES systems discussed in the above sections apply a mixture of textual and graphical user interfaces. Recently, few studies are also focusing on MES with 3D graphical interface [27]. Further, today's operators take the responsibility of several machines on the shop floor with increasing level of automation and reducing labor requirements. This fact necessitates having the MES functions on mobile devices (e.g. smartphones, tablet PC, PDA), enabling the operator with mobile data acquisition and access [2]. Mobile solutions and device interfaces has become an important factor over the last years to evaluate the MES vendors (see the recent survey of [3].

B. Industry 4.0 and Opportunities for MES

Industry 4.0 aims to leverage advanced technologies to allow a greater level of integration of interconnected “things” on the shop floor, leading to the establishment of smart, adaptive and resource efficient factories, which can further integrate the business processes across entire supply chains [29]. Driven by the diffusion of Information and Communication Technology (ICT), Industry 4.0 has been defined in terms of the following key technologies [30].

Internet of Things (IoT) is broadly used to refer to (i) the resulting global network interconnecting smart objects by means of extended internet technologies, (ii) the set of supporting technologies necessary to realize such a vision (including, e.g., RFIDs, sensor/actuators, machine-to-machine communication devices, etc.), and (iii) the ensemble of applications and services leveraging such technologies to open new business and market opportunities [31].

Visual Computing can be defined as the entire field of acquiring, analyzing, and synthesizing visual data by means of computers that provide relevant-to-the-field tools [30], e.g. Augmented Reality (AR).

Industrial Automation is the use of control systems, such as computers or robots, and information technologies for handling different processes and machineries in an industry to replace a human being. It is the second step beyond mechanization in the scope of industrialization.

Intelligent Robotics is a part of the growingly important Artificial Intelligence (AI) and Robotics field. Precisely, AI will assist in the creation of complex "smart" networks, capability to learn, reason and act based on the information gathered during the industrial process [32].

Cybersecurity can be described in terms of the requirement of Industry 4.0 technologies to prevent unauthorized access to production systems to prevent environmental or economic damage and harm to humans [33].

Industrial Big Data refers to data sets whose size is beyond the ability of typical database software tools to capture, store, manage, and analyze [34].

Semantic Technologies include tools for auto recognition of topics and concepts, information and meaning extraction, and categorization. Semantic technologies provide an abstraction layer above existing IT technologies that enables bridging and interconnection of data, content, and processes.

Given the definitions of the Industry 4.0 technologies, following Table II summarizes the opportunities of Industry 4.0 for MES.

TABLE II
OPPORTUNITIES OF INDUSTRY 4.0 FOR MES

Internet-of-Things	Offers the potential to develop MES solutions for entire supply chains and demand-driven value networks rather than simply providing functionality for inter-firm planning and control. Also allows for the creation of digital twins that can be used for simulations and "what-if?" analyses.
Visual Computing	Promises to allow for effective real-time decision making by interactive AR based user interfaces, both remotely and at point-of-use.
Industrial Automation	A greater level of industrial automation promises to allow for a greater level of the industrial process to be brought "online" in the MES of the future.
Intelligent Robotics	Intelligent Robotics will function as a support mechanism where machines can begin to use real time data from MES to reconfigure the production system and the external supply chain.
Cyber Security	Provides capabilities to ensure secure inter- and intra-firm connectivity, for example to allow a greater level of vertical integration and information sharing in IPR-sensitive supply chains.
Industrial Big Data	Industrial Big Data provides the foundation for advanced analytics allowing proactive decision support functionality in MES.
Semantic Technologies	Together with Intelligent Robotics, Semantics provides the possibility to provide a fault detection and early warning system within the MES such that unplanned events can be foreseen.

V. CONCLUSION

This paper proposed a taxonomy for characterizing the MES, based on a literature study. Integrating the business and manufacturing functions, MES will play a vital role in the transition of manufacturing companies and utilizing the promises of Industry 4.0. The fundamental opportunity of Industry 4.0 is creating new values from data in terms of both offering new services to the customers and increasing efficiency of internal operations. With data collection, analysis, and communication functions across the value chains, MES will serve as a platform for implementing the Industry 4.0 technologies and realizing this opportunity.

In this respect, the paper contributed to theory and practice by providing a taxonomy for helping with the MES selection/design decisions as well as outlining the potential future improvements of MES in the light of Industry 4.0.

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