Chapter 11
Manufacturing Execution System State-Of-The-Art: Its Evolution and Dynamism Focused on Industry 4.0

Saúl Manuel Favela-Camacho, Javier Molina-Salazar, and Lázaro Rico-Pérez

Abstract The utilization of applied knowledge, specifically related with information and communication technologies (ICT) for supporting production processes, from top management to operational levels, is a trend that has been increased throughout the time. Its use seeks support in functions like organization planning, management and controlling devices related with manufacturing processes. Likewise, the manufacturing execution system (MES) has become the bridge that connects enterprise resource planning systems with operations within organizations, becoming a *Digital Twin*, helping to know virtually what is happening on productive processes in real time. Like any practical concept, an updated state-of-the-art is needed to understand its evolution, functions, importance level, and dynamism, particularly nowadays when we are immersed in Industry 4.0 paradigm. This chapter will expose an outline of the state-of-the-art about MES, its implications in the manufacturing processes, and its transformation as a dynamic productive system, because sometimes it is used as a tool for quality management. Based on the global trends, standards, and industrial behavior, we can have a baseline for the design of new and related technologies that will support the core processes within businesses.

Keywords Manufacturing execution systems · State-of-the-art · Industry 4.0 · Quality management system

11.1 Introduction

It is well known that manufacturing industry currently is going through significant changes related to its adaptation to Industry 4 (Schwab 2016). This new industrial revolution not only poses a change in the way production processes are defined, but also influences the way we live, work, and interact. For example, people are continuously connected due to the technology of mobile devices such as cell phones; robots can perform surgical interventions using artificial intelligence (Strickland

S. M. Favela-Camacho (✉) · J. Molina-Salazar · L. Rico-Pérez
Department of Industrial Engineering and Manufacturing, Universidad Autónoma de Ciudad Juárez. Av. Del Charro 450 Norte. Col. Partido Romero. Juárez, Chihuahua, México
e-mail: saul.favela@uacj.mx

J. L. Garcia Alcaraz et al. (eds.), *Trends in Industrial Engineering Applications to Manufacturing Process*, https://doi.org/10.1007/978-3-030-71579-3_11

2016); autonomous vehicles are increasingly used (Anderson et al. 2016); energy storage technologies have had great advances (Oberhofer and Meisen 2012); and there are solutions for the factories of the future (Rodriguez et al. 2019; Witzel et al. 2019).

The above are based on new concepts, such as *Internet of Things* (IOT), which refers to the connectivity of everyday devices with the Internet for decision making (Velez-Martinez 2017); *Cyber-physical* systems, where computer systems are used in networks to monitor and control physical processes (Mabkhot et al. 2018); or the so-called *Smart Factory,* where flexible cyber and physical systems solve problems in productive environments and optimize processes (Radziwon et al. 2014).

Despite the evolution of these technologies, some of these are in developing stages. However, they are expected to be implemented in everyday life, searching the integration and emergence of new technologies in both cyber and physical world.

The integration of these technologies changes the dynamics of companies and industries, since they stimulate the emergence of new business models, redefining the production, consumption, transport, and delivery systems, at the same time offering the potential for the support of product manufacturing systems.

Industry 4.0 has led companies to assimilate new and advanced technologies to turn them into competitive companies, where automation, interconnectivity and access to information are integrated into their production processes, thus turning them into smart factories, a fundamental concept for Industry 4.0 (Mantravadi and Møller 2019).

Although there have already been some information and interconnectivity systems that have been applied to production systems (such as in the case of *Enterprise Information Systems*) for almost 50 years with the emergence of the computer, many of them have been transformed as there are new advances in science, research, and technology. One of the systems that are important because it connects the planning systems to the resources available for operations is the *Manufacturing Execution System* or *MES* (McClellan 1997).

11.2 Methodology

This conceptual review is based on an exploration of the literature. The primary source of information was scientific articles, indexed journals, books, and academic texts whose theme included aspects about the history, evolution, regulations, classification, and trends of Industry 4.0 and MES. Various databases were used, including *Google Scholar*, *Scopus,* and *Elsevier*; the existence of texts in the library of the Institute of Engineering and Technology of the Ciudad Juarez Autonomous University was also reviewed. Most of the texts were written in English, but texts in Spanish and German were also found. Information published from 1997 to 2019 was considered in order to understand the evolution of the concept. The literature review conducted in this exploration was descriptive, where the reader is provided with an update on the useful concepts in constantly evolving areas, which is useful for teaching and for the interest of the parties involved (Guirao Goris 2015). The literature review is divided into the background of manufacturing execution systems, temporal evolution, regulatory standards and guidelines, taxonomy, its use in quality operations, and their dynamics in the context of Industry 4.0.

11.3 Literature Review

11.3.1 Background of Manufacturing Execution Systems

The beginnings of the manufacturing execution system concept can be traced from the starting of the use of computers in organizations and with the emergence of *Enterprise Information Systems* (EIS), which are information systems to support functional activities of the company, such as planning, manufacturing, sales, finance, human resources, project management, and others (Rashid et al. 2002). Its widespread use was caused by the integration and extension of business processes between the own organizational functions and those of other companies, including the dynamics of the globalized economy (Xu 2011).

As the technology evolved in terms of sophistication, the EIS were actively used in the key processes of the organizations, including in the processes related to material planning, inventory systems and forecasts. In the seventies of the last century, the first *Information Management System* (IMS) appeared, while more EIS were developed related to *Material Requirements Planning* (MRP) and *Manufacturing Resource Planning* (MRPII) in the following years. In contrast, the first commercial software packages for *Enterprise Resource Planning* (ERP) emerged in the 1990s, evolving at the beginning of the new century into advanced systems where there was a collaboration between all the functions of the organization (Møller 2004).

Meanwhile, ERP systems have included various integrated modules for the functions of logistics, purchasing, sales, marketing, human resources, and finance, where their use has been extended at the online level, where the application of entities such as the Internet, social networks, and Big Data, in order to have a broader picture of corporate performance (Romero and Vernadat 2016). However, ERP systems such as MRP and MRPII were focused on the planning and control of materials and production and were not able to have a real-time management of what happened in the manufacturing processes and production stations. That is where a new EIS entity emerged: the manufacturing execution system or MES (Kletti 2007).

11.3.2 Manufacturing Execution Systems Evolution

To assist in the execution of production, the MES connects the planning systems with the control systems and uses the information generated in the manufacturing processes to support the same processes. Like any information system, the MES has evolved over time by integrating several extensions to carry out various manufacturing activities using the advances in computer technology (Mcclellan 2001).

The MES conceptually emerged in 1992 in Boston by AMR Research Inc. as the level of execution of manufacturing activities that connects business functions and direct process control systems, providing visibility and functional control (Salazar 2009).

For example, previously some companies adapted information systems tailored to the production areas, so that they could compile information in databases, which made consolidation and maintenance difficult. As it was implemented as a dynamic system, the MES was developed with the purpose of integrating multiple points of the system and companies that developed software were able to gather production execution functions in the form of an MES software (Saenz de Ugarte et al. 2009).

However, manufacturing systems, with the aim of constantly being in continuous development, have implemented automated tools and systems that work in real time to avoid the expense and use of material resources. As progress is made over time and with technologies, extensive use of smart or intelligent factories is expected, where wireless technology and mobile information and communication technologies are the key to the future industry. Also, intelligent factories will rely on information and communication systems that allow them to have a real-time management of productive systems, where the MES would have a great role in that scheme (Sauer 2014).

Romero and Vernadat (2016) have classified the MES also based on this temporal evolution. The first generation MES (MES/I) was developed to support data collection, centralization and processing to offer support in planning, programming, traceability, quality assurance, and generation of reports in manufacturing processes by providing visualization in real time for management and operators. The second generation MES (MES/II) became a dynamic system of integral information control to control the execution of manufacturing operations using real-time data to control operations from when orders are generated until delivery of the product. The third generation MES (MES/III) is currently inserted in the context of Industry 4.0 and in the paradigms of mass customization, where its functionality is directly related in detailed manufacturing processes to have a flexible capacity, turning them in smart production systems, so that there is an integration between data and applications along with materials, tools, and machines.

11.3.3 Manufacturing Execution Systems in the Normative Setting

To contextualize the concept of what the manufacturing execution system is from a normative and standardized perspective, several models are taken into consideration. First, the vision proposed by the International Automation Society (ISA), which as an international organization, oversees establishing the guidelines and standards for the instrumentation of industrial processes. The model is exposed in two of its standards: ISA-S88 and ISA-S95.

ISA-S88. The first regulation, which was also included as a national standard in the USA at the American National Standards Institute (ANSI), defines models for batch control in industrial processes, where process relationships are specified. The core of everything is to identify what is called a "recipe" of the mode of operation, which allows the division between the structure of the plant and the processes involved. A batch creates a defined quantity of a product, which is composed of one or more components and is manufactured in one or more devices in a defined order. The production instructions are indicated in that "recipe," which contains the set of operations, which are also made up of a set of functions or phases. Each phase has its own parameters depending on the requirement in each function. The recipe management is related with production planning and scheduling and production information management, which depend from the output and input of the process management systems, where MES is one of them. Some of the functions under process management control are how control recipes must be generated, how batches must be initiated and supervised, what unit activities require coordination, and which logs and reports must be generated. All the systems included in the model proposed by ISA-S88 are related with control activities. The proposed model shows the main relationships achieved via information flow between systems. Figure 11.1 depicts the control activity model relationship of recipe management in the ISA-S88 regulation (ISA 2006; Meyer et al. 2009).

ISA-S95. In contrast, the ISA-S95 standard specifies both the terminology and the models that are used to integrate the ERP systems at the business level with the automated systems at the production level. In this regulation, there is a model of levels, which are counted from zero to four, where at the highest level (4), the systems responsible for operations and tasks related to the administration of raw materials, components, are defined. Other things that can be managed are energy resources, production plans, supply management, and optimization. Some commercial ERP systems are used in this level (SAP®, Microsoft Dynamics®, Odoo®, Oracle ERP®, Baan®, JDEdwards®, GPAO®, APS®, GPI®, etc.). On the next level (3), there are the manufacturing management systems, which are responsible for evaluating the relevant data generated in the production, inventory, personnel, raw material, replacement of parts, and energy processes. The same regulation includes functions or activities of managing information about the schedules, use, capability, definition, history, and status of the previous processes. Manufacturing execution systems are included here. In the last levels (2, 1, 0) the monitoring, supervision systems (such

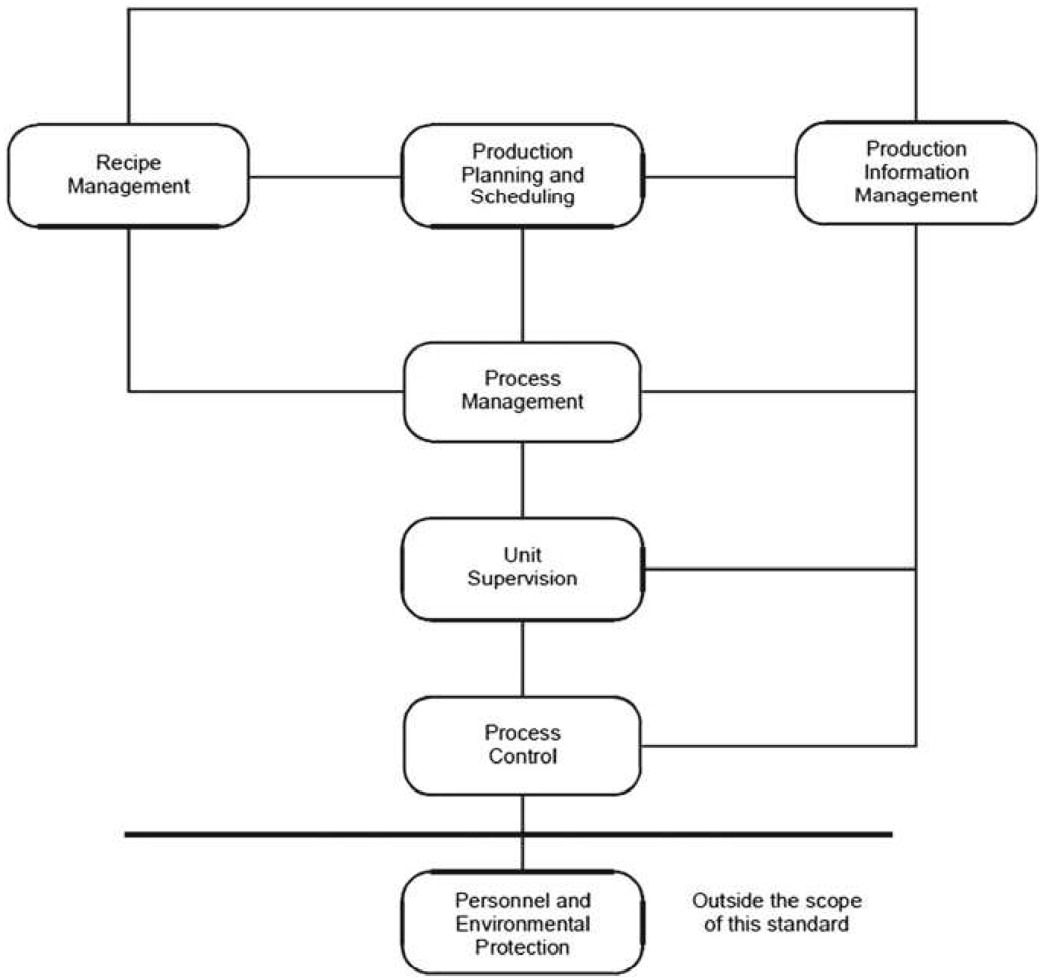

Fig. 11.1 Control recipe model based on the ISA-S88 (ISA 2006)

as process data historians, HMI/SCADA, OPC servers, relational databases such as Oracle, SQL Server, and others), control of the process, sensors, process manipulation, and current production processes are included (ISA 2005). Figure 11.2 depicts the levels of the systems according with ISA-S95.

Manufacturing operations management in level 3 is subdivided into four categories: production operations management, maintenance operations management, quality operations management, and inventory operations management. The ISA-S95 shows a manufacturing operations management model and relationships between their categories that are depicted in Fig. 11.3.

MESA. On the other hand, the guidelines proposed by the *Manufacturing Enterprise Solutions Association* (MESA) are considered to define all the operations that are included in the whole manufacturing processes that MES can manage: genealogy and traceability of the product, status and allocation of resources, performance analysis, process management, data acquisition and collection, quality management, labor management, shipments of production units, logistics, and controls (MESA 2019). The same association defines the MES as "a dynamic information system

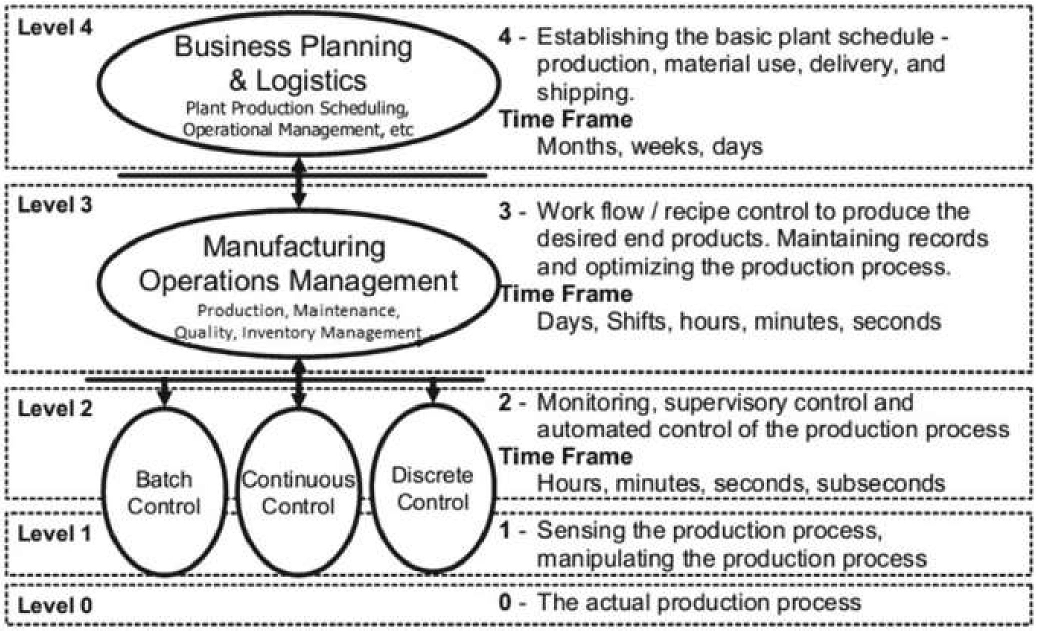

Fig. 11.2 Multi-level functional hierarchy of activities based on the ISA-S95 (ISA 2005)

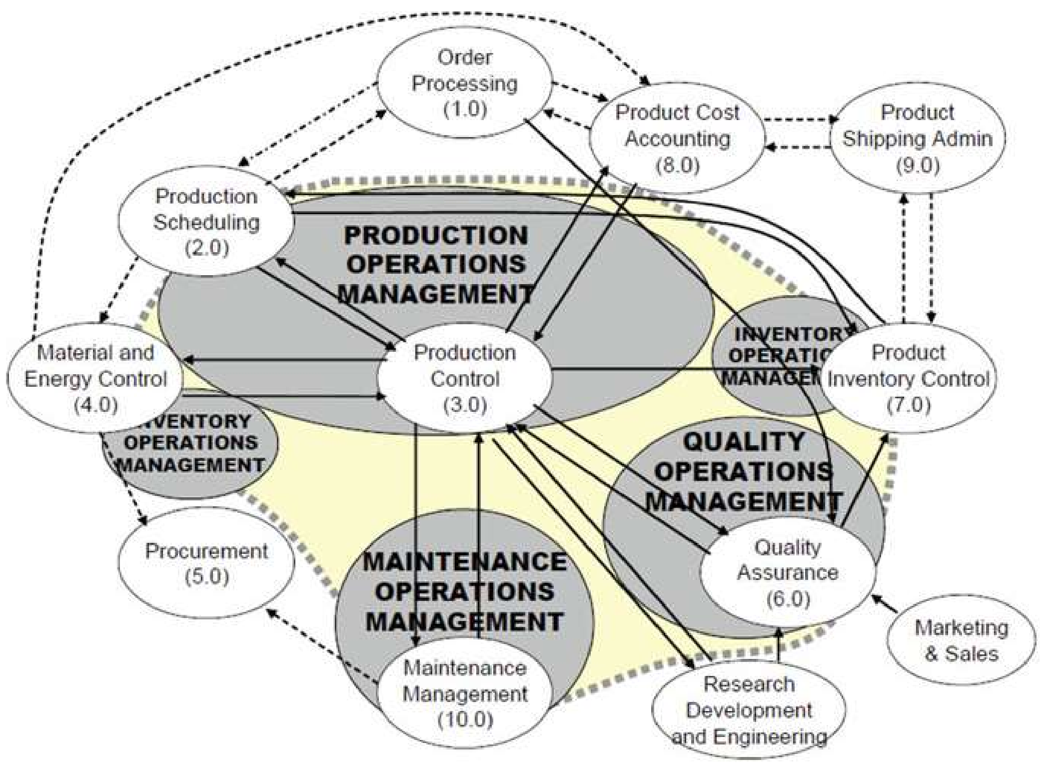

Fig. 11.3 Manufacturing operations management model based on ISA-S95 (ISA 2005)

application that handles the execution of manufacturing operations, and by using current and accurate data, the MES guides, triggers, and reports factory activities as events. The set of functions of the MES manages the production operations from the point where the order to manufacture is released to the point of delivery of the product as finished. The MES provides critical information about production activities to other related systems throughout the organization and supply chain through two-way communication. In general terms, the MES is defined as a stratum that integrates the business systems with the control systems of the companies, commonly referred to as an integration of the production floor with the management floor" (MESA 1997).

This definition implies the following characteristics of the MES:

- High level of detail (data acquisition of manufacturing processes);
- A relatively short horizon for planning (reactive planning);
- Bidirectional communication with ERP systems and production floor systems (interface).

MESA has been developed a model that shows the relationship between the company's strategic initiatives from business operations to plant operations. This model is exposed in Fig. 11.4.

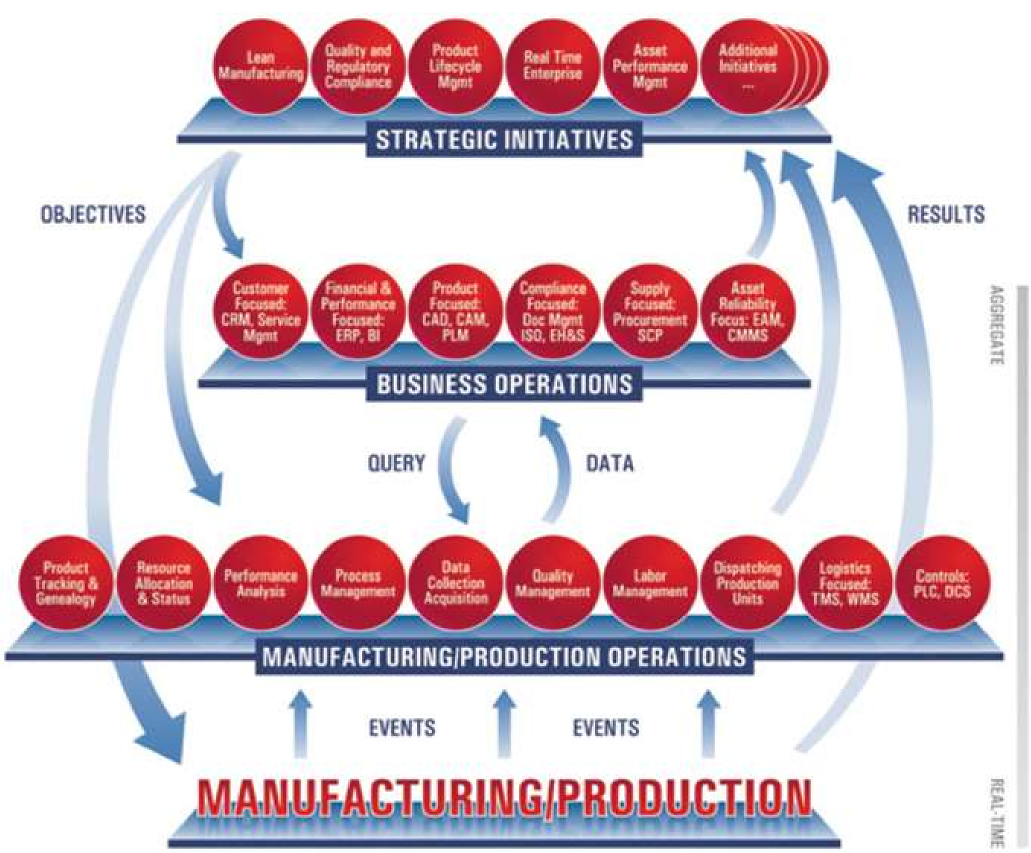

Fig. 11.4 MESA model based on business strategic initiatives (MESA 2019)

VDI. Another normative guideline is that proposed by the Association of German Engineers or *Verein Deutscher Ingenieure* (VDI), which is published in its regulation number 5600, from which information on the functions of the MES and its integration into the company operations. Based on the standards and regulations together with the findings and the development of the market, VDI developed such regulations to give the MES a fixed meaning preventing the indiscriminate use by some companies who have used any new buzzword for purposes of marketing. The goal is to maintain a perception oriented to the eyes of industrial manufacturing leaders. This guideline seeks to attract attention to distinguish the requirements and functions of the MES between different types of manufactures (Kletti 2007). The guidelines highlight the importance of the dependence and coupling that the MES has with the machines and devices that are used in the production lines. Without this union, specific MES tasks cannot be executed correctly. For this reason and due to the fact that there is heterogeneity in each of the organizations together with the connectivity between the elements of their processes, the regulations provide users with the possibility of standardizing the contents of the data that need to be exchanged between the machines and the MES (VDI 2016). In that sense, the MES needs to provide the following functions:

- Data extraction and synchronization with planning data to have the ability to respond to changing conditions in real time.
- Have a connection with the level of automation to achieve vertical integration.
- Have an exchange of data with other applications at the MES level, such as logistics applications, which could be considered as a horizontal integration.
- Carry out a comprehensive evaluation of the current data in the MES by means of data mining to auto-optimize the production system, as, for example, by allowing the MES to identify connections between quality data and process parameters and adjust the latter when necessary, and;
- Identify interrelated data from multiple volumes of either the MES or operational processes and combine them for meaningful information (Sauer 2014).

VDMA. The *Industrial Association of Mechanical Engineering* or *Verband Deutscher Maschinen und Anlagenbau* (VDMA, for its acronym in German) presented a regulation under number 66412, where the MES guidelines are expressed under the context of Industry 4.0 (VDMA 2009) which also they are associated with the standards of the *Architecture References Model for Industry 4.0* or *Referenzarchitekturmodell Industrie 4.0* (RAMI) (ZVEI 2015). These reference guidelines consist of the description of the crucial aspects of Industry 4.0, describing the levels of hierarchies (such as the one presented in the ISA-S95 standard) for information technology systems and control systems. They also provide the required elements including an orientation to trace what is necessary in each of the production sectors at national and international level to be able to define and develop Industry 4.0.

IEC. *The International Electrotechnical Commission* (IEC) has an international standard under number 62264 Enterprise Control System Integration, which describes the domain (level 3 according to ISA-S95) of manufacturing operations management and its activities, including the interfaces and associated transactions between the same level 3 and between level 3 and level 4. This description allows the integration between manufacturing operations and the control domain (levels 3, 2, and 1) and the domain business or business (level 4). Its objective is to increase the uniformity and consistency with the terminology of the interfaces and reduce the risk, costs, and errors associated with the implementation of those interfaces. For the application of the MES system, this regulation is for its effective application (IEC 2013). The standard IEC 62264 is considered the de facto MES standard (Karadgi 2014) and covers production, maintenance, quality, and inventory domains (Arab-Mansour et al. 2017).

NAMUR. The *Association of Users of Automated Technology in Industrial Processes* (NAMUR by its acronym in German) is a group of users who are involved in the chemical and pharmaceutical industry. The association presented the regulations under number 94 and gave some recommendations beyond those based on the definitions of ISA-S95 to make specific distinctions in the flow of information and functions. The recommendations made by NAMUR are a practical representation of information to configure and adapt the MES system in an environment oriented to industrial processes (NAMUR 2003).

11.3.4 Manufacturing Execution Systems Taxonomy

Arica and Powell (2018) proposed a taxonomy to characterize MES, which can be used for its selection or design. Taxonomy consists of two main categories of factors:

- Business and manufacturing factors.
- Technological factors.

Next, each of the main categories of factors will be analyzed.

11.3.4.1 Business and Manufacturing Factors

Business and manufacturing factors classify MES systems according to their approach, scope, and functionality. In relation to the classification of approach, there are significant differences in each industry in the way in which MES deals with manufacturing monitoring processes and control tasks, due to the manufacturing of each product consists of a series of products, data, machinery, and unique systems. For this reason, the adjustment that the MES has with a certain industry is an important factor for its implementation. That is why there are some implementations of the MES system in various companies, for example, in a car engine manufacturing company (Huang and Liu 2012); in a steel company (Govindaraju and Putra 2016); in a microcircuit production line (Zhang et al. 2017); including also in software development (Naedele et al. 2015).

In relation to the classification of scope, the MES has two associated factors: business level and operational level. The first refers to the coverage that the MES has within the value chain system that can be applied to a single plant or to several (Helo et al. 2014). The second refers to the activities or functions that the MES can operate, and as already mentioned in relation to the ISA-S95 regulations, it can support production, maintenance, quality, and inventory operations (ISA 2005). However, most MES systems are designed based on contextual requirements, they may cover part, or all of the functions suggested by ISA-S95 (Wang et al. 2010; Cottyn et al. 2011; Köksal and Tekin 2012; Menezes et al. 2018).

For the classification of functionality, there are three factors that characterize MES: functional configuration, functional integration, and structural design. As explained before, some standards had been created in order to have a basis in the functional configuration of the MES. However, some manufacturing companies have customized or configured the systems long before the standards were published. Making a comparison of what is published in the standards and what has been done, it is imperative that organizations select the appropriate system according to their integral and core functions. In relation to the functional structure, it can be categorized into centralized/hierarchical and decentralized/heterarchical structures. But decentralized systems are being widely used due to the reaction to the dynamic external changes of organizations (Trentesaux 2009).

11.3.4.2 Technological Factors

The technological factors, which are predominant when selecting the right MES for the organization, include aspects of data management and communication and support in the logical decision and the user interface. Regarding the aspect of data management and communication, the primary functionality of the MES is data collection and communication in real time. Regardless of the type of industry, companies primarily use MES as a tool to collect data. For data collection to be done correctly from the organization's devices, you need to obtain the desired data and transmit it efficiently and accurately within the MES system. For that reason, schemes have been designed for data collection using radio frequency identification devices or through advanced location algorithms (Lee et al. 2012; Yang et al. 2016). Therefore, the communication and integration of the MES with other systems is also an important factor, due to functional overlaps, information exchange, requirements, and interfaces. In this regard, improvements in storage technology are useful for the capabilities of the MES, as is the case with the use of cloud-based systems (Jiang et al. 2015), or communication protocols for the flow of material in a simulated system (Timo et al. 2016).

Like any decision support system, MES contains various types and techniques. For example, Zhong et al. (2013) proposed the use of decision support through optimization using real-time programming techniques. Grauer et al. (2010) proposed an MES that uses data mining algorithms.

A critical component for the MES is the user interface for its successful implementation and use. Studies on ERP systems suggest that one of the important keys to its implementation is the ease of use (Ratkevičius et al. 2012). This is because the users of the system would generally be the staff of the production floor and its use would be frequent.

One of the uses of the MES can also be described in terms of transparency in manufacturing processes and as a result establishes horizontal and vertical (closed) control circuits (Kletti 2007). These control circuits allow a rapid reaction to incidents in the production floor, as the information feeds the planning systems to trigger respective measures to the subsequent manufacturing stages (horizontal integration) (Schmidt et al. 2010).

11.3.5 Manufacturing Execution Systems as a Quality Tool

According with the models and standards reviewed (like IEC 62264 and MESA), one of the important tasks that MES helps in businesses is in the process of quality management by performing real-time management and analysis of product specifications and requirements in order to identify any deviation or non-conformance established on the company's quality system. Such deviations could influence in a negative way all the processes involved. So, it is important that any MES used in quality management has the characteristic of being a real-time system, which means that speed, time, and responsiveness should help the system to be able to adjust to the internal and external changes, remain alert to any special event, to react within the time constraints or deadlines (Karadgi 2014). Also, it helps the user/operator not only to know the current state of the production process, but also to identify any abnormal or critical state that compromise the quality of the product (Kulcsar et al. 2005).

In the actions of improving the quality of the manufacturing system, MES can provide information for the interested parts, so the problems can be solved in a quick manner to reduce interruptions in the production system. Managers, supervisors, or users can be notified to act or proceed properly (Engelbrecht 2007).

Some of the quality functions that can be performed by MES as part of quality management are the following: (1) statistical process control or SPC: specific data acquisition of measured values, comparing the measured values against standard values, warnings and indication of different values or that are out of tolerance, and tracking trends; (2) tracking non-conformance events: sometimes products that are not complaint with the quality system need to be registered and stored for analysis, and information about their technical aspects, manufacturing conditions, input materials, root-cause events, and traceability can be managed by a MES; (3) quality checks and inspection of incoming and finished goods: MES is capable of getting information about the characteristics and dimensions of the inputs and outputs of manufacturing processes and provides alarms if certain values are not in complaint with the quality system; (4) tool and resource management: a MES can perform inspection, measurement, and test of equipment, machines and tools used in manufacturing processes to ensure that they meet the required specifications and have the correct setups to operate under the desired conditions; (5) process data processing:

MES can be implemented in a way that can gather information from different factors and circumstances of the production process directly, verifying them against standard limits through correlations, and in events of deviations being capable to act with countermeasures (Kletti 2007); and (6) document control: MES is useful to control the records needed in the production process, like work instructions, drawings, standard operation procedures, part programs, batch records, engineering change notices, policies, standards, and regulations (Van Dyk and Van Schoor 2012).

There are some examples of MES that had been applied for quality management processes in different industries, such in a way to improve the quality of oil refinery process (Kuvykin and Petukhov 2019); as a tool of integration of process and quality control using multi-agent technology in a home appliance company production line (Cristalli et al. 2013); and to comply with the regulations of the manufacturing of pharmaceutical products (Blumenthal 2004).

11.3.6 Manufacturing Execution Systems and Industry 4.0

The MES have been essential in the performance, quality, and agility necessary for the challenges that arise in the business world of the globalized manufacturing which will continue to be in the future. However, a new generation of systems is required to meet the new challenges that Industry 4.0 has brought. Below are some of those challenges and opportunities that can be applied in MES.

Internet of Things. This term is used to refer to a global network of interconnection of intelligent objects through the Internet, making use of connectivity technologies like radio frequency identification devices, sensors/actuators, and inter-machine connection devices (Patel et al. 2016). This trend offers the potential to develop MES solutions for the entire supply and value chain instead of simply providing functionality in terms of planning and control. *Digital twins* could also be created, which is a virtual representation of a production system capable of running in different simulation disciplines and is characterized by synchronization between virtual and real systems, thanks to the data generated by the connectivity between sensors and devices, mathematical models, and real-time monitoring (Cimino et al. 2019), that can be used for simulations and scenario analysis (Golfarelli et al. 2006).

Decentralization and vertical integration. What is sought in future systems is that they have a logical decentralization, that the devices can identify themselves and that they connect in a centralized physical system, providing their position and status within that system. For this reason, the new MES trends will require decentralized connectivity with connection possibilities with other entities, for example, intelligent materials. It is also sought that the connectivity of the MES not only be at the horizontal level, but also serves as a bridge between the ERP systems of the business and the productive processes, with an orchestration of that system with those of quality, logistics, engineering, and operations (Almada-Lobo 2016).

Virtual Reality. It is the field of acquisition, analysis, and synthesis of visual information through computers that provide a virtual experience of a real situation

(Posada et al. 2015). MES can be designed to allow the interaction of the real system through the so-called augmented reality through interfaces, which can be used for training or control of production systems (Posada et al. 2018).

Industrial automation. It is the use of control systems, such as computers or robots and information technologies to handle different processes and machines in an industry to replace the human being. It is the second step beyond mechanization in the scope of industrialization. A higher level of industrial automation would result in complex levels of control and management that could be controlled and manipulated through the MES (Filipov and Vasilev 2016).

Autonomous Robots. It is an important part of artificial intelligence and robotics. They are used for the creation of complex intelligent networks, capable of learning, reasoning, and acting based on the information gathered during the industrial process (Dopico et al. 2016). Smart robotics will work as a support mechanism where machines can use real-time information from the MES to reconfigure the production system and the external supply chain.

Cybersecurity. It can be described in terms of requirements of Industry 4.0 technologies to avoid unauthorized access to production systems to prevent economic, environmental, and human damage (Drath and Horch 2014). The new MES systems should have the ability to be secure between the internal and external connectivity of companies.

Big Data. It refers to the set of data that, due to its size, is far from the capacity of databases and software tools to capture, store, manage, and analyze (Yin and Kaynak 2015). MES can be developed to have the ability to perform those functions that cannot be done by typical and common systems (Li et al. 2019).

Mobile technology. Communication technologies have evolved to meet industry demand by providing real-time information on production, predictive maintenance, and automation. The communication technology that is required by the needs of the industry is mobile. Some of them, such as GSM, LTE, or mobile applications, have been the trends used in today's factories (Meredith and Pope 2018). The new MES must have the ability to interact with mobile technology (Meyer 2012).

Cloud Computing. As a model to have access to different computing resources (networks, servers, storage, applications, and services) that can be provided quickly without efforts in their administration and reducing costs, MES systems can be configured to have the ability to use those computing resources. You can even combine cloud storage to analyze a large amount of data (Vitliemov 2016; Atobishi et al. 2019).

Smart MES. There is a proposal for a smart MES that can be used in small and medium-sized manufacturing companies, where features of the Internet of Things are applied for connectivity of manufacturing machines, through the use radio frequency identification tags together with sensors embedded in critical components, tools, and controllers of the machines, which together generate data that can be sent in real time for analysis to the interested parties (Menezes et al. 2018). Also, it can be applied under sustainability trends (Larreina et al. 2013).

System integration. Known also as intelligent or cyber-physical systems, which cover the hardware and software, as well as integrated physical components that interact closely with each other, where physically mechanical devices interact with IT systems, hardware, software, digital, and electronical components (Chukalov 2017). A cyber-physical system architecture MES had been applied in a shop floor (Liu and Jiang 2016).

Additive Manufacturing. Defined as “the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining” (ASTM International 2012), there are technologies of the use of design for additive manufacturing, which uses MES architecture, as information framework able to real-time acquire, analyze, and synthesize process and product data (D’Antonio et al. 2017).

11.4 Conclusions and Industrial Implications

This work proposed a review on MES, based on an analysis of the literature. Within the functions of the business and manufacturing processes, MES has played a vital role in companies in achieving its objectives. However, as technology and knowledge evolve, it is also seen that the MES has evolved, even within the Industry 4.0 paradigm. This evolution is not only palpable in the way of the application of technology, but also in its interpretation within the normative and standardized context, as it was shown when presenting some of the regulations that are used for its implementation.

The fundamental opportunity for Industry 4.0 is to create new information value in offering new services to customers and increasing efficiency in internal operations. Through the new technologies of data collection, analysis and communication functions through the value chain, the MES would serve as a platform to implement Industry 4.0 technologies.

References

Almada-Lobo F (2016) The industry 4.0 revolution and the future of manufacturing execution systems (MES). J Innov Manag 3:16–21. https://doi.org/10.24840/2183-0606_003.004_0003

Anderson J, Kalra N, Stanley K, et al (2016) Autonomous vehicle technology: a guide for policymakers. RAND Corporation

Arab-Mansour I, Millet PA, Botta-Genoulaz V (2017) A business repository enrichment process: a case study for manufacturing execution systems. Comput Ind 89:13–22. https://doi.org/10.1016/j.compind.2017.03.006

Arica E, Powell DJ (2018) Status and future of manufacturing execution systems. In: IEEE international conference on industrial engineering and engineering management 2017 Dec, 2000–2004. https://doi.org/10.1109/IEEM.2017.8290242

ASTM International (2012) ASTM: F2792–12a. Standard technology for additive manufacturing technologies, West Conschohocken

Atobishi T, Gábor Szalay Z, Bayraktar S (2019) Cloud computing and big data in the context of industry 4.0 : opportunities and challenges. https://doi.org/10.20472/iac.2018.035.004

Blumenthal R (2004) Manufacturing execution systems to optimize the pharmaceutical supply chain. Pharm Ind 66:1414–1424
Chukalov K (2017) Horizontal and vertical integration, as a requirement for cyber-physical systems in the context of industry 4.0. Int Sci J "Industry 40" 2:155–157
Cimino C, Negri E, Fumagalli L (2019) Review of digital twin applications in manufacturing. Comput Ind 113:103130. https://doi.org/10.1016/j.compind.2019.103130
Cottyn J, Van Landeghem H, Stockman K, Derammelaere S (2011) A method to align a manufacturing execution system with Lean objectives. Int J Prod Res 49:4397–4413. https://doi.org/10.1080/00207543.2010.548409
Cristalli C, Foehr M, Jager T et al (2013) Integration of process and quality control using multi-agent technology. IEEE Int Symp Ind Electron 374–379.https://doi.org/10.1109/ISIE.2013.6563737
D'Antonio G, Bedolla JS, Chiabert P (2017) A novel methodology to integrate manufacturing execution systems with the lean manufacturing approach. Procedia Manuf 11.https://doi.org/10.1016/j.promfg.2017.07.372
Dopico M, Gomez A, De la Fuente D, et al (2016) A vision of industry 4.0 from an artificial intelligence point of view. In: Proc 2016 international conference on artificial intellgence ICAI 2016—WORLDCOMP 2016, pp 407–413
Drath R, Horch A (2014) Industrie 4.0: hit or hype? IEEE Ind Electron Mag 8:56–58. https://doi.org/10.1109/MIE.2014.2312079
Engelbrecht GJ (2007) Successfully implementing a manufacturing execution systems (MES) solution
Filipov V, Vasilev P (2016) Manufacturing operations management—the smart backbone of industry 4 . 0. Int Sci Conf "Inudstry 40" 27/213:8–13
Golfarelli M, Rizzi S, Proli A (2006) Designing what-if analysis: Towards a methodology. Dol Proc ACM Int Work Data Warehous Ol 51–58.https://doi.org/10.1145/1183512.1183523
Govindaraju R, Putra K (2016) A methodology for manufacturing execution systems (MES) implementation. IOP Conf Ser Mater Sci Eng 114.https://doi.org/10.1088/1757-899X/114/1/012094
Grauer M, Karadgi S, Metz D, Schäfer W (2010) An approach for real-time control of enterprise processes in manufacturing using a rule-based system. MKWI 2010—Multikonferenz Wirtschaftsinformatik 2010, pp 301–302
Guirao Goris SJA (2015) Utilidad y tipos de revisión de literatura. Ene 9:. https://doi.org/10.4321/S1988-348X2015000200002
Helo P, Suorsa M, Hao Y, Anussornnitisarn P (2014) Toward a cloud-based manufacturing execution system for distributed manufacturing. Comput Ind 65:646–656. https://doi.org/10.1016/j.compind.2014.01.015
Huang D, Liu M (2012) Design and implementation of manufacturing execution system (MES) for automobile main gear reducer assembly line. Adv Mater Res 468–471:111–114.https://doi.org/10.4028/www.scientific.net/AMR.468-471.111
IEC (2013) 62264 Enterprise-control system integration—part 1: models and terminology. Geneva
ISA (2005) Enterprise control system integration part 3 : activity models of manufacturing operations management. International Society of Automation
ISA (2006) Batch control, part 1: models and terminology, ISA-88.01–1995 (R2006)
Jiang P, Zhang C, Leng J, Zhang J (2015) Implementing a WebAPP-based software framework for manufacturing execution systems. IFAC-PapersOnLine 28:388–393. https://doi.org/10.1016/j.ifacol.2015.06.112
Karadgi S (2014) A reference architecture for real-time performance measurement. Springer, Berlin
Kletti J (2007) Manufacturing execution system—MES. Springer-Verlag, Berlin
Köksal A, Tekin E (2012) Manufacturing execution through e-FACTORY system. Proc CIRP 3:591–596. https://doi.org/10.1016/j.procir.2012.07.101
Kulcsar G, Hornyak O, Erdelyi F (2005) Shop floor control decision supporting and MES functions in customized mass production. JOUR

Kuvykin VI, Petukhov MY (2019) Improving the quality of process models in oil refinery information systems. Int J Qual Res 13:539–552. https://doi.org/10.24874/IJQR13.03-03
Larreina J, Gontarz A, Giannoulis C et al (2013) Smart manufacturing execution system (SMES): the possibilities of evaluating the sustainability of a production process. In: The 11th global conference on sustainable manufacturing, pp 517–522
Lee SW, Nam SJ, Lee JK (2012) Real-time data acquisition system and HMI for MES. J Mech Sci Technol 26:2381–2388. https://doi.org/10.1007/s12206-012-0615-0
Li P, Jiang P, Liu J (2019) Mini-MES: A microservices-based apps system for data interconnecting and production controlling in decentralized manufacturing. Appl Sci 9. https://doi.org/10.3390/app9183675
Liu C, Jiang P (2016) A cyber-physical system architecture in shop floor for intelligent manufacturing. Proc CIRP 56:372–377. https://doi.org/10.1016/j.procir.2016.10.059
Mabkhot M, Al-Ahmari A, Salah B, Alkhalefah H (2018) Requirements of the smart factory system: a survey and perspective. Machines 6:23. https://doi.org/10.3390/machines6020023
Mantravadi S, Møller C (2019) An overview of next-generation manufacturing execution systems: how important is MES for industry 4.0? In: Procedia manufacturing
McClellan M (1997) Applying manufacturing execution systems. Lucie Press, Boca Raton, FL, St
Mcclellan M (2001) Introduction to manufacturing execution systems Baltimore, Maryland. MES Conf Expo 1–12
Menezes S, Creado S, Zhong RY (2018) Smart manufacturing execution systems for small and medium-sized enterprises. In: Procedia CIRP
Meredith JM, Pope M (2018) How mobile IoT is changing the industrial landscape
MESA (1997) MES explained : a high level vision. Pittsburgh
MESA (2019) MESA model. In: Manufacturing enterprise solutions association. https://www.mesa.org/en/modelstrategicinitiatives/MESAModel.asp. Accessed 17 Nov 2019
Meyer H (2012) OS independent mobile solutions for manufacturing execution systems. In: WMSCI 2012—16th world multi-conference systemics, cybernetics and informatics, Proc 1, pp 168–171
Meyer H, Fuchs F, Thiel K (2009) Manufacturing execution systems: optimal design, planning , and deployment. The McGraw-Hill Companies, Inc.
Møller C (2004) ERP II-Next-generation extended enterprise resource planning. In: Organizing for networked information technologies: readings in process integration and transformation
Naedele M, Chen H, Kazman R et al (2015) The journal of systems and software manufacturing execution systems: a vision for managing software development. J Syst Softw 101:59–68. https://doi.org/10.1016/j.jss.2014.11.015
NAMUR (2003) NA 94 functions and examples of operations control level solutions
Oberhofer A, Meisen P (2012) Energy storage technologies. https://www.geni.org/globalenergy/research/energy-storage-technologies/Energy-Storage-Technologies.pdf
Patel KK, Patel SM, Scholar PG (2016) Internet of Things-IOT: definition, characteristics, architecture, enabling technologies, application and future challenges. Int J Eng Sci Comput 6:1–10. https://doi.org/10.4010/2016.1482
Posada J, Toro C, Barandiaran I et al (2015) Visual computing as a key enabling technology for industrie 4.0 and industrial internet. IEEE Comput Graph Appl 35:26–40. https://doi.org/10.1109/MCG.2015.45
Posada J, Zorrilla M, Dominguez A et al (2018) Graphics and media technologies for operators in industry 4.0. IEEE Comput Graph Appl 38:119–132. https://doi.org/10.1109/MCG.2018.053491736
Radziwon A, Bilberg A, Bogers M, Madsen ES (2014) The smart factory: exploring adaptive and flexible manufacturing solutions. Proc Eng 69:1184–1190. https://doi.org/10.1016/j.proeng.2014.03.108
Rashid M, Hossain L, Patrick J (2002) The evolution of ERP systems: a historical perspective. Enterp Resour Plan Solut Manag 1–16.https://doi.org/10.4018/978-1-931777-06-3
Ratkevičius D, Ratkevičius Č, Skyrius R (2012) Erp selection criteria: theoretical and practical views. Ekonomika 91:97–116. https://doi.org/10.15388/ekon.2012.0.893

Rodriguez I, Mogensen RS, Khatib EJ et al (2019) On the design of a wireless MES solution for the factories of the future, pp 1–6. https://doi.org/10.1109/giots.2019.8766419
Romero D, Vernadat F (2016) Enterprise information systems state of the art : past, present and future trends.https://doi.org/10.1016/j.compind.2016.03.001
Saenz de Ugarte B, Artiba A, Pellerin R (2009) Production planning and control: the management of operations manufacturing execution system—a literature review. Prod Plan Control Manag Oper 20:525–539. https://doi.org/10.1080/09537280902938613
Salazar V (2009) Análisis de la Integración de los Sistemas MES—ERP en industrias de manufactura. In: Energy and technology for the Americas: education, innovation, technology and practice. Latin American and Caribbean Conference for Engineering and Technology, San Cristobal, Venezuela, pp 1–6
Sauer O (2014) Information technology for the factory of the future—state of the art and need for action. Proc CIRP 25:293–296. https://doi.org/10.1016/j.procir.2014.10.041
Schmidt A, Otto B, Kussmaul A (2010) MES services in the automotive industry. St, Gallen
Schwab K (2016) The fourth industrial revolution. Geneva
Strickland E (2016) Autonomous robots surgeon bests humans in world first. In: IEEE Spectr. https://spectrum.ieee.org/the-human-os/robotics/medical-robots/autonomous-robot-surgeon-bests-human-surgeons-in-world-first
Timo IF, Mónica RL, Christian B et al (2016) Agent-based communication to map and exchange shop floor data between MES and material flow simulation based on the open standard CMSD. IFAC-PapersOnLine 49:1526–1531. https://doi.org/10.1016/j.ifacol.2016.07.796
Trentesaux D (2009) Distributed control of production systems. Eng Appl Artif Intell 22:971–978. https://doi.org/10.1016/j.engappai.2009.05.001
Van Dyk L, Van Schoor CD (2012) Realising the potential of manufacturing execution systems. South African J Ind Eng 12:101–118. https://doi.org/10.7166/12-1-358
VDI (2016) 5600 part 1: manufacturing execution systems. Beuth-Verlag
VDMA (2009) 66412—Manufacturing execution systems kennzahlen. Berlin
Velez-Martinez C (2017) Internet de las Cosas. Gac Inst Ing 1:20–21
Vitliemov P (2016) From cloud manufacturing to cloud-based manufacturing execution system. In: International scientific conference “Industry 4.0.” pp 7–10
Wang M, Dai Q, Zhang X, et al (2010) A RFID-enabled MES for real-time pharmaceutical manufacturing supervision. In: Proceedings of 2010 IEEE international conference on RFID-technology and applications, RFID-TA 2010, pp 49–53. https://doi.org/10.1109/RFID-TA.2010.5529858
Witzel O, Wilm S, Karimanzira D, Baganz D (2019) Controlling and regulation of integrated aquaponic production systems—an approach for a management execution system (MES). Inf Process Agric 6:326–334. https://doi.org/10.1016/j.inpa.2019.03.007
Xu LD (2011) Enterprise systems: State-of-the-art and future trends. IEEE Trans Ind Informatics 7:630–640. https://doi.org/10.1109/TII.2011.2167156
Yang Z, Zhang P, Chen L (2016) RFID-enabled indoor positioning method for a real-time manufacturing execution system using OS-ELM. Neurocomputing 174:121–133. https://doi.org/10.1016/j.neucom.2015.05.120
Yin S, Kaynak O (2015) Big data for modern industry: challenges and trends. Proc IEEE 103:143–146. https://doi.org/10.1109/JPROC.2015.2388958
Zhang J, Jiang Y, Jiang W (2017) Quality management of manufacturing process based on manufacturing execution system, 020025. https://doi.org/10.1063/1.4979757
Zhong RY, Dai QY, Qu T et al (2013) RFID-enabled real-time manufacturing execution system for mass-customization production. Robot Comput Integr Manuf 29:283–292. https://doi.org/10.1016/j.rcim.2012.08.001
ZVEI (2015) Reference architecture model industrie 4.0 (RAMI4.0)