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Development of manufacturing execution systems in accordance with Industry 4.0 requirements: A review of standard- and ontology-based methodologies and tools

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ABSTRACT

This work presents how recent trends in Industry 4.0 (I4.0) solutions are influencing the development of manufacturing execution systems (MESs) and analyzes what kinds of trends will determine the development of the next generation of these technologies. This systematic and thematic review provides a detailed analysis of I4.0-related requirements in terms of MES functionalities and an overview of MES development methods and standards because these three aspects are essential in developing MESs. The analysis highlights that MESs should interconnect all components of cyber-physical systems in a seamless, secure, and trustworthy manner to enable high-level automated smart solutions and that semantic metadata can provide contextual information to support interoperability and modular development. The observed trends show that formal models and ontologies will play an even more essential role in I4.0 systems as interoperability becomes more of a focus and that the new generation of linkable data sources should be based on semantically enriched information. The presented overview can serve as a guide for engineers interested in the development of MESs as well as for researchers interested in finding worthwhile areas of research.

Contents

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1. Introduction

Manufacturing execution systems (MESs) monitor, control and optimize manufacturing processes [1]. Information provided by MESs helps decision makers to understand how the subsystems involved in production are interlinked, and this knowledge can facilitate the continuous improvement of manufacturing [2]. MESs provide a suitable solution for linking enterprise-level operations with shop-floor-level control of stations (see Fig. 1); as such, they also involve data exchange with the automation layer (for example, programmable logic controllers – PLCs – or supervisory control and data acquisition – SCADA). Manufacturing operations management (MOM) extends the functionality of an MES and can cover all activities necessary to ensure operational excellence, from quality management to capacity management [3]. In this paper, the terms MOM and MES will both be used to refer to a system with these extended functionalities.

The operation and control of manufacturing systems have changed substantially in recent decades. The traditional centralized approach for controlling discrete processes has undergone several important steps of development to reach its present level of industrial application. A recent review of currently available control engineering tools to support the development of smart manufacturing systems (SMSs) [4] highlights that cyber-physical systems (CPSs) integrate information technologies with physical processes and therefore exhibit complex cyber-physical behavior. Emerging technologies, such as the Internet of Things (IoT), the Internet of Services (IoS), cloud computing, and big data analytics, are giving a boost to Industry 4.0 (I4.0) initiatives and giving rise to new paradigms for manufacturing systems. Although in everyday life, the terms “Industry 4.0” and “Fourth Industrial Revolution” are often used interchangeably, “Industry 4.0” originally refers to a concept of factories in which machines are extended with sensors and wireless connectivity and connected to an adaptive system that makes decisions on its own and can analyze and visualize the entire production line. One part of I4.0 is the “smart factory” concept, in which a virtual copy of the physical environment is created and CPSs collect information from physical processes and make decentralized decisions; as a result, among other things, I4.0 includes technologies related to the Industrial IoT (IIoT), artificial intelligence (AI), process simulation and optimization, cognitive computing, and cloud computing [5]. As seen from this definition, the I4.0 revolution is expected to strongly influence the future of MESs [6].

This work aims to study this influence, review the current trends in research and development and identify future trends. Three questions have to be answered to develop an I4.0-ready MES. i.) What are the requirements of MESs in Industry 4.0? ii.) What kind of standards do exist which needs to be considered? iii.) What kind of modern, effective methods do exist in this area? The structure of this paper follows these questions, i.e., one section belongs to each question, where each literature review is followed by a conclusion with a proposal derived from it. In summary, the paper provides

- a detailed analysis of I4.0-related requirements for MES development (in Section 2),
- a systematic overview of MES development methods and standards (in Section 3), and
- a discussion of how semantic models can support the development of the new generation of MESs (in Section 4).

This systematic review is based on an examination of the literature available through Google Scholar, Scopus and Web of Science, following the PRISMA-P protocol. The PRISMA-P (Preferred Reporting Items for Systematic reviews and Meta-Analyses for Protocols) workflow consists of a 17-item checklist intended to facilitate the preparation and reporting of a robust protocol for systematic reviews. In the following, only the main details of the process are given. The information sources were last fully queried in October 2019. The inclusion and eligibility criteria were defined based on how closely the reviewed publications were related to the topics listed above:

- Section 2 reviews I4.0-related requirements for MESs, the keywords for the search were “Industry 4.0” and “MES”. The time window covered the years from 2013 to 2020. Forty-four scientific articles and 9 books and white papers were identified. After the removal of duplicate papers, 47 of the original 53 sources remained. Twenty-five articles were eligible due to their relevance to the link between I4.0 and MESs. The remaining 22 of the 47 were excluded because they did not focus on the examined topic. All of the 25 eligible papers were included in this review.
- Section 3 discusses how the ISA-95 standard and other methods used for the formal description of manufacturing systems can support MES development, and how they are related to I4.0 requirements, the keywords for the search were “ISA-95” and “MES”. Thirteen papers were found that were relevant to the review and were included in the qualitative synthesis. Quantitative analysis was not applied. The time window of these papers was from 2002 to 2019.
- Section 4 highlights how semantic models can support the development of MESs, the keywords for the search were “ontology” and “MES”. The time window was from 2005 to 2019. Thirty-two scientific articles were identified and screened. Four records were excluded: two conference reports and two articles for which the full text was not available. The remaining 28 full-text articles were assessed for eligibility, and 4 of them were excluded because they were not relevant to the ontological description of MESs. The remaining 24 studies were included in the qualitative synthesis. Because we fully covered the relevant literature, a meta-analysis was not performed.

The resultant overview can serve as a guide for engineers interested in the development of MESs as well as for researchers interested in finding worthwhile areas of research.

2. I4.0-related requirements for MESs

In this section, we discuss how paradigm changes arising from the emergence of CPSs, the IoT, and other related technologies and concepts are influencing the development of MESs.

2.1. Requirements extracted from the I4.0 maturity model

The I4.0 paradigm assumes a fully digitized, complex system that affects all units and classes in a factory. For an existing factory to meet I4.0 requirements, digital transformations, reorganizations and investments are required. The degree of conversion depends on the level of development of the factory. If the actual state of the factory can be effectively determined and small improvements can be made along the utility path toward the final goal, ongoing operational benefits will be gained from increased efficiency, while the investment costs will be spread out over time [7].

As shown in Fig. 2, according to the recent I4.0 maturity model, there are six stages of related development [8]. The first two (computerization and connectivity) are prerequisites for I4.0, while the other four (visibility, transparency, predictive capacity and adaptability) are part of I4.0 [9].

In accordance with these stages, the development of MESs should focus on the following:

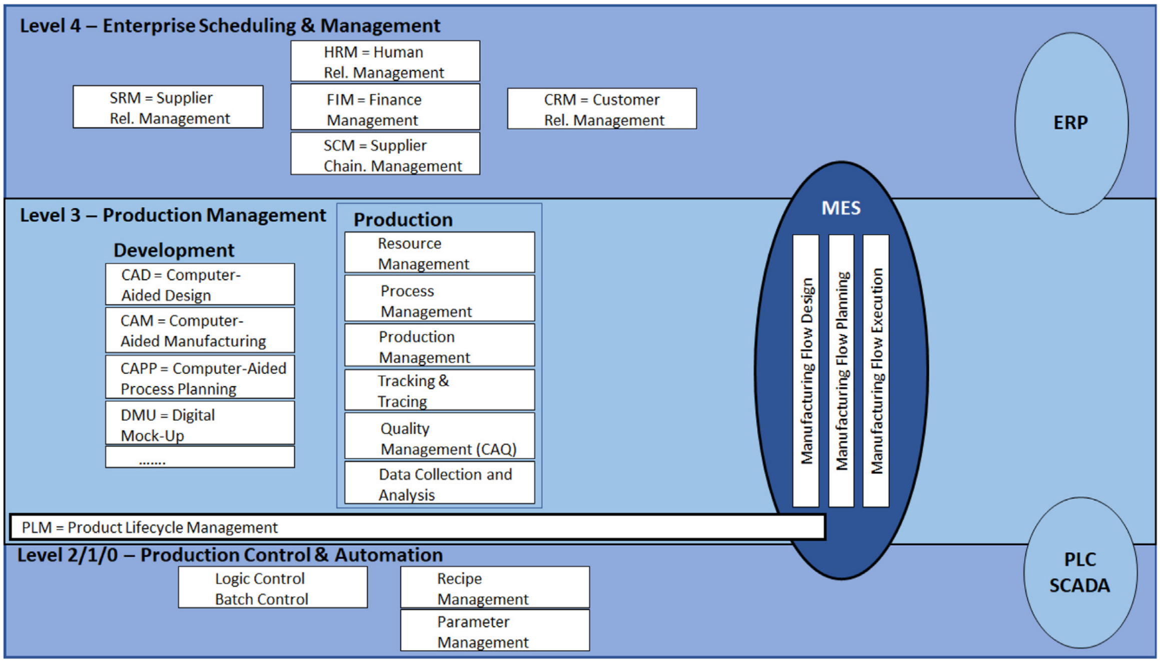

Fig. 1. Layers of the vertical hierarchy [1].

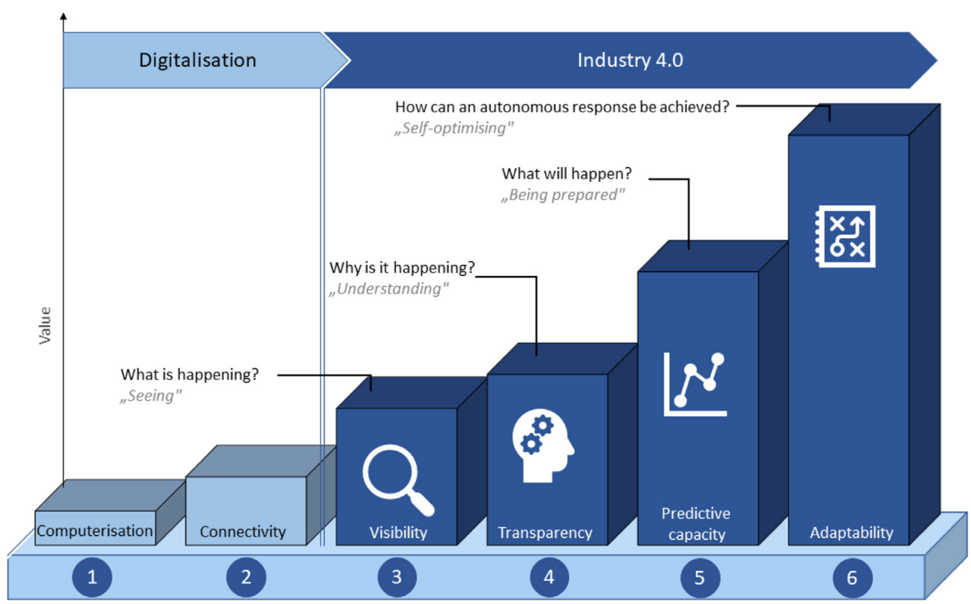

Fig. 2. The stages of I4.0 development [8].

1. **Support computerization.** Use computer-based control throughout the whole production chain.
2. **Improve connectivity.** Use computerized solutions that are able to communicate with other components. Efficiency can be improved only if the overall state of the whole production chain can be monitored and the traceability of the products is ensured. Each information source automatically sends information about itself to the MES in real time.
3. **Ensure visibility.** Show what is happening in the production chain. Product lifecycle management (PLM) systems, MESs and enterprise resource planning (ERP) systems all create visibility, but the design and integration of these systems raise a number of questions. Who has access to the data? How should a given type of data be presented? What kinds of data are needed by a decision maker?
4. **Ensure transparency.** All data related to all processes can potentially be observed with the help of the third stage. At this level, it is necessary to understand why something is happening and use this knowledge to improve processes. Engineering knowledge is necessary to develop such an understanding, and often, very large amounts of data need to be processed for this purpose. Consequently, the big data paradigm is useful and sometimes unavoidable in this stage. Accordingly, the next generation of MES solutions will be required to have such machine learning (ML)/data mining functionalities.
5. **Increase predictive capacity.** When a company understands its processes, it will be able to find the answer to the questions “what will happen?” and “how should it happen?” Doing so will require the next generation of MES solutions to have corresponding simulation and optimization functionalities. The

integration of simulation modeling with PLM will require modeling using the virtual factory concept and the use of AI for process control enabling autonomous adjustment (self-organization). This new simulation paradigm is best described in terms of the Digital Twin concept. A Digital Twin should provide simulation modeling of all phases of the lifecycle, thus enabling product development and testing in a virtual environment, and should thus support each subsequent phase while gathering and using information from the previous phases. This approach relies on high-fidelity models, i.e., Digital Twins. Automation of model development, construction and adaptation can significantly facilitate the modeling and investigation of complex systems [10].
6. **Improve adaptability.** The goal of this level is to use (almost real-time) data to make the best possible choice in the shortest possible time. Many times, this means a close-to-real-time reaction time. Adaptation decisions can range from simple to highly complex; hence, the next generation of MES solutions should support multiobjective real-time decision making.

2.2. Requirements extracted from the concepts of horizontal and vertical integration

I4.0 assumes connected networks and services, which theoretically enable greater operational efficiency, higher flexibility and more extensive automation in production processes. These networks are formed through horizontal and vertical integration, as shown in Fig. 3.

Both horizontal and vertical integration should be supported by MESs:

- **Horizontal integration** takes place across multiple production facilities, or even the entire supply chain, on the production floor. A horizontally integrated company concentrates on the kinds of activities that are closely related to its competencies, and in addition, it builds up partnerships to support the end-to-end value chain. If a company's production facilities are distributed, horizontal integration can help facilitate information flow, for example, across plant-level MESs. In this case, manufacturing-related data (for example, unexpected delays, unexpected failures and inventory levels) must flow with minimal delay among the production facilities. If necessary, the exact locations of production tasks can be automatically changed among facilities. Supply chain integration requires high levels of automated collaboration in the upstream supply and logistics chain as well as in the downstream chain. Here, the upstream supply and logistics chain refers to the production processes themselves, while the downstream chain represents the process of bringing the finished products to market. The challenge with this kind of horizontal integration is that all service providers and third-party suppliers must be safely integrated into the logistical control and production systems of the company in question. Thanks to such integration, all communication units on the production floor become objects with well-defined properties that can communicate with each other and share any important data (e.g., performance status) about the production process [11]. They can respond autonomously to dynamic production requirements with the help of this shared information. At the end of the integration process, a smart production floor comes into being that can cost-effectively produce products while reducing the occurrence of unexpected events [12].
- **Vertical integration** is another direction of I4.0 development, with the main goal of integrating all logical layers within an organization, starting from the field layer (i.e., the production floor). Such integration assists in making strategic and tactical decisions because relevant data can flow transparently and freely up and down among these layers. The main advantage of this kind of integration is that the reaction time of the company can be dramatically reduced, which translates into a competitive advantage in the market. For example, the works of Choi et al. [13] and Schneppe et al. [12] illustrate the importance of vertical integration.

Fig. 4 illustrates vertical and horizontal integration from another viewpoint. In this case, the two ends of the vertical axis are the business side (top) and the production side (bottom). The suppliers (left) and the customers (right) are the two ends of the horizontal axis. For example, ERP is more closely related to the business side, while SCADA and PLC technologies are nearer to the production side. Supplier relationship management (SRM) supports suppliers, while customer relationship management (CRM) keeps in touch with customers. PLM systems help to manage the processes of the product lifecycle. To meet all requirements of I4.0, as previously discussed in this paper, it is necessary for digital information to flow as efficiently as possible among all subsystems under controlled conditions. All important user groups in the company, from marketing to purchasing and from the worker to the manager, should have access to the relevant data through the collaborative production management (CPM). The MES occupies a central position and it is inside in the CPM; thus, logically, it can assist in connecting the other, more "peripheral" systems.

2.3. Main functionalities of MESs - Current directions of development

It is interesting to see how the directions of development of MESs are aligned with the previously presented requirements. The functional areas of MESs have continually developed over the years. Table 1 concludes research directions, with a focus on recently developed functional areas for MESs.

Data collection is a key process into the MES systems. Currently, large volumes of data are stored in relational databases or by data historians, but the usage number of the cloud-based technologies continually grows, e.g. recently a cloud-based MES has been developed for a manufacturing process tracked by RFID-based solutions [19].

One of the highlighted functions of using stored data is **tracking and tracing of production**. MESs ensure that complete histories of lots, orders and equipment are recorded. This functionality is essential for all industrial activities, from shipbuilding [14] to automotive production [18]. Precise tracking of individual products is essential in these processes, as can be seen from many industry examples [13]. Recently it has been pointed out that up to 481 times faster process flow can be achieved with accurate tracking of the raw material [14]. Similar conclusions concerning the benefits of product tracking and optimal design have been mentioned in [15].

The tracking capability of the MES makes it possible **auditing and evaluation of performance**. MESs can extract useful information about the current status of production from raw data. This information can be used to evaluate production performance as well as the overall effectiveness of the equipment. Choi et al. [13] and Schneppe [12] show examples in which control and performance management require the integration of data into the production flow. The efficiency can be further increased by using AI and ML techniques [17].

A modern factory must strive for efficient operation. Therefore the **resource management** is paramount in this area. It may include the exchange and analysis of resource information, registration, data availability and the preparation and execution of production orders with resources of the correct capabilities. Schneppe shows clearly how important the resources management and the information flow between the key elements of the production

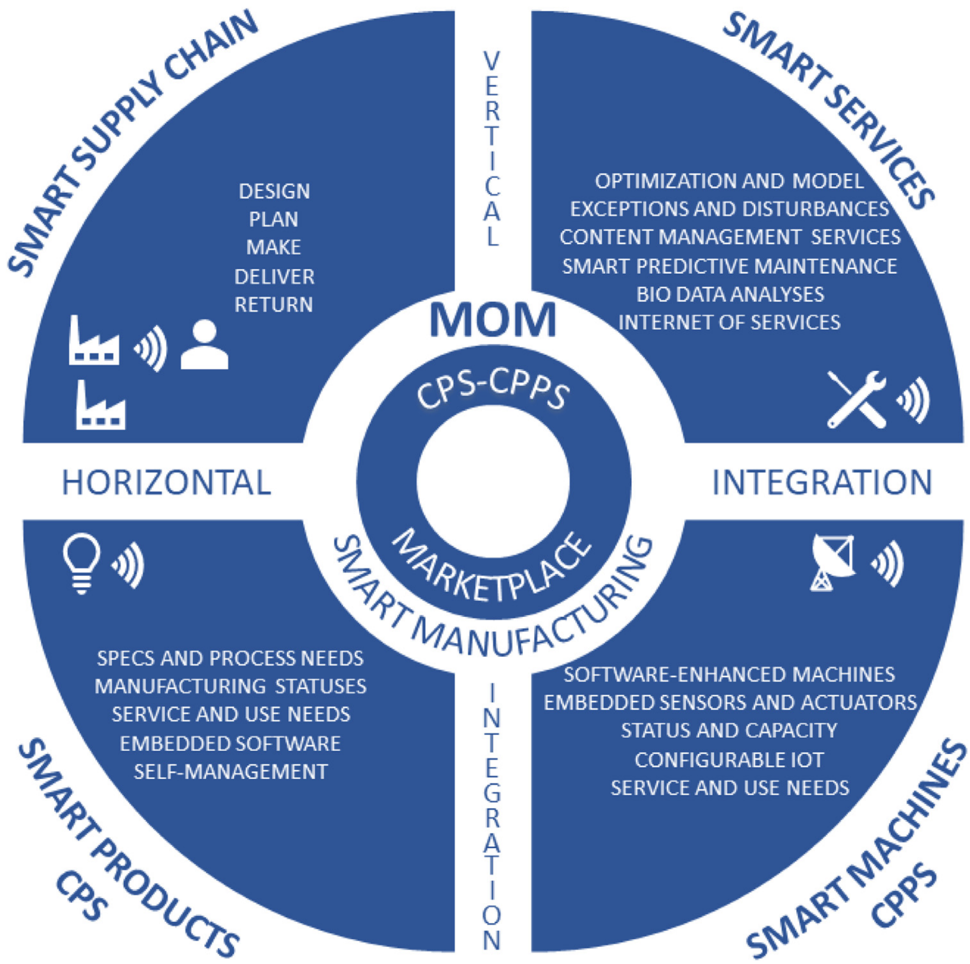

Fig. 3. Horizontal and vertical integration in MESs [3].

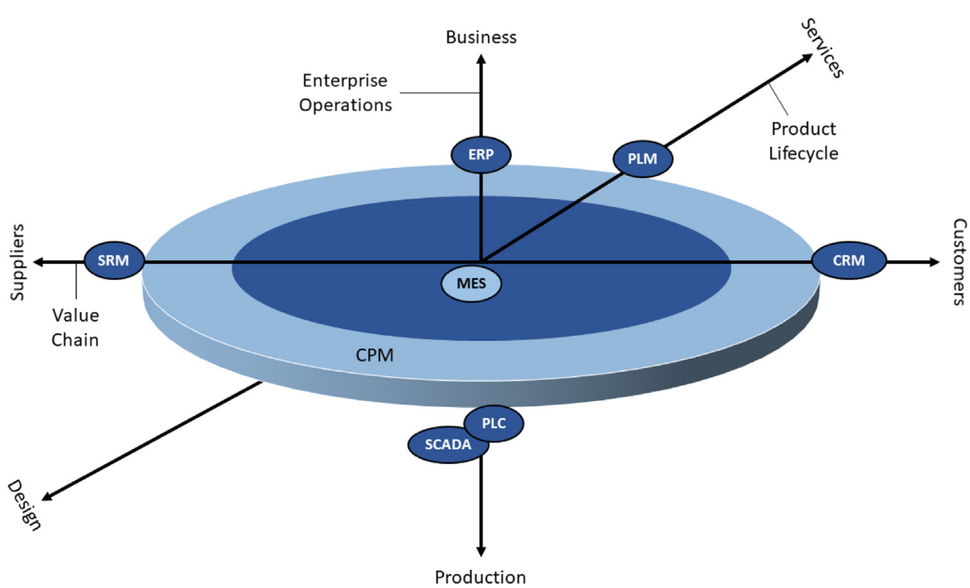

Fig. 4. Another perspective on vertical and horizontal integration [1].

[12]. This observation is confirmed by examining the efficiency of MES systems in the industrial 4.0 environment [18]. Mantravadi et al. developed a multi-agent MES where this property is one key element of the system [16] and the importance of the resource management was confirmed again in an overview paper [17].

Production scheduling stands close connection with the the resource management. Although process control systems supervise actual execution, MESs can perform checks on resources and can inform other systems about the progress of production processes [16]. Generally, ERP systems or other specialized

Table 1
MES-related research directions.

Author	Year	Collection of production data	Tracking and tracing of production	Auditing and evaluation of performance	Resource management	Production scheduling	Product definition	GUIs
Choi [13]	2019		*	*				*
Fernández-Caramé [14]	2018		*					
Gjeldum [15]	2018		*					
Mantravadi [16]	2019				*	*		*
Mantravadi [17]	2018			*	*			
Schnepp [12]	2017			*	*	*		
Skrzeszewska [18]	2020		*		*		*	*
Wang [19]	2018	*						

advanced planning and scheduling systems are responsible for production scheduling. The main benefit of involving the MES in (micro)scheduling is ensuring the optimal usability of local resources. The advantages of this can be seen in vertical and horizontal integration, among other contexts [12].

Product definition contains all necessary information for the production. It can include the management of any digitized data related to PLM. Related functionalities could include, for example, version control, storage, and exchange with other systems of master data such as bills of materials, bills of resources, (product) production rules, recipe data and process setpoints. What these functionalities all have in common is that they all focus on defining how a product is made. Research in the automotive sector, which examined three different levels of control (operational, tactical and strategic), has effectively demonstrated the importance of such functionalities [18].

For every system that people use, the **Graphical user interfaces (GUIs)** is paramount, which is especially true for systems that support complex industrial systems, such as MES. Various GUIs have been developed for MESs, for example, GUIs for web browsers, tablets or smartphones. The data sources used can be any digitized data storage tools, such as log books or SCADA or ERP systems. These functionalities are particularly important for supporting collaboration among people who work at different levels, and a clear GUI is essential for any integration (horizontal or vertical). The importance of GUI is shown in the work of Choi et al. [13], Skrzeszewska [18] and Mantravadi [16] with similar conclusions.

Summarising the above, we can conclude that the recent trends of MES function development are the following:

- **Collection of production data** is one of the basic functions of MES. It can collect, store and exchange process data and production logs. Example [19].
- **Tracking and tracing of production.** MESs could ensure that complete histories of lots, orders and equipment are recorded. Examples [13–15,18].
- **Auditing and evaluation of performance.** Data - that store in the MES system - contains useful information about the current status of production. This can be used to evaluate effectiveness of the different level of the production. Examples [12,13,17].
- **Resource management** needs every kind of data that is necessary to calculate the (optimal) production plan and operation from the available resources. Examples [12,16–18].
- **Production scheduling.** Although process control systems (generally ERP contains it) supervise the actual execution, but MESs can collect necessary information for the decision and MES could be involved in (micro)scheduling is ensuring the optimal usability of local resources. Examples [12,16].
- **Product definition** is showing how a product is made and it contains all necessary information for the production. Example [18].
- **Visualization and information sharing - Graphical user interfaces (GUIs).** It is important for users to display MES data in a well organized (with right permissions) and aggregated manner. Examples [13,16,18].

2.4. I4.0-related MES developments

In the I4.0 context, MESs need to handle rapidly flowing streams of disparate unstructured and structured data that often must be transformed into useful, targeted information in a near-real-time fashion. Furthermore, an MES should be able to handle the information flows that are needed in CPSs and cyber-physical production systems (CPPSs). In practice, a CPS is an object with a certain computing capacity and embedded software, and with the help of CPSs, the manufactured products themselves can become smart products. Smart products can cooperate with the production facility and are able to manage their own production flow. On the other hand, a CPPS (which is related to the manufacturing equipment, for example, sensors, actuators, and so on) has the same or higher intelligence. A CPPS includes a fully interconnected network that knows its own capacity, state and possible configurations. Naturally, this subsystem is also able to make independent decisions, similar to a CPS. Accordingly, MESs must play several roles in the I4.0 context, as follows:

- Coordinate vertical and horizontal integration in the I4.0 paradigm.
- Monitor, coordinate and supervise the manufacturing workflow and the CPS-CPPS marketplace. Use data from the CPSs and CPPSs to ensure the compliance and quality of activities.
- Compile final capacity schedules online on the basis of real-time information received from the CPSs and capacity information reported by the CPPSs.
- Integrate any non-CPS-enabled devices into the system.
- Implement and apply advanced optimization algorithms and, in case of incidents, support emergency replanning.
- Play a central role in smart supply chains and product lifecycles.
- Provide intranet content management system functionalites for facilitating true collaboration within a plant.
- Provide complex statistical analysis and support condition-based and smart predictive maintenance.
- Manage big data related to the manufacturing processes and provide services that can deliver aggregated information.

The new generation of MESs should become a critical part of the information technology (IT) infrastructure of I4.0. However, MESs must also provide answers to challenges summarised in Table 2.

Decentralization is one of the main directions of I4.0-driven MES development [15,21]. Since centralized solutions are not well suited for I4.0, further R&D efforts are necessary to support closely connected yet decentralized production and supply chain processes. Logical decentralization of computing resources should be investigated in the context of links between service providers and service consumers as well as vertical and horizontal integration of the involved manufacturing processes and the supply chain [6]. It

Table 2
I4.0 properties supported by MESs.

Author	Year	Decentralization	Horizontal integration	Vertical integration	Advanced analysis and cloud computing	Connectivity, mobility and sensing	Localization
Almada [6]	2016	*					
Ayvarnam [20]	2017		*	*			
Choi [13]	2019				*	*	
Demartini [21]	2017	*			*	*	
Du [22]	2019				*		
Fernández-Caramé [14]	2018				*	*	
Gjeldum [15]	2018	*					
Kletti [23]	2015			*			
Mantravadi [17]	2019				*		
Modrák [24]	2009						*
Schnepp [12]	2017		*	*	*		
Sim [25]	2019				*		
Skrzeszewska [18]	2020				*		
Tamas [26]	2019		*				
Theuer [27]	2018		*	*			
Urbina [28]	2018					*	
Wang [19]	2018				*	*	

is important to note that in the decentralized case, every independent entity has some intelligence and is able to make decisions. In this structure, CPSs (smart products and materials) are service consumers, while CPPSs (smart equipment) are service providers. This approach is important because every product is potentially unique in the I4.0, and it would be very difficult to solve the corresponding problems using traditional centralized solutions. An MES needs contextual solution capabilities because the ever-changing dynamic marketplace – where dynamics are introduced by CPSs and CPPSs, among other factors – does not permit the creation of a unified model. In this manufacturing concept, each smart product knows its actual state, its production steps (along with all possible alternatives), its history, and its target final state, while each smart resource provides information about its actual state, its actual capacity, its maintenance needs, and its possible configurations. In practice, this means that, for example, a smart product is well aware of its current position and can ask for information from or provide information to other systems, such as the MES. In other words, while the MES is centrally located, it becomes logically decentralized.

Another essential question in the I4.0 and the next generation of the MES is the horizontal and vertical integration. **Horizontal integration** is a challenge in MES development [20] because it enables a smart supply chain whose status is always (in real-time) transparent and visible to the participants. Since new-generation MESs have a modular structure, they can be extended to play this role [23].

While **vertical integration** also presents challenges for MES development as Thomas et al. [26] point out. The main reason why the need for change is that the communication paradigm of smart products and smart resources creates new data flows, and the integration of these autonomous entities is critical to ensure efficient cooperation among the company and its (IT) systems. On the one hand, the various independent, intelligent entities must continuously obtain the data that are needed to make their decisions. On the other hand, the MES (or another system) must receive and transmit those operational data and other data of the entities. Satisfactory vertical integration of the MES (or another similar solution) is the only avenue by which the whole system can be operated as expected in the I4.0 context. Theuer [27] showed how MES can meet the new integration requirements and what the current status is with regard to the implementation of those requirements in MES solutions.

The **advanced analysis and cloud computing** is also essential functionalities of I4.0 solutions. The next generation of MESs must support or integrate these kinds of applications. The real-time analysis of the generated data will be unavoidable in future enterprise contexts. Because of the complexity of such analysis tasks, cloud computing is probably the only solution with the potential to support them. In addition to real-time analysis, advanced offline analysis is similarly critical. The importance and timeliness of this topic are illustrated by the large number of related articles that are currently being published. Through his research, Choi [13] highlighted how important advanced data analysis and modern IT solutions are for I4.0. Du [22] developed a proactive scheduling method, while Fernández-Caramés [14] used an advanced tracking solution in the ship construction process using, among other technologies, cloud computing and RFID [19]. The usage of AI and ML is also becoming increasingly important in the I4.0 paradigm. A good example of this is the work of Mantravadi [17]. Research conducted by Schneppe [12] provides a practical example of collaboration between firms and shows how important vertical integration, horizontal integration and advanced data storage and analysis techniques. Sim [25] studied the necessary components of a smart factory and presented advanced benchmarks and data analysis solutions concerning one of the most important key elements related to this topic. Skrzeszewska [18] demonstrated how important advanced data analysis is at the operational, tactical and strategic levels of management.

The properties are so far taken into account also make it clear that **connectivity, mobility and sensing** are key factors determining the success of operations in the I4.0 context [28]. Many endpoints and data sources are already present in modern manufacturing processes [19], but the number of such devices is expected to increase dramatically in the future [21].

Localization of actual workpieces and machines, at an adequate level of accuracy, is necessary for the real-time control of manufacturing operations as well as the tracking and optimization of manufacturing processes. This is because the effectiveness of new manufacturing solutions greatly depends on the synchronization of data from the production control layer. Modrák and Mandulák [24] showed that appropriate tracking and traceability of material flows significantly improve information validity and that the application of RFID technology practically eliminates the time dependence of information in ERP/MES solutions. These authors concluded that automated identification (AID) techniques influence MES functionalities and can lead to significant improvement in the rationality of the control of manufacturing processes. Due to the introduction of AID techniques and the consequent improvement in the localization of material and product flows, further research regarding the necessary changes in the concepts applied for control, scheduling, routing, tracking and monitoring is necessary [24].

The position of MES is adequate to become an important part in the modern (I4.0 ready) factory with extended functionalities. Tables 1 and 2 give examples of the research directions discussed above. One focuses the MES related research directions, where the collection of production data, tracking production, auditing/evaluation of performance, resource management, production scheduling, product definition and GUIs are the key areas. While the another concentrates the I4.0-related challenges facing MES development. In this context, decentralization, horizontal and vertical integration solutions with advanced data analysis, cloud, mobility, sensing and localization capabilities are critical.

3. I4.0-based standards, methodologies and tools for MES development

MES emerged to provide a suitable link between the enterprise-level operation and the shop floor control. A similar development happened earlier in the control of batch processes leading to the ISA-88 standard, defining a well-organized approach for batch operations. The following steps formalized the connection between the enterprise and process operations in the ISA-95 standard. Several methodologies and modelling approaches were developed to support the effective integration of the management of different levels of operations. In the followings we overview the I4.0 requirements for MES and current MES approaches and tools to highlight the necessity of new concepts.

Note that in this area expressions Cyber-Physical Production System (CPPS) and Industrial Cyber-Physical System (ICPS) are also used. According to Zhou et al. [29] CPPS are based on the 5C architecture of CPS [30] and ICPS is a service-oriented system [31], but in practice these terms are hard to distinguish [32]. In the following, the term CPPS will be used for uniformity.

Commercially available engineering tools that support CPPS technology support the automatic generation of PLC codes, human-machine interfaces (HMIs), and IoT connectivity at the levels of Software as a Service, Platform as a Service or Infrastructure as a Service [4]. Digital Twin modeling tools offer component-based modeling approaches and often real-time simulation capabilities through, e.g., OPC connections. In [4], it was concluded that the standardization and certification of these tools, their interoperability, their real-time modeling and related cybersecurity solutions need to be investigated more closely to develop and shape future systems, methods and tools. Many of the emerging new approaches are still in a preliminary phase; therefore, deeper insight into decentralization, CPPS architectures, real-time modeling tools and AID techniques is greatly desired. One of the most important issues is the need to conduct further research on possible architectures and frameworks for CPPSs to enable the standardization of such a framework and the development of suitable tools. Potential future research should lead to a standard platform of engineering tools supporting the export of related data to other engineering tools. Real-time modeling and reconfiguration solutions should also be studied and developed to permit full integration. Since modeling tools for MES/ERP solutions require a multilevel modeling approach, the challenge of validating such multilevel models will require further research attention. In these models, the uncertainties affecting their validity accumulate across multiple levels. The impact of these uncertainties should therefore be studied and considered before these models are applied in manufacturing solutions. Another issue is that multilevel modeling requires the integration of different types of models, which individually require further study [10].

The place of the MES in the plant hierarchy as well as its functions and interfaces are defined and standardized in ISA-95. This standard clearly defines the concepts required for the integration of dissimilar factory systems. The relation between the layers of an enterprise and the ISA-95 layers mapped on the activity model are depicted in Fig. 5.

The ISA-95 standard is aimed at integrating business logistics into manufacturing, increasing the effectiveness of manufacturing and making integration simpler at a lower cost. The main components and information models of this standard have been well summarized by Brandl [33,34]. The models of information exchange between the business and manufacturing operation systems, related to the activities of manufacturing operations, are defined from the following perspectives: models and terminology, object attributes, models of manufacturing operations, business-to-manufacturing transactions.

ISA-95 uses a 5-level hierarchical control model (see Fig. 5) representing business logistics, MOM, production control and production process functions. The standard considers four categories of resources (personnel, equipment, materials and energy, and process segments) and four process, product and production models (the definitions of capability and capacity, a product, a production schedule, and production performance). The formal data models represent the information exchanged between the ERP system and the MES. These models are defined using standard Unified Modeling Language (UML) and implemented as XML schema definitions using the Business To Manufacturing Markup Language (B2MML) representation [33,34].

At the enterprise level, MOM comprises the supervision of a wide range of elements from shop floor activities to management activities and involves various manufacturing operations, raw materials, recipes, maintenance, quality tests, shipping, etc. These activities should operate collaboratively under business management procedures, thus necessitating global collaborative MES functions.

Despite the availability of the ISA-95 standard, other approaches have also been developed for connecting an MES to enterprise-level management functions. Zagidullin and Frolov derived their approach from a similar multilevel representation of the production system that includes ERP functions in the top level [35]. While the ERP system is simply supposed to provide production plans, the MES is responsible for shop floor operations. Following a control-oriented scheme, these authors selected a decentralized structure with two dispatch loops. The external loop solves planning and tracking functions, while the internal loop provides MES functionality and handles the time discrepancy between production specification and actual production. The MES functions are highly subject specific, in contrast to the ERP functions, and usually can be based on complex and accurate mathematical models of planning and dispatching.

However, mere consideration of new technologies and the challenges of interoperability and reconfigurability does not guarantee support for the necessary integration of the components. These challenges are expected to be handled by a new distributed SMS model suggested by Lu et al. [36]. The ISA-95 control pyramid and the proposed smart distributed manufacturing architecture are shown in Fig. 6. The mapping between them is based on the conversion of the production-level ISA-95 components into smart entities (squares), i.e., CPSs, and high-level functionalities (circles).

Fundamental reference architectures proposed for CPS/CPPS are the Reference Architecture Model for I4.0 (RAMI4.0) and the Industrial Internet Reference Architecture (IIRA). While IIRA offers an open platform for IIoT solutions for a broad range of application domains, RAMI4.0 provides a unified solution for applying I4.0 concepts in smart manufacturing. Nevertheless, these and other models can be aligned, e.g., in the form of Industrial Internet Integrated Reference Model (I3RM) [37].

Fig. 7 shows the Reference Architecture Model for I4.0. The three main aspects of manufacturing systems are the axes: IT infrastruc-

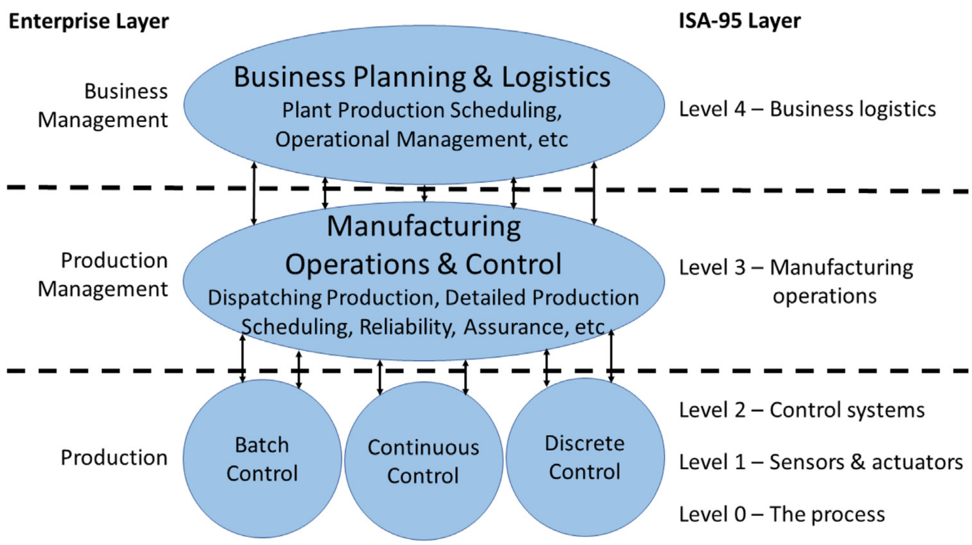

Fig. 5. ISA-95 activity model of a manufacturing enterprise (based on [1,33]).

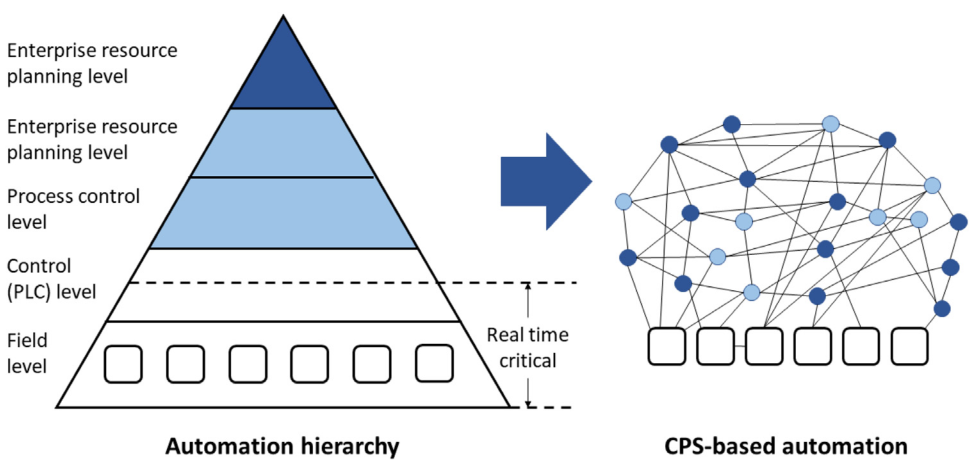

Fig. 6. Mapping of the ISA-95 control hierarchy to a distributed model [36].

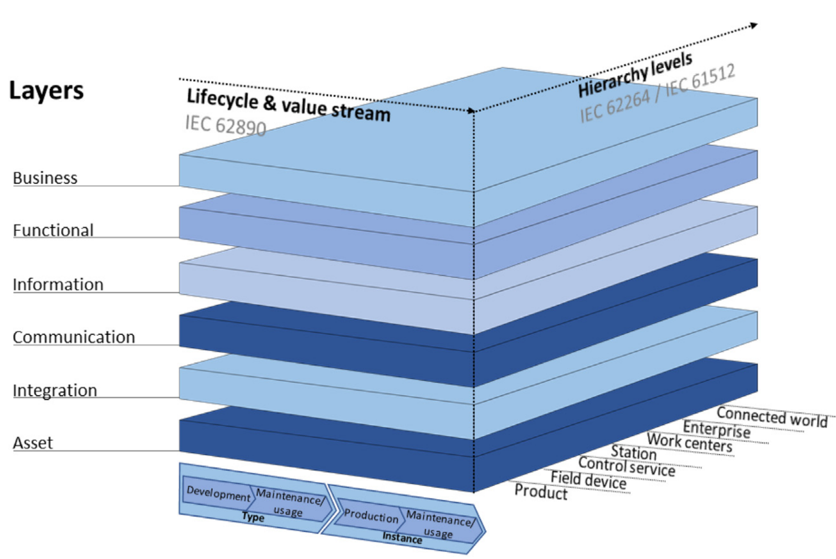

Fig. 7. I4.0 preference model [38].

ture (business, functional, communication, integration and asset layers), factory hierarchy (the physical and logical structure of the system), and SMS lifecycle (reflecting the integration and digitalization of different stakeholders).

Based on RAMI4.0, CPPSs have the following main components in a distributed manufacturing environment:

- **Controllers**: PLCs are used mostly in manufacturing automation. I4.0 requires three essential components: programs for automation, communication links and a virtual representation for the administration. In addition, other features, such as reconfigurable elements, large data storage, services, networking, interoperability, and open programming standards, should be included.
- **HMI**: The HMI is the interface for monitoring and controlling an CPPS. Furthermore, it should support various functionalities, such as automatic adaptation throughout the lifecycle, IoT protocols, smart device integration, and 3D visualization.
- **IoT connectivity**: Integrating operational technology (OT) with an IT infrastructure requires IoT technology to reach smart devices and IoS technology to provide services and IoT compatibility between IT and OT components.
- **Cybersecurity**: CPPSs involve connectivity with cloud and big data services, and consequently, many cybersecurity issues emerge (e.g., confidentiality, integrity, availability, access control and auditability).
- **Digital Twins**: To support interaction between the physical and cyber worlds, virtual modeling and simulation tools are applied in the form of Digital Twins to mimic the operation of manufacturing systems. Digital Twins assist in process planning, 3D visualization, scenario investigation and risk assessment.

Another proposal separates production-oriented functionalities (such as computer aided design and manufacturing, product data management – PDM, and MES functionalities) from ERP system functions [39]. To avoid duplication of functions while enabling the efficient integration of production and management operations, an information-oriented approach is adopted. The suggested unified information space would permit the mutual exchange of data between applications and facilitate rapid adaptation to new applications and technologies. The expected outcome is the provision of consistent information on both product and manufacturing details for all involved entities. In this sense, the PDM system lies at the center of the operations by formulating, storing and exchanging information between the MES and the ERP system. There are several possible degrees and forms of integration, from the simple exchange of suitable structured data files, to the use of Application Programming Interfaces (APIs), to the complete integration of the systems involved. While using APIs promises greater productivity, the first method offers greater flexibility. Complete integration is the most difficult to implement; however, it offers simpler handling of modifications and connections to other systems.

It is clear that ad hoc solutions are often applied for the integration of factory-wide information systems, even if these solutions rely on available manufacturing standards, such as ISA-95. Since industrial systems have become increasingly software intensive, extensive research is being conducted to support the effective interconnection of systems related to manufacturing operations and to refine methods for the system development lifecycle.

He et al. [40] presented a tool supporting the application of ISA-95 principles. They used UML to define the object models, objects and attributes covered in the standard, allowing users to implement their own specific information. The "ISA-95 Tool" is, in essence, visual operating software supporting the implementation of the involved models. The basic information carrier of this tool at all levels of the standard is an "order". An order is transferred to the manufacturing control system in B2MML form and results in the generation of a production recipe represented in the Business Process Execution Language (BPEL). The authors demonstrated the effective operation of their tool on the FASTory line, that represents operations and parts by simple drawings.

Manufacturing systems are becoming increasingly flexible with regard to both products and production processes. Smart manufacturing requires that product variants, schedules, etc., can be changed at run time. Wally et al. [41] proposed a model-driven approach for automatically transforming system specifications into a production plan by using automated planning. In their view, automated planning combines three methods to solve this problem. i) Production system engineering provides the necessary specifications by means of standard or specific modeling languages. ii) Model-driven engineering (MDE) allows the specification of discrete models and their validation and transformation. iii) Automated reasoning serves as the basis for a solver to find the sequences of production steps needed to reach initially unknown production system states or products. ISA-95 models and the applied standardized data formats and languages are well consistent with the MDE concept. There are a number of well-established tools for automated planning, such as the Planning Domain Definition Language (PDDL), which divides a planning problem into two parts: (i) a domain-specific part containing the predicates and actions and (ii) a problem-specific part defining the initial and goal states.

The method is implemented by converting the relevant ISA-95 metamodels and the instance data of these models into PDDL form. Two separate input files (ISA-95 models) describe the production system (equipment, materials, process segments, and resource connections) and the production process. After transforming these models into PDDL form, the PDDL solver generates corresponding processing sequences, which are finally transformed into ISA-95 operation elements. The application of the proposed workflow was demonstrated on a real production system designed for research purposes called the Industry 4.0 Testbed. The success of the tests proved that the proposed mapping strategy between ISA-95 and PDDL could effectively support the creation of production plans for flexible manufacturing systems.

The drive to increase the flexibility, agility, efficiency and quality of manufacturing processes also requires flexible and adaptable platforms enabling ERP/MES integration for extended enterprises. To improve the integration of the business and manufacturing layers, Prades et al. [42] proposed a methodology in which process models using Business Process Modeling Notation (BPMN) are applied based on the ISA-95 standard. In the case of extended enterprises, i.e., multiple companies sharing resources and services, the collaborative environment makes integration especially important. The BPMN process modeling technique allows workflows to be defined in a flexible way and facilitates their automated execution while providing a comprehensive model (informational, functional and behavioral). The graphical notation supports effective workflow modeling, and the resulting models can be translated into BPEL for execution. The proposed framework starts with a partial model of the production process that serves as a conceptual reference model and describes the activities and information flows defined in ISA-95. The sequence of activities, i.e., the temporal view of execution, is modeled using UML sequence diagrams. The activities, objects and messaging sequences are then modeled using BPMN. The particular models are developed after a detailed analysis of the involved company-related elements by adapting the sequence diagrams and BPMN models. Finally, the model is modified based on emerging new aspects and lessons learned. The proposed methodology facilitates integration in a distributed manufacturing environment through a unified framework

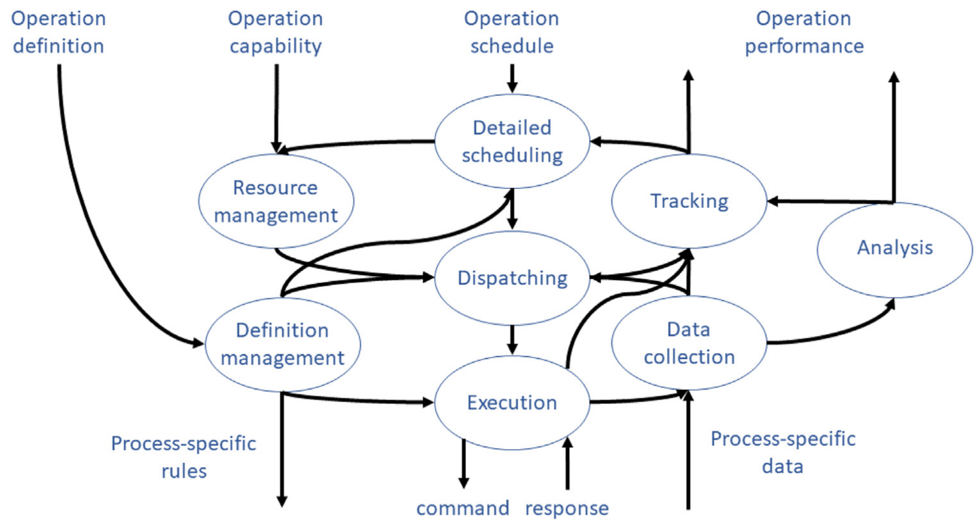

Fig. 8. Generic activity model for MOM [43].

combining BPMN models with other complementary modeling techniques.

User requirement specifications (URSs) are intended to provide a clear and formal description of the functionalities of MESs in a user-oriented approach. A well-composed URS can greatly enhance and facilitate communication between users and MES vendors/integrators. Standardizing the process of defining URSs for MESs can therefore help every partner to build successful manufacturing systems. Since the ISA-95 standard clarifies the boundaries between shop floor and office floor systems as well as the functions to be covered by an MES, it provides a sound basis for developing methodologies for this process. Yue et al. [43] elaborated and proposed a framework for handling the MES problem space, the steps of authoring a URS and the structure of URS documentation. In their representation, the URS describes the user's expectations in terms of functions, performance, constraints, etc., and serves as the input for the subsequent definition and development of the functions and features of the target software system. This input information is extracted by applying "to-be" analysis of the requirements and enables the compilation of a documented functional specification. The proposed methodology for URS definition has several main stages. The first is the construction of the problem space, which includes the core MOM categories (production, maintenance, quality testing, and inventory movement), supporting activities (management of information, configuration, incidents and deviations, security, documentation, and compliance) and the generic activity model. The definition of the generic activity model covers daily production management in terms of both business management and work execution (see Fig. 8).

The types of activities differ in their relation to time; they include time-independent reference data activities as well as time-dependent prework, actual work and postwork activities, executed sequentially. The reference data for the MES are determined on the basis of the ISA-95 object model of resources (materials, personnel, equipment, physical assets, and process segments). A time-based view of the generic activity model is presented in Fig. 9.

The next step is the determination of the system boundaries, from which are derived five activity categories (operation management for production, maintenance, quality, inventory and support activities). The system boundaries basically depend on what activities are to be supported by the MES; therefore, they may depend on either the industry or the plant. In the domain framework, a 3D problem space is established, as described before. The three dimensions represent different aspects of MOM, and each functional MES requirement is expressed with respect to these dimensions. Based on the problem space, the requirement definitions are derived by considering certain scenarios. The requirement definition language can be nonformal, semiformal, or formal. The authors suggest using the semiformal approach since it eliminates ambiguity while allowing comprehensibility and usability to be maintained. The elements of the requirements are then handled as goal-scenario tuples. The elicitation of the URS definition starts with an As-Is/To-Be analysis based on the actual business and execution management practices and leads to the setting of goals and the planning of future MES functions. The proposed methodology relies on a guideline system and reference practices, as depicted in Fig. 10.

Further steps of research and development should focus on the modeling of production performance and the validation of these models based on shop floor data. Another point to be noted is that in addition to application specialists (providers and engineers), managers should also be treated as users, and corresponding usability needs should be met. This can be achieved by, e.g., transforming B2MML information into the form of simple Excel tables [40].

Since smart manufacturing in flexible systems requires that product variants, schedules, etc., can be changed at run time, meaning that planning must be performed dynamically. Consequently future research regarding ISA-95 mapping for automated planning should consider temporal specifications and allow for the parallelization of production tasks [41].

In response to the introduction of SMSs, Yue et al. [43] suggested paying more attention to emerging information and communication technologies in the implementation of MESs as well as updating and supplementing the ISA-95 standard with models of operation management events.

As conclusion of the overview presented in this section we can state that standardization of tools and methods is a key for smart manufacturing solutions. Still a solid standard platform of engineering tools supporting MES development and application is missing, especially considering real-time and multilevel modelling as well as reconfiguration problems. Current methodologies and tools do work well in practice, however I4.0 concepts and CPPS solutions are weakly supported. There is a clear demand to bridge these gaps by introducing suitable new development approaches like ontology-driven MES development.

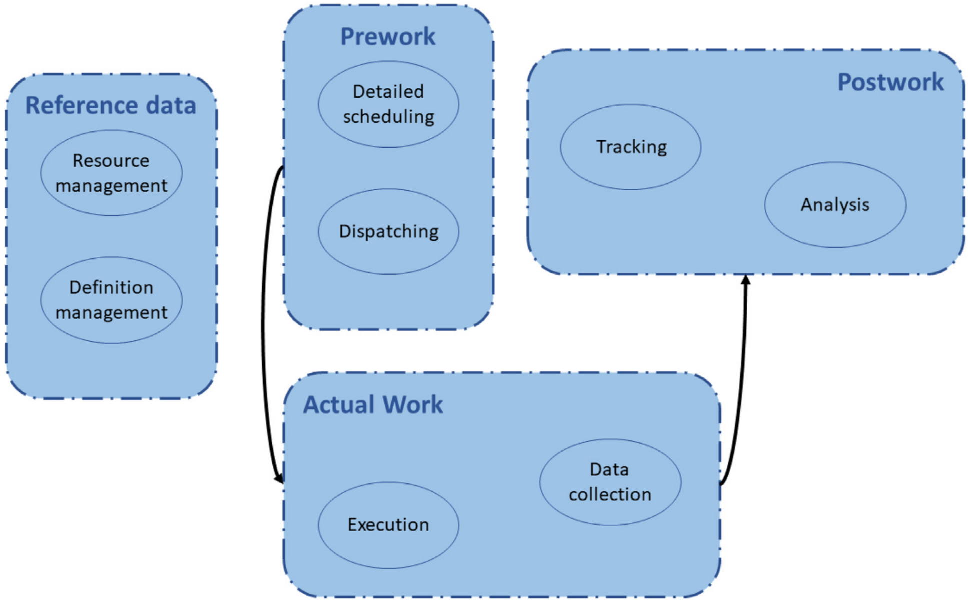

Fig. 9. Temporal view of the generic activity model [43].

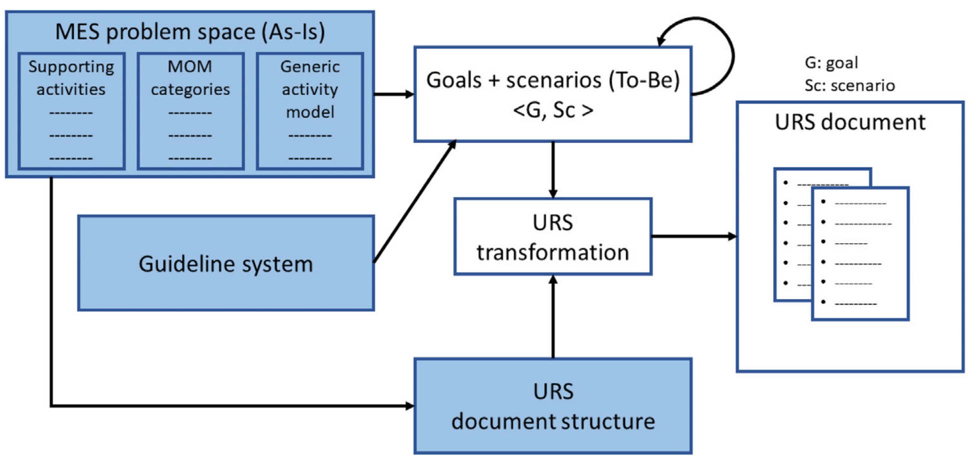

Fig. 10. Proposed methodology for defining an MES URS [43].

4. Ontologies and semantic models applicable for MES development

As it has been summarized in the previous chapter, the currently used software development methodologies and standards lack efficient tools to develop an MES, which fulfills all requirements of the Industry 4.0 concept. Among the newest approaches the most promising method is the ontology-driven software engineering for this work. The aim of this section is to highlight the importance of recent and future research in this field.

Traditionally, an MES software is developed in accordance with the waterfall model. This means that software development is separated into the following steps: requirement analysis, system analysis, software design, software implementation, software testing and software maintenance. Because MES software is quite complex, however, the traditional development method is difficult to apply and may cause many problems, such as a long development period, high cost, low reliability and weak integration ability. To overcome these difficulties, a component-based, ontology-driven MES development methodology can be used [44]. This methodology has three major phases: MES ontology engineering with the Web Ontology Language (OWL), ontology-driven MES domain engineering and ontology-driven MES application engineering. The component-based, ontology-driven MES development flow is illustrated in Fig. 11. As this figure shows, ontologies may play an important role in the development and application of MESs.

4.1. Semantic models and ontologies

Semantic models have proven to be useful in domains that intensively rely on information and automation technologies. Ontologies may support intraorganizational and interorganizational integration of different domains, functions, layers and processes [45]. Manufacturing is one such domain, in which technologies such as ontologies, semantics and the Semantic Web may be used to support collaboration and interoperability. In smart manufacturing, both horizontal and vertical interoperability exist among the activities of the production system lifecycle. Interoperability means that information is exchanged among activities based on information models. Information models organize data from a knowledge perspective and enable a common understanding and representation among different model consumers. Data models provide generic descriptions of data with certain syn-

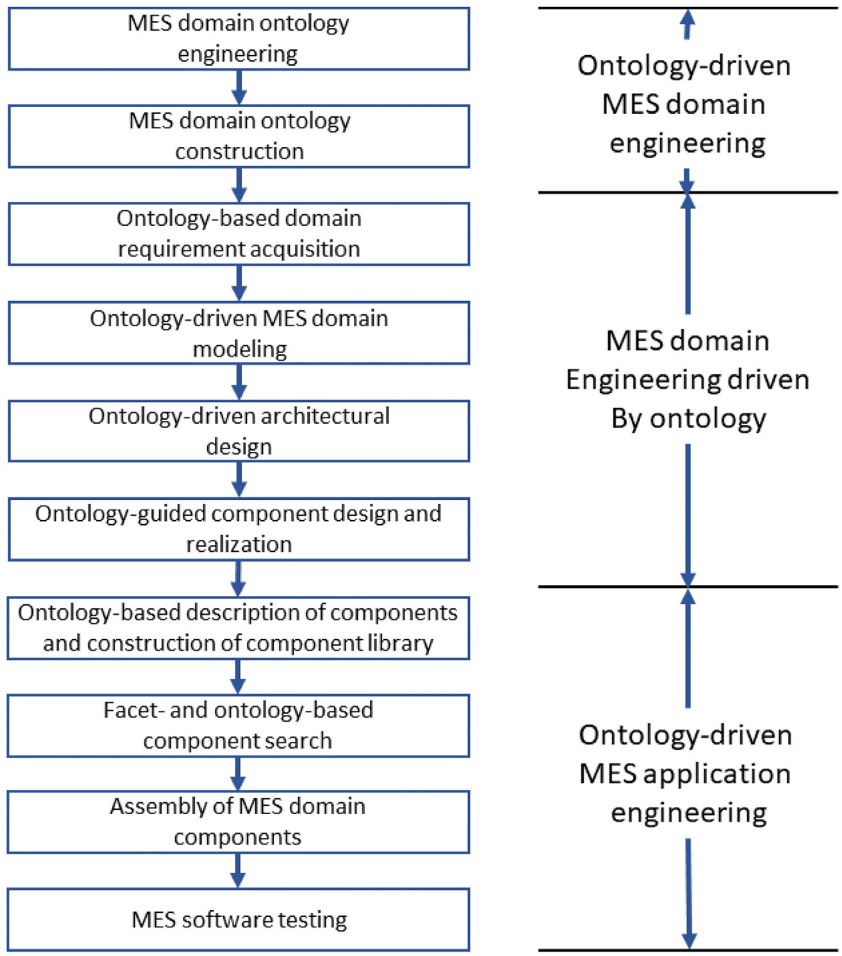

Fig. 11. Component-based, ontology-driven MES development flow [44].

tax and semantics. Ontologies represent an extension of generic data models. They enable the use of domain-specific concepts and introduce semantics into the modeled data. Ontologies include concepts, relations, properties, and axioms and define possible constraints on the use of those concepts. In practice, ontologies can be either simple or complex, with several thousands of terms. The complexity of an ontology depends on the corresponding application domain. The World Wide Web Consortium offers several techniques for representing ontologies in a standard format. The most commonly used formats are the Resource Definition Framework and OWL. The next subsection gives an overview of how different MES ontologies can support the I4.0 readiness of MESs.

4.2. I4.0 requirements supported by ontologies

The I4.0 requirements for MESs are discussed in Chapter 2. These requirements can be addressed from various perspectives. This subsection discusses how visibility, transparency, modularity, predictive capability, adaptability and interoperability can be supported using ontologies. Table 3 summarizes how the various studies reviewed here address the I4.0 requirements for MESs. Notably, most of the reviewed articles focus on certain narrow or specific aspects of the industrial domain. Furthermore, the elaborated ontologies have been developed independently of each other; thus, they are incoherent and incompatible. They cannot be merged and applied together and are not applicable to meet connected information goals.

Visibility: An MES ontology is a formal specification of concepts in the MES domain. It plays an important role in the development and application of an MES by providing concepts, relations, properties and instances. An MES ontology is usually described and represented with OWL [63].

The representation of MES domain knowledge can be improved using several methods. One method is ontology-driven MES domain analysis. This method has proven to be useful for improving the level of standardization of MES domain knowledge representation [61]. Another method is component-based MES development [59]. Component-based development means that the reuse of technology for software components is introduced into the domain ontology model. A critical requirement for this development approach is the ability to retrieve the appropriate components from a domain ontology with high retrieval efficiency and performance [60].

In addition to the above methods, the international standard ISA-95 provides consistent terminology, information and operations models for clarifying application functionality and the use of information. On the basis of this standard, various specific ontologies supporting the development and integration of enterprise information systems at different enterprise levels may be generated. This framework makes it possible to integrate a core metaontology constructed following the ISA-95 model with various domain-specific ontologies that provide specific information for a given enterprise [50].

To achieve context awareness and provide added-value information to improve operational performance and monitoring, the

Table 3
Ontologies supporting I4.0 requirements.

Author	Year	Visibility	Transparency	Modularity	Predictive capability	Adaptability	Interoperability
Arab-Mansour [46]	2017						*
Bayar [47]	2016				*		
Block [48]	2018					*	
Chen [49]	2008	*					
Dobrev [50]	2008	*					
Ferrer [51]	2015				*		
Fumagalli [52]	2014		*				
Gellrich [53]	2012		*				
Giustozzi [54]	2018	*					
Iarovyi [55]	2015		*				
J”arvenp”a”a [56]	2019			*			
Joglekar [57]	2005	*					
Liu [58]	2013						*
Long [59]	2009	*					
Long [60]	2009	*					
Long [61]	2010	*					
Long [44]	2010	*					
Treytl [62]	2007		*				
Wen [63]	2008	*					
Xu [64]	2015		*				
Yue [65]	2018		*				

execution of industrial processes should depend not only on their internal states and on user interactions but also on the context of their execution. Context awareness is the capability of a system to gather information about its context or environment at any given time and to adapt its behaviors accordingly by means of suitable services. To develop a context-aware MES, a rule-based framework can be used that aims to maximize the automation of the complete production lifecycle via the establishment of a flexible prototype of a context ontology for the workshop [49]. An ontology-based context model for different industries can also be introduced [54]. This model facilitates context representation and reasoning by providing structures for context-related concepts and rules as well as their semantics.

A recipe description is a block of information used in a batch process. Two related standards have evolved for formally representing recipe information: general recipes and master recipes. Master recipes have achieved wider acceptance for batch processing in industry. In contrast, the development of a general recipe standard was lacking for a long time. However, an ontology-based representation of the concepts described in the general recipe standard has now been presented using OWL [57].

Transparency: A batch recording system (BRS) is a system that electronically controls and reviews manufacturing processes. At the end of a manufacturing process, it provides a record that details everything that happened during the production of the batch. A flexible hybrid ISA-95 and ISA-88 architecture is suitable for implementing an electronic BRS for the life science industry. In this model, MOM activities are modeled using an activity ontology. Physical activities are specified by means of a scenario-based semantic structure. Scenario authorization is performed using a linguistics-based approach [65].

Agent-based systems enable flexible vertical integration for distributed plant automation. The agents autonomously fulfill their tasks, allowing the manufacturing process to more rapidly adapt to product or production variations. In such a distributed architecture, interoperability is a key issue. Ferrarini et al. [66] proposed the PABADIS'PROMISE (P2) architecture, which provides an agent-based system for a three-level automation pyramid including ERP, an MES and field control. To provide a common understanding among the different entities involved in the system, an ontology covering concepts for the description of products, production processes and resources is defined, called the P2 Ontology. Semantic interoperability is ensured by the P2 Ontology. The P2 Product and Production Process Description Language (P5DL) extends P2 by defining the format of the information used in a P2 system [62], thus solving the problem of technical interoperability, i.e., the layer of data syntax. Consequently, P5DL can be regarded as a representation-independent approach that comprises the following two core concepts: (i) a set of representation languages that conform to the same ontology, (ii) a set of transformations among these representation languages.

A multiple ontology workspace management system provides the user with his or her own ontology workspace as a repository [64]. The aim is to facilitate the storage and manipulation of ontology models for knowledge-driven MESs by allowing ontologies for different manufacturing systems to be separately maintained and queried.

The eScop project has defined the concept of an open knowledge-driven MES, which is a representation of a real-world manufacturing system in a knowledge base. The central concept of eScop is to combine the power of embedded systems with an ontology-driven service-based architecture for the realization of a fully open automated manufacturing environment [52].

One of the main characteristics of manufacturing systems is the wide variety of possible configurations. This makes it difficult to easily adapt and reconfigure the control of advanced manufacturing systems. Knowledge on the physical and logical structures encountered in the domain is required. If this knowledge is stored in the machine control systems, easy reconfigurability and interoperability are not possible. To overcome this challenge, an ontology can be used as a dynamic knowledge base to control the shop floor. Not only are the static aspects of the manufacturing system described by the ontology, but the ontology is also used as a tool that is responsible for the control of the system. The mapping of data from service descriptions to the ontology is automated [55].

Rule-based components are very common in MESs. Rule-based systems present the challenge of maintaining possibly large rule sets that accumulate over the years of a factory's lifetime. Such rule sets may contain up to several tens of thousands of rules operating on the basis of hundreds of different criteria. The capability of automated reasoning on rule sets allows the development of useful validation schemes to cope with the corresponding maintenance challenges. Automated reasoning is performed by modeling the master data and rules of the factory as ontologies represented in the Description Logic subset of OWL [53].

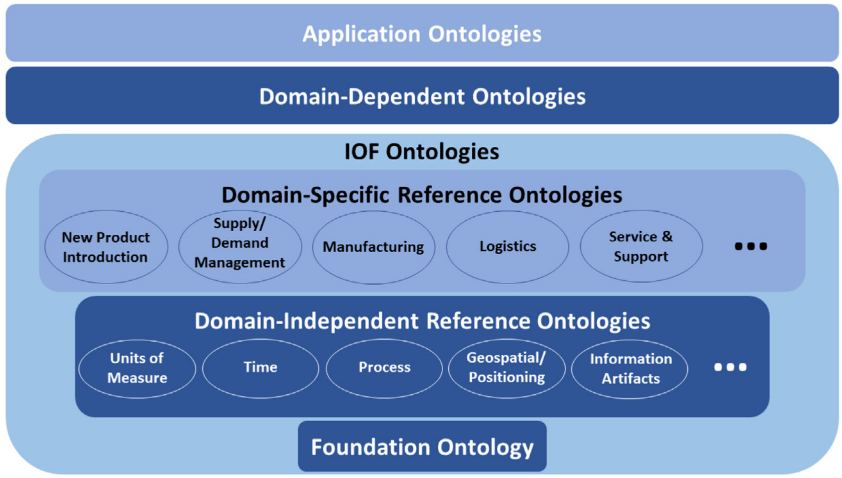

Fig. 12. Architecture of the IOF ontologies [68].

Modularity: To achieve adaptive, rapidly responsive production, system reconfigurability is a key issue. A modular architecture for production systems aims to promote system reconfigurability through the interchangeability of resources and components. The automation of reconfiguration decision making requires a formal resource model that describes the capabilities, e.g., functionalities, properties and constraints of manufacturing resources. The OWL-based Manufacturing Resource Capability Ontology (MaRCO) [56] supports the representation of and automatic inference on combined capabilities based on representations of the simple capabilities of cooperating resources.

Predictive capacity: Manufacturing systems are subject to several kinds of disruptions and risks. Disruptions break the continuity of workflows and prevent a production system from reaching its expected level of performance. To monitor disruptions and risks in manufacturing systems, a knowledge-based approach involving functions dedicated to dealing with disruptions and risk detection can be used to identify the consequences of and reactions to disruptions. A prototype implementation based on ontologies and multiagent systems has demonstrated the relevance of this approach in monitoring disruptions and risks [47].

Complex event processing (CEP) is the monitoring of streams of events to identify and analyze the cause-and-effect relationships among events in real time. CEP can be used to predict the future behavior of a manufacturing system and to react ahead of events that will reduce the efficiency of production. The use of knowledge representations in ontologies permits the description of the system status in knowledge bases, which can be queried and updated at run time. SPARQL extension languages can be used for processing and reasoning based on streams of events in knowledge-driven MESs [51].

Adaptability: Short-term production planning and control (PPC) is of great importance due to decreasing batch sizes (customized products). The corresponding planning process is complex. It requires real-time information, the acquisition of which is supported by new technologies. An approach for event-driven PPC has been proposed on the basis of a manufacturing ontology, simulation and optimization [48]. Valid PPC input data are generated via the simulation of future processes. The ontology is used for the construction of simulation models to map manufacturing processes.

Interoperability: Heterogeneous enterprise applications, at either the business or the manufacturing level, either within a single enterprise or among networked enterprises, need to share information and cooperate in order to optimize their performance. This information may be stored, processed and communicated in different ways by different applications. The problem of managing heterogeneous information coming from different systems is referred to as the interoperability problem. Interoperability issues may be addressed by means of ontologies that capture the semantics necessary to ensure interoperability.

"MES On Demand" is a platform launched by a consortium of manufacturing software publishers. It uses services from various packages, including MES services and supply chain execution services. Usually, aligning two structures means that for each entity in the first structure, an attempt is made to find a corresponding entity with the same meaning in the second structure. In contrast to approaches that seek complete and generic alignment, a semantic alignment process for repositories is used in the construction of an MES solution for "MES On Demand" [46]. Semantic alignment involves neither modifying the structure of one of the repositories nor merging them. Instead, a new version Vi+1 of a given business repository Vi, regarded asof a given business repository Vi, regarded as the reference repository, is created by adding several elements or semantic relationships from a second business repository, depending on the level of granularity or consistency.

For MESs with distributed architectures, information integration and access control are of great importance. Access control is the process of mediating every request for access to the resources and data maintained by a system and determining whether the request should be granted or denied. Traditional access control and security administration models present various problems and impose certain constraints in environments where the available authorization-related information is imprecise. The Fuzzy Trustworthiness-involved Role Based Access Control model is adequate for implementing fine-grained security management and access control for MESs [58].

4.3. Summary of the development of MES-relevant ontologies and semantic models

Ontologies for industrial problems have been a research topic for several years. This chapter showed that many different ontologies have been developed in the industrial manufacturing domain. As mentioned before, these ontologies focus on specific characteristics of the manufacturing processes and they are incompatible. Ontologies can be regarded as the next generation of standards for connected information. The standardization of information models is one of the most relevant research topics in the field of smart manufacturing [67]. To overcome the problem of incompatible ontologies, the Industrial Ontologies Foundry (IOF) (https://www.industrialontologies.org/) was formed with the goal of creating a set of open core reference ontologies that span the entire domain of digital manufacturing [68]. Because the scope of the IOF project is quite large, it has been proposed that multiple layers of ontologies should be provided, with the upper layers making use of the lower layers. As Fig. 12 shows not all of these layers will be maintained under the auspices of the IOF. Organizations must extend the IOF ontologies to specific subdomains and applications that are relevant to them. If the commonality among these ontologies can be maintained, then long-term interoperability among the different engineering, manufacturing, and supply chain disciplines will be better served. The effort of developing ontologies for new areas will be reduced through the ability to add to already existing work rather than starting anew. It will be possible to develop new ontologies that are more robust and reliable by building on existing foundations.

5. Conclusions

In this work, we have presented how the new concepts, tools and requirements of Industry 4.0 (I4.0) solutions will influence the functionalities of manufacturing execution systems (MESs) and how these trends will determine the development of the next generation of these systems. In this systematic and thematic review, we have provided a detailed analysis of the I4.0-related requirements for MES development and an overview of MES development methods and standards. We have highlighted that MESs should interconnect all components of cyber-physical systems in a seamless, secure, and trustworthy manner to enable high-level automated smart solutions and that semantic metadata can provide contextual information to support interoperability and modular development.

The observed trends show that in the future, formal models and ontologies will play an even more essential role in I4.0 systems as interoperability becomes more of a focus and that the new generation of linkable data sources should be based on semantically enriched information.

The presented overview can serve as a guide for engineers interested in the development of MESs as well as for researchers interested in finding worthwhile areas of research. The paper focused on issues which the developers of MESs have to be aware, especially industry standards, methodologies, and the semantic models.

The limitations of this review arise from its focused perspective, as it focuses only on MES-related issues arising in the exponentially developing area of I4.0. The new algorithms that have been developed to support the extraction of information from MES data are not discussed because these and other results from the rapidly developing fields of semantic data analysis, big data, and linked data deserve their own review.

Abbreviations

The following abbreviations are used in this manuscript:AIartificial intelligenceAIDautomated identificationAPIapplication programming interfaceB2MMLbusiness to manufacturing markup languageBPELbusiness process execution languageBPMNbusiness process modeling notationBRSbatch recording systemCEPcomplex event processingCPScyber-physical systemCPPScyber-physical production systemCRMcustomer relationship managementERPenterprise resource planningGUIgraphical user interfaceHMIhuman–machine interfaceI4.0Industry 4.0ICPSIndustrial cyber-physical systemIOFIndustrial ontologies foundryIoTInternet of thingsIoSInternet of servicesIIoTindustrial internet of thingsMDEmodel-driven engineeringMESmanufacturing execution systemMLmachine learningMOMmanufacturing operations managementOToperational technologyOWLweb ontology languagePDDLplanning domain definition languagePDMproduct data managementPLCprogrammable logic controllerPLMproduct lifecycle managementPPCproduction planning and controlRAMI4.0reference architecture model for Industry 4.0RFIDradio frequency identificationSCADAsupervisory control and data acquisitionSMSsmart manufacturing systemSRMsupplier relationship managementUMLunified modeling languageURSuser requirement specificationsXMLextensible markup language

AI	artificial intelligence
AID	automated identification
API	application programming interface
B2MML	business to manufacturing markup language
BPEL	business process execution language
BPMN	business process modeling notation
BRS	batch recording system
CEP	complex event processing
CPS	cyber-physical system
CPPS	cyber-physical production system
CRM	customer relationship management
ERP	enterprise resource planning
GUI	graphical user interface
HMI	human–machine interface
I4.0	Industry 4.0
ICPS	Industrial cyber-physical system
IOF	Industrial ontologies foundry
IoT	Internet of things
IoS	Internet of services
IIoT	industrial internet of things
MDE	model-driven engineering
MES	manufacturing execution system
ML	machine learning
MOM	manufacturing operations management
OT	operational technology
OWL	web ontology language
PDDL	planning domain definition language
PDM	product data management
PLC	programmable logic controller
PLM	product lifecycle management
PPC	production planning and control
RAMI4.0	reference architecture model for Industry 4.0
RFID	radio frequency identification
SCADA	supervisory control and data acquisition
SMS	smart manufacturing system
SRM	supplier relationship management
UML	unified modeling language
URS	user requirement specifications
XML	extensible markup language

Declaration of Competing Interest

The authors report no declarations of interest.

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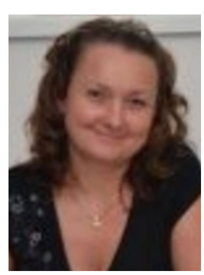

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