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# Recent Advancements in Smart Manufacturing Technology for Modern Industrial Revolution: A Survey

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## Abstract

Smart manufacturing (SM) or Industry 4.0 is a term generally applied to the improvement in manufacturing operations through integration of systems, linking of physical and cyber capabilities, and taking advantage of information including leveraging the big data evolution. SM adoption has been occurring unevenly across industries, thus there is an opportunity to look to other industries to determine solution and roadmap paths for industries such as biochemistry or biology. In this paper, we analyzed evaluation in smart manufacturing systems based on modern industrial revolution. Since, Industry 4.0 holds the promise of increased flexibility in manufacturing, along with mass customization, better quality, and improved productivity. It thus enables companies to cope with the challenges of producing increasingly individualized products with a short lead-time to market and higher quality. Intelligent manufacturing plays an important role in Industry 4.0. Moreover, we review key technologies for information and communications technology (ICT) that are used to enable intelligent manufacturing. Also, the major key technologies related to smart Manufacturing were identified through the analysis of the policies and technology roadmaps of Germany, China and the U.S for smart manufacturing. In addition, we answered the three-key question in this paper. First, how small and medium enterprises (SMEs) are build and setting-up from conventional manufacturing practices to the smart manufacturing/Industry 4.0? Second, comparative analysis of the key architectures adopted for the Industry 4.0. Third, review, select and suggest the standards from the pool of standard bodies for Industry 4.0. Finally, we present current challenges and future research directions. The concepts discussed in this paper will spark new ideas in the effort to realize the much-anticipated Fourth Industrial Revolution.

**Keywords:** Smart Manufacturing, Industrial Revolution, Cyber-Physical Systems, Modern Technology

## 1. Introduction

Cyber Physical Systems (CPS) and sensor world has entirely revolutionized the world from the traditional business/manufacturing tricks and tools to the modern digital industrial techniques to facilitate every corner of the world. In the mean-time with the progress of world trade and globalization, and the development of information & communication technology (ICT) and industrial technology, manufacturing pattern and technology are facing a turning point. Lots of developed or developing countries published their national strategies to support their economic transformation, which include, integration of Industrialization & Informatization (iI&I) and Manufacturing 2025 of China, Industry4.0 of Germany, re-industrialization and industrial internet of US. Industry 4.0, a German strategic initiative, is aimed at creating intelligent factories where manufacturing technologies are upgraded and transformed by cyber-physical systems (CPSs), the Internet of Things (IoT), and cloud computing (Lee, Bagheri, and Kao 2015). In the Industry 4.0 era, manufacturing systems are able to monitor physical processes, create a so-called “digital twin” (or “cyber twin”) of the physical world, and make smart decisions through real-time communication and cooperation with humans, machines, sensors, and so forth (Shah et al. 2018). Industry 4.0 combines embedded production system technologies with intelligent production processes to pave the way for a new technological age that will fundamentally transform industry value chains, production value chains, and business models.

Cyber-Physical Systems (CPS) is defined as transformative technologies for managing interconnected systems between its physical assets and computational capabilities (Thoben, Wiesner, and Wuest 2017). With recent

developments that have resulted in higher availability and affordability of sensors, data acquisition systems and computer networks, the competitive nature of today's industry forces more factories to move toward implementing high-tech methodologies. Consequently, the ever-growing use of sensors and networked machines has resulted in the continuous generation of high-volume data which is known as Big Data (Lidong and Guanghui 2016). In such an environment, CPS can be further developed for managing Big Data and leveraging the interconnectivity of machines to reach the goal of intelligent, resilient and self-adaptable machines. Furthermore, by integrating CPS with production, logistics and services in the current industrial practices, it would transform today's factories into an Industry 4.0 factory with significant economic potential (Lee, Bagheri, and Kao 2015). For instance, a joint report by the Fraunhofer Institute and the industry association Bitkom said that German gross value can be boosted by a cumulative 267 billion euros by 2025 after introducing Industry 4.0 (Lars Adolph, Bundesanstalt, n.d.)(Frank, Dalenogare, and Ayala 2019). A brief comparison between current and Industry 4.0 factories is presented in Table 1 (Lee, Bagheri, and Kao 2015; Carvalho et al. 2018). Since CPS is in the initial stage of development, it is essential to clearly define the structure and methodology of CPS as guidelines for its implementation in industry. To meet such a demand, a unified system framework has been designed for general applications. Furthermore, corresponding algorithms and technologies at each system layer are also proposed to collaborate with the unified structure and realize the desired functionalities of the overall system for enhanced equipment efficiency, reliability and product quality (Lee, Bagheri, and Kao 2015).

The goals of Industry 4.0 are to achieve a higher level of operational efficiency and productivity, as well as a higher level of automation (Ahmadi et al. 2019). The five major features of Industry 4.0 are digitization, optimization, and customization of production; automation and adaptation; human machine interaction (HMI); value-added services and businesses, and automatic data exchange and communication (Gürdür et al. 2016). These features not only are highly correlated with internet technologies and advanced algorithms, but they also indicate that Industry 4.0 is an industrial process of value adding and knowledge management. Despite of the dynamic nature of the research on Industry 4.0, however, a systematic and extensive review of recent research on Industry 4.0 is not available. Accordingly, this paper conducts a comprehensive review on of Industry 4.0 and presents an overview of the content, scope, and findings of Industry 4.0 by examining existing literatures.

The rest of the paper is structured as follows: section 2 and 3 presents the detailed related work. Section 4 includes industry 4.0 applications in manufacturing systems. Section 5 presents the existing reference architectures of Industry 4.0. Global trends in future manufacturing technologies is discussed in Section 6. Standards at Different Layers of the Smart Manufacturing Ecosystem is presented in section 7. Challenges and directions for future research are introduced in Section 8. Section 9 concludes this paper.

## 2. Related Work Methodology

This section presents the methodology that we used to retrieve relevant related studies of Industry 4.0, Industry 4.0 architecture, Industry 4.0 standardization and future research direction of Industry 4.0. Due to the high volume of available papers in the three scientific databases we use (Google scholar, IEEE, and Web of Science), and our interest in recent technological paradigm shifts in manufacturing, we focused on keywords related to CPS, Industry 4.0 (Smart Manufacturing), and standardization. The research in this area is receiving attention from researchers who are exponentially increasing. Most research was conducted in 2016 and 2018. Table 1 shows the number of papers for each keyword in each considered database. Between 2010 and 2019, the topic which triggered the most interest is Smart Manufacturing with a total of 581,108 papers. The second one is CPS with a total of papers of 33,782. Standardization is in the third position with 12,490 papers. Those results are consistent with the fact that Smart Manufacturing is a more general topic than CPS or standardization that is more specific. Furthermore, CPS and standardization are part of Smart Manufacturing.

Table 1. Numbers of papers per-database and keyword from 2010 to 2019

Keywords	Google Scholar	IEEE	Web of Science
CPS	17,300	8,769	7,713
Smart Manufacturing	576,000	1,467	3,641
Standardization	7,410	4,611	469

However, there is a huge number of papers related to the three studied topics. We have to refine the search in order to eliminate the less relevant ones. To that end, we focused on CPS application, and standards application, more specifically on CPS for Smart Manufacturing, standards for CPS, and standards for Smart Manufacturing. After applying this filter, 615 papers remained. This set of papers is then subjected to an evaluation process. The goal of this process is to keep only the papers whose content is fully relevant regarding our concern. The process consists of three steps. At each step we apply a filter based on some specific criteria. The first step is based on a language filter. It aims to remove non-English papers. The second and third steps are based on the content. In the second step, we focus on abstracts while in the third one, we focus on the core of the paper.

Those two steps aim to keep papers that are completely relevant to our work. From the 615 initial papers, 269 have been eliminated during the first step, 155 have been eliminated from the second step, and 151 have been eliminated when applying the third and last step. The 40 papers remaining at the end are studied in the state of the art. The evaluation process is represented in Figure 1.

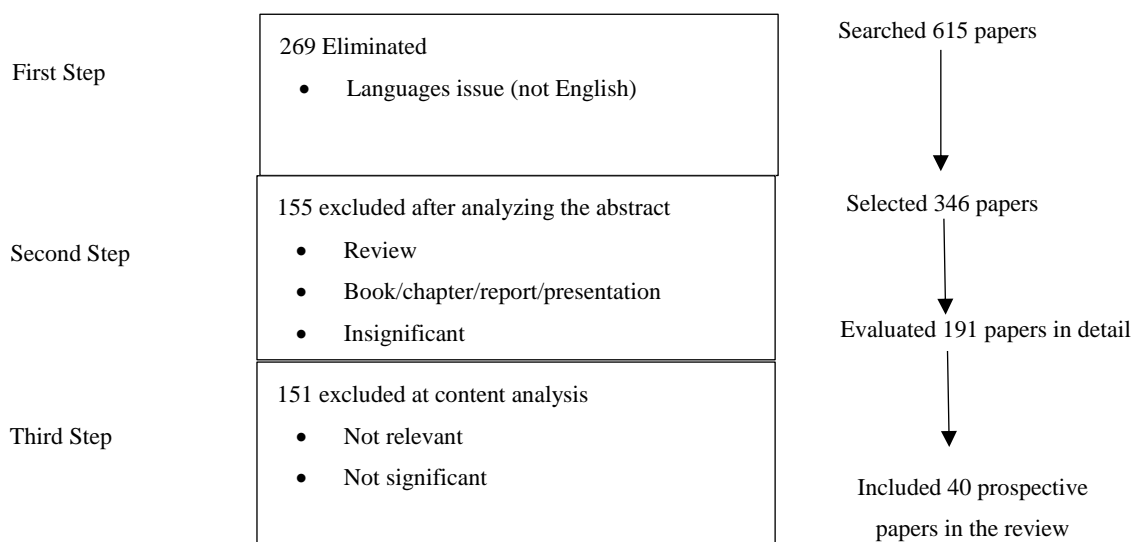


Figure 1. Review Methodology Steps

### 3. Related Work

Several researchers have worked on the Industry 4.0 its role and importance in today's emerging world. But very few talked about the coordination between very well-known CPS architectures for Industry 4.0 and standards at the common platform. Some related works are described below.

In the context of Industry4.0, manufacturing systems are updated to an intelligent level. Intelligent manufacturing takes advantage of advanced information and manufacturing technologies to achieve flexible, smart, and reconfigurable manufacturing processes in order to address a dynamic and global market (Zhong et al. 2017). It enables all physical processes and information flows to be available when and where they are needed across holistic manufacturing supply chains, multiple industries, small and medium-sized enterprises (SMEs), and large companies (Wan et al. 2017). Intelligent manufacturing requires certain underpinning technologies in order to enable devices or machines to vary their behaviors in response to different situations and requirements based on past experiences and learning capacities (Fang et al. 2016). These technologies enable direct communication with manufacturing systems, thereby allowing problems to be solved and adaptive decisions to be made in a timely fashion.

Modern industry industrial development has lasted for several hundred years and has now the era of Industry 4.0 come. The concept of Industry 4.0 was initially proposed for developing German economy in 2011 (Yang Lu 2017)(Ahmadi et al. 2019). The first industrial revolution begins began at the end of the 18th century and is was represented by mechanical production plants based on water and steam power; the second industrial revolution starts started at the beginning of the 20th century with the symbol of mass labor production based on electrical energy; the third industrial revolution begins began in the 1970s with the characteristic of automatic production

based on electronics and internet technology; and right now, the fourth industrial revolution, namely Industry 4.0, is ongoing, with the characteristics of CPS production, based on heterogeneous data and knowledge integration. The main roles of CPS are to fulfill the agile and dynamic requirements of production, and to improve the effectiveness and efficiency of the entire industry. Industry 4.0 encompasses numerous technologies and associated paradigms, including Radio Frequency Identification (RFID), Enterprise Resource Planning (ERP), Internet of Things (IoT), cloud-based manufacturing, and social product development (Manufacturing and Modeling 2018)(Jiang 2018)(Yang Lu 2017).

After extensive analysis of the orthodox manufacturing methods it is analysed and observed that there is a dire need to answer the three key questions for instance, First, how small and medium enterprises (SMEs) are build and setting-up from conventional manufacturing practices to the smart manufacturing/Industry 4.0? Second, comparative analysis of the key architectures adopted for the Industry 4.0. Third, review, select and suggest the standards from the pool of standard bodies for Industry 4.0 for improving the business and industrial world. Besides, after entertaining these highly demanding queries it can be guaranteed that industrial/manufacturing world will change the landscape of the entire globe.

The traditional manufacturing methods are compared with the state-of-the art methods, technologies and tools as shown in the Table 2. In addition, various entities, data sources, performance metrics and technologies are presented with the extensive detail to portray the clear image and importance of the digital manufacturing in association to the conventional tools and techniques.

Table 2. Comparison between Traditional Manufacturing and Industry 4.0

Entity	Data Source	Traditional	Manufacturing	Smart Manufacturing	
		Metrics	Technologies	Metrics	Technologies
Parameters	Connectors, Sensors and Actuators	Accuracy	Manual operation	Self-driven and predictive	Delay-tolerant and high outcome based
Machine	Adaptive Contoller	Production	Condition based maintenance	Flexible and scalable	Adaptive and Autonomous
Production System	Heterogeneous networks	Complexity	High resource consumption	Economical and effective	High connectivity Cyber- Physical System

#### 4. Industry 4.0 Applications in Manufacturing Systems

Industry 4.0 is particularly exciting within the manufacturing industry. It brings together Big Data, 3D printing, Industrial Internet of Things, Cloud Computing, Smart Factory, and more, into a single concept. This offers an impressive amount of potential for manufacturing operations of all shapes and sizes. Industry 4.0's basic principal is that interconnected machines and systems will form an intelligent network spanning the entire value chain. Below are several examples of applying these principles across the manufacturing value chain. Each element of this process can enjoy the benefits that Industry 4.0 offers (Gradišar et al. 2015)(Lars Adolph, Bundesanstalt, n.d.)(Thoben, Wiesner, and Wuest 2017).

##### 4.1 Design Engineering

One of the most important elements of the manufacturing value chain rests in research and development. Design engineers can take full advantage of the catalog of information and related data available to them. During their preliminary product research, this data can reveal a more specific scope of a product's potential. And it can help designers to focus on efficiency throughout the production process for a better overall product, which will reduce the amount of time it takes to get to market.

##### 4.2 Predictive Maintenance & Service

Typically, problems within the manufacturing process are addressed reactively – or as they occur. While routine maintenance is a part of the process, Industry 4.0 makes this even easier. Ongoing data reporting can indicate failure rates and notify technicians on where they should prioritize preventative maintenance. This type of predictive reporting ensures fewer interruptions and delays in production.

##### 4.3 Connecting to Customers

Beyond the process itself, Industry 4.0 products and services can also facilitate a better connection with customers.

This type of customer information can yield a robust set of data that can be used for learning more about customers' needs, wants, and preferences. And this can allow a manufacturer to produce more marketable products that better address these consumer needs.

#### 4.4 Business Expansion

When a business focuses on expansion into greater operational capacity or a broader scope of products, data collected through Industry 4.0 serves as an invaluable asset. As the physical-digital-physical cycle presses onward, better or newer products and services can be identified from the data. And this information will give a manufacturing firm more relevant insight on how to remain competitive in their specific market.

#### 4.5 Planning & Logistics

From an operational standpoint, the overall function of the middle stage in the value chain will also benefit from Industry 4.0. These technologies offer insight within the nuts-and-bolts of a production process. This data can come together to help manufacturers identify bottlenecks or pain points. From there, they can integrate new and improved solutions to keep their operations well-supported for efficient production and realistic growth.

### 5. Existing Reference Architectures of Industry4.0

In this section, we present and analyze the key existing reference Smart Manufacturing architectures, namely the reference architecture model Industry 4.0 (RAMI 4.0) (Smith 2015), Smart Manufacturing ecosystem (SME) (Yan Lu, Morris, and Frechette 2016), and intelligent manufacturing system architecture (IMSA) (Vural et al. 2010). An architecture is the initial step for the design of systems. It consists of a description (model) of the basic arrangement and connectivity of the parts of a system, which can either be a physical or conceptual objects or entities (Pisching et al. 2016). Architectures are widely used to describe top structures and internal relationships of systems. In the context of Smart Manufacturing, different architectures have been designed by different industrial organizations.

#### 4.1 Reference Architecture Model Industry 4.0 (RAMI 4.0)

RAMI 4.0 was proposed by German in 2015 (Lars Adolph, Bundesanstalt, n.d.). The architecture provides a common understanding of the relationships between various individual parts such as layers, lifecycle, and hierarchy levels of the Smart Manufacturing solutions landscape. It also provides a common viewpoint for different industry branches. RAMI 4.0 includes terminal emulation data (BITCOM), Verband Deutscher Maschinen – und Anlagenbau (VDMA), and ZWEI. RAMI 4.0 is a 3D model that represents all the different manually interconnected features of the technical economical properties. It is based on the smart grid architecture model (SGAM) which was developed for communications in networks of renewable energy sources. It appeared to be an appropriate model for Smart Manufacturing applications too. The RAMI 4.0 model enables perspectives from different aspects such as layers, lifecycles, and hierarchy levels as shown in Figure 2.

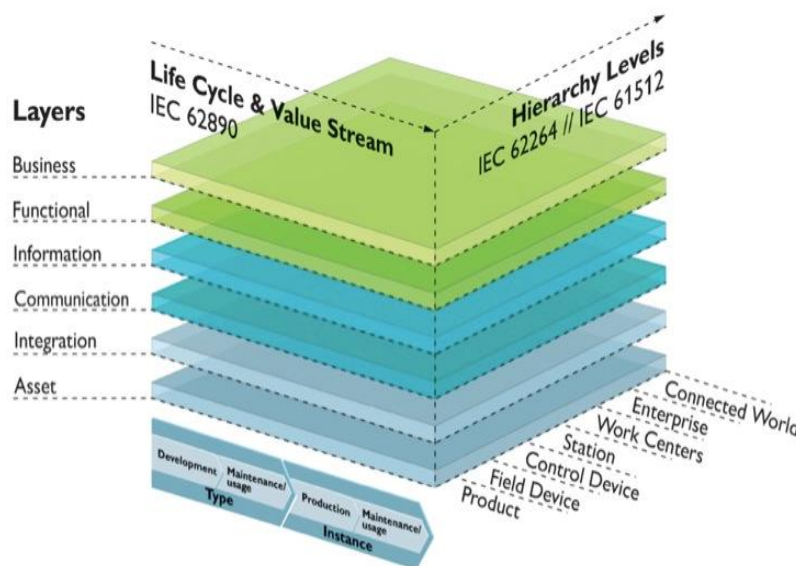


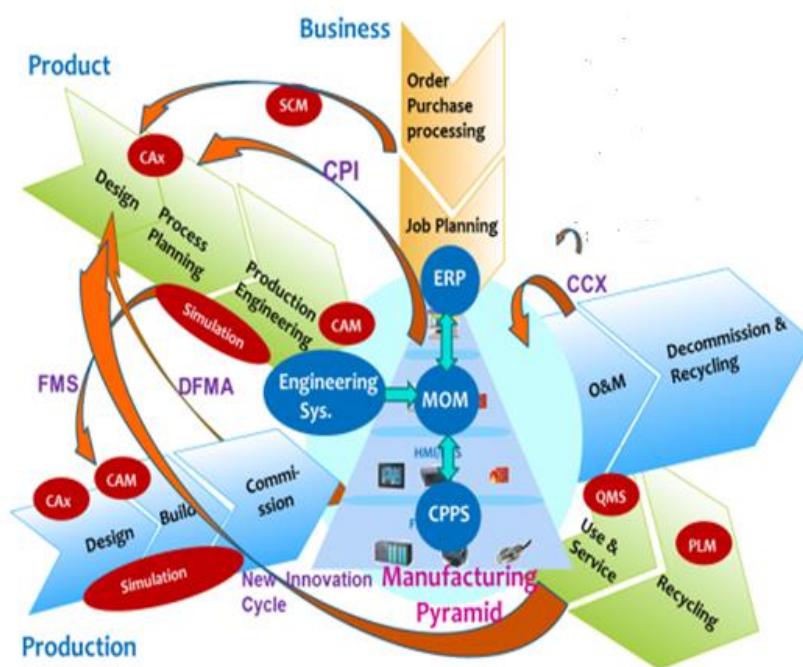
Figure 2. RAMI 4.0 (Smith 2015)

A critical principle in modern engineering is the product lifecycle because of the value stream that contains. The left side of the horizontal axis displays the relationship between the lifecycle and the value stream. The lifecycle is obtaining fixed information. The complete digitization of the entire market chain for development has great potential for the development of products, machines, and other layers of the Smart Manufacturing architecture, during the products' entire lifecycle. This corresponds to the IEC 62890 draft standard. The right side of the horizontal axis describes the functions and positions of the components of Smart Manufacturing. The left horizontal axis only specifies the components' functionality and function assignments, without specifying their implementation. The hierarchy levels axis respects both IEC 62264 and 61512 standards. (Ota, 2017, and 2017 2017; Marcon et al. 2017; Afanasev et al. 2018; Xu, Xu, and Li 2018).

### 5.2 Smart Manufacturing Ecosystem (SME)

In the United States, in date, the National Institute of Standards and Technology (NIST) and International Society of Automation (ISA) have published a standards landscape for Smart Manufacturing systems. This Smart Manufacturing Ecosystem (SME) (Yan Lu, Morris, and Frechette 2016) is illustrated in Figure 3. The SME has three dimensions namely product production, and business displayed within their own lifecycle. The product

Figure 3. Smart Manufacturing Ecosystem (Yan Lu, Morris, and Frechette 2016)



lifecycle is concerned with the information flows, the controls at the early stage of the product design, the process planning stage, and continues throughout the product's end-of-life. The production system lifecycle focuses on the design, deployment, operation, and decommissioning of an entire production facility, including its engineering systems. The business cycle addresses the functions of supplier and customer interactions. Each dimension comes into play in the vertical integration of enterprise systems (ERP) manufacturing operations management (MOM), and cyber-physical production system (CPPS) as shown in Fig. 2.3. However, vertical integration is also called a manufacturing pyramid (Colombo, Bangemann, and Karnouskos 2013), as shown in Figure 4.

The standards manufacturing pyramid has the same classification as the ecosystem (Yan Lu, Morris, and Frechette 2016), (Yan Lu et al. 2017). Indeed, the pyramid's hierarchy is based on the IEC/ISO 62264 (Luis, Lastra, and Sciences 2018) and its functions. Enterprise Level standards are mainly about the enterprise's functions, such as decision design and decision implementation. Manufacturing operations management Level represents standards that refer to applications controlling plant-level operations. Supervisory control and data acquisition (SCADA), as well as device Level standards, are shop floor standards that describe control systems such as the human-machine interface (HMI), programmable logic controllers (PLC), and field components and their communication protocols. The integration of manufacturing software applications along each dimension enables advanced control at the shop floor level and optimal decision-making at the plant and enterprise level. The combination of these perspectives and the systems that support them make up the ecosystem of manufacturing software systems. Historically, these



dimensions have been dealt with as silos of concern (Yan Lu, Morris, and Frechette 2016). Integration along even one of these dimensions is a non-trivial challenge and is being actively worked on. The NIST has observed and was formed to integrate single dimensions in ecosystem system. It is expanding in scope to address the digital thread across the dimensions illustrated in Fig 4. Paradigms such as continuous process improvement (CPI), flexible manufacturing systems (FMS), and design for manufacturing and assembly (DFMA) rely on information exchange between the dimensions. Tighter integration within and across the three dimensions will result in faster product innovation cycles, more efficient supply chains, and more flexibility in production systems. The combination of these benefits allows for optimal control of the automation and decision-making, high quality of production, highly customized goods in tight synchronization with the demand for these goods.

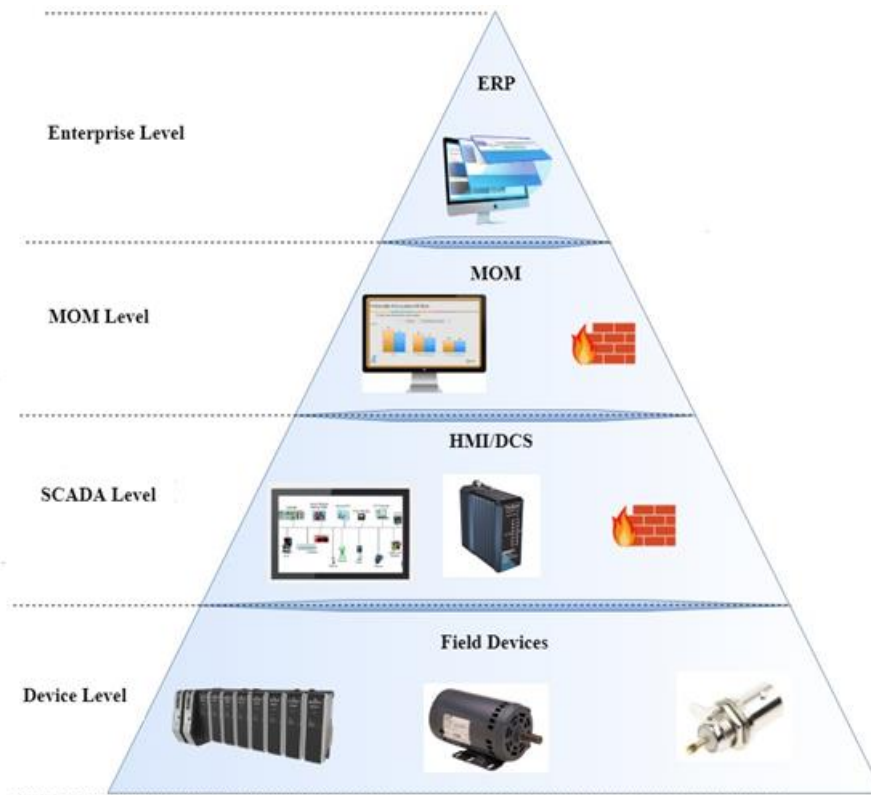


Figure 4. Manufacturing Pyramid (Colombo, Bangemann, and Karnouskos 2013)

### 5.3 Intelligent Manufacturing System Architecture (IMSA)

In China, the Ministry of Industry and Information Technology (MIIT) and the Standardization Administration of China (SAC) have published a joined report “National Smart Manufacturing Standards Architecture Construction Guidance” in December 2015. There are three steps in constructing an intelligent manufacturing standards framework (China National Standards 2015). First, a 3D intelligent manufacturing system framework, consisting of lifecycles, system hierarchy, and intelligent functions. Moreover, it is constructed by extracting the general and abstract features of all kinds of intelligent manufacturing application systems. However, they are studied to define the connotations, extensions of intelligent manufacturing standards, recognize available and unavailable intelligent manufacturing standards, and understand the overlapping relationships between existing standards. Second, the plane consisting of the lifecycle dimension and system hierarchy dimension of intelligent manufacturing system framework is applied to the five-level intelligent function dimension from the upper to lower levels is based on an analysis of standard demand and by comprehensively considering. The logistic relationships between all the dimensions of intelligent manufacturing systems are comprehensively considered to form key technical standards. These standards are intelligent equipment, intelligent factories, intelligent service, industrial software, big data, and industrial internet. Third, the intelligent manufacturing standard system architecture is decomposed to establish an intelligent manufacturing standard system framework and guide. Figure 5 depicts the construction of intelligent manufacturing standard systems and architecture, and the approval of relevant standards from three



dimensions namely Lifecycle, System hierarchy, and Intelligent functions. The lifecycle refers to chain integration, consisting of a series of mutually connected value creation activities such as design, manufacture, logistics, sales, and service. All activities in the lifecycle are associated and mutually influence each other. Note that lifecycles differ from industry to industry. From lower to upper levels, the system hierarchy refers to equipment level, control level, workshop level, enterprise-level, and cooperation level. The system hierarchy of intelligent manufacturing also represents the intelligence and Internet protocol of equipment and network flattening. The intelligent functions include five layers which are resources elements, system integration, interconnection, information fusion, and new business patterns (Wang and Liang 2016; Li et al. 2018; Grángel-Gonzalez et al. 2018; China National Standards 2015; Zhang et al. 2017).

In overall, we talked generally about three fundamental reference architectures of Industry4.0 individually. In the next section, we provide a comparison of them.

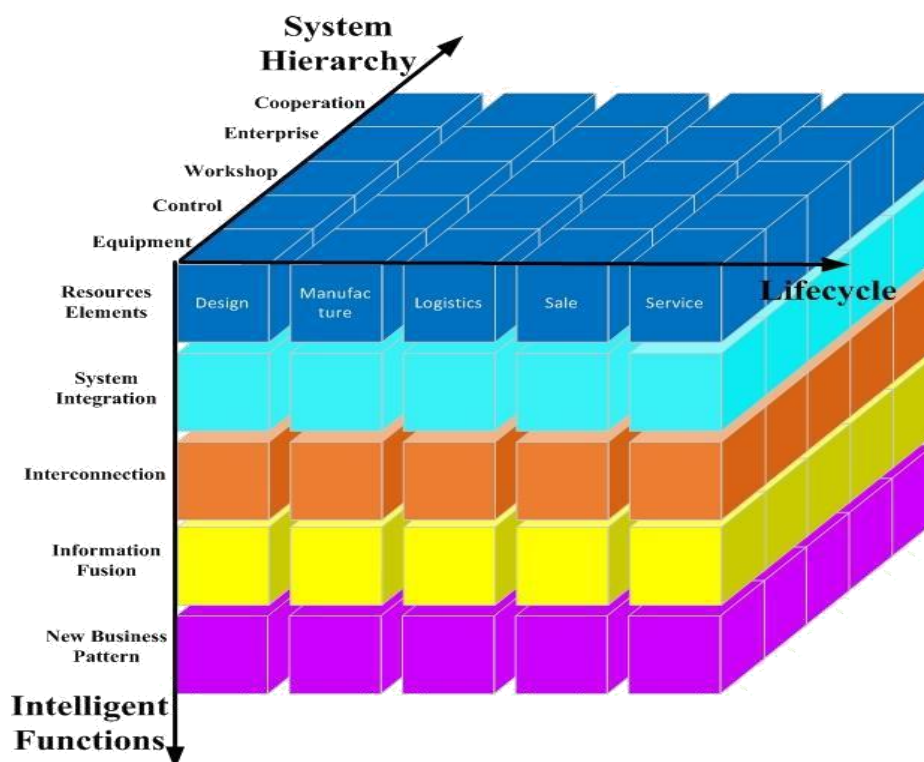


Figure 5. Intelligent Manufacturing System Architecture (Vural et al. 2010)

#### 5.4 Comparison of Significant Reference Architectures

In this section, we compare the RAMI 4.0, SME, and IMSA industrial reference architectures for Smart Manufacturing.

The three key architectures are compared through four criteria, business/management, industrial technology revolution, information technology revolution, and human/organization promotion. The four criteria can develop and standardize Smart Manufacturing (Li et al. 2018).

All those dimensions can be declined into sub-dimensions. Business/ management links to system hierarchy, product lifecycle, business lifecycle, and manufacturing mode development sub- dimensions. Industrial technology revolution relates new equipment, new manufacturing process techniques, new energy, and new materials to sub-dimensions. Information technology revolution relates to function layers, communication technology development, network technique development, data storage technology development, database technology development, IT infrastructure development, and simulation technology development sub-dimensions. Human/organization promotion relates to organization management scope, human resource talent levels, and capability performance sub-dimensions.

Table 3 presents the outcome of the SME, RAMI 4.0, and IMSA Smart Manufacturing architectures comparison. One can see that SME architecture is more complete than RAMI 4.0 and IMSA. It covers additional sub-

dimensions' criteria such as manufacturing mode development, new materials, communication technology development, data storage technology development, organization management scope, and capability/performance.

The three fundamental industrial reference architectures are also defined in connection with each other. Such as, RAMI 4.0 contains various layers that exploit connection between assets, integration, communication, information, functions, and business. It also provides a complete description of the lifecycle and value stream from the development and monitoring of products with IEC 62890, IEC 62264, and IEC 61512. Similarly, SME architecture is also an enterprise model and it contains four main layers: product, production, business, and manufacturing pyramid. IMSA architecture is manufacturing-oriented and describes the smart industry.

As discussed above, Smart Manufacturing is the convergence of information, manufacturing, and management technology. It aims to apply new capabilities and core competencies to manufacturing enterprises. Note that besides the three key architectures, we also have industrial value chain reference architecture (IVRA) (IVRA 2018), industrial Internet reference architecture (IIRA) (Smith 2015), a framework for cyber-physical systems (F-CPS) (Griffor et al. 2017), and the Internet of things architectural reference model (IoT-ARM) (Carrez et al. 2013).

The goal of Smart Manufacturing implementation is to achieve new skills and core competencies. In Smart Manufacturing ecosystems, the significant capabilities that enable Smart Manufacturing are classified as sustainability, agility, quality, and productivity. Smart manufacturing is a systematic technology that relates to ICT, industrial technology and management technology. The Smart Manufacturing system is a large-scale and complex system. Nevertheless, standardization is a powerful tool to push the development and implementation of Smart Manufacturing technologies. Plant data is used to make quick decisions, optimize production throughput and quality, achieve accurate measures of energy and material use, improve shop-floor safety, and enhance manufacturing sustainability. The sets of international standards related to Smart Manufacturing was developed by ISO, IEC, ITU, IEEE, and other international standards development organizations (SDOs). Furthermore, the SDOs in the US, Germany, China, and other countries have developed their own national standards landscapes or roadmaps that present an efficient standardization solution for Smart Manufacturing (Smith 2015).

Table 3. Comparison of SME, RAMI 4.0 and IMSA Reference Architectures

Dimension	Sub -dimensions	SME	RAMI 4.0	IMSA
Business / Management	System Hierarchy	X	X	X
	Product Lifecycle	X	X	X
	Business (Supply Chain) Lifecycle	X	X	X
	Production Lifecycle	X	X	X
	Manufacturing Mode Development	X		
Industrial Technology Revolution	New Equipment	X	X	X
	New Manufacturing Process Techniques	X	X	X
	New Energy			
	New Materials	X		
Information Technology Revolution	Function Layers	X	X	X
	Communication Technology Development	X		
	Network Technique Development	X		X
	Data Storage Technology Development	X		
	Database Technology Development		X	X
	IT Infrastructure Development		X	X
	CAX / Simulation Technology Development	X	X	
Human/Organization Promotion	Organization Management Scope	X		
	Human Resource Talent Levels			
	Capability/Performance	X		

## 6. Global Trends of Smart Manufacturing Technology

This section summarizes the policies and research trends of advanced manufacturing countries. It thus identifies the critical technologies needed to realize Smart Manufacturing and summarizes the studies and reports for the related technologies. We focus on Germany, China, and USA.

### 6.1 *Germany Standard*

In 2011, Industry 4.0 was the name given to the German strategic initiative to launch Germany as a lead market and provider of advanced manufacturing solutions. Germany has the ideal conditions to become a global leader in innovative, Internet-based production technology, service provision, and standardization. Germany's technological leadership and vision in the fields of manufacturing, automation, and software-based embedded systems, as well as its historically secure industrial networks, lay the cornerstone for the long-term success of the Smart Manufacturing project. The German government announced Industry 4.0 to establish smart factories that are the ultimate realization of Smart Manufacturing (Rojko 2017). It is a combined project that involves the private sector, government, and academia. The Smart Manufacturing concept was first announced at the 'Hannover Messe 2011' (H. P. Lu and Weng 2018) in Germany. The final report on Smart Manufacturing specified that it creates new values. Germany instructed new business models and resolved various social problems by linking inside and outside a factory's services, through the communication networks based on CPS, IoT, and the Internet of Services (IoS).

The integration of existing systems or platforms such as MES (Manufacturing Execution Systems), ERP (Enterprise Resource Planning), and CRM (Customer Relationship Management), and the construction of a data backbone, effectively manage complex systems and provide various functions that can be utilized for applications. In (Lars Adolph, Bundesanstalt, n.d.), it is reported that IoT, IoS, and CPS must be established to integrate existing complex systems and that various IT technologies, modeling, simulations, big data, cloud computing, sensors, and smart energy technologies are required. Additionally, Smart Manufacturing is being propelled not only for the realization of smart factories but also in the following areas to achieve innovations in their overall conditions, such as personnel and laws:

- standardization and reference architecture,
- management of complex systems,
- comprehensive broadband infrastructure for the smart industry,
- safety and security,
- work organization and design,
- training and continuing professional development,
- regulatory framework,
- resource efficiency.

### 6.2 *United States of America Standard*

The USA is planning research development and executing programs for manufacturing. This development and programs are also called advanced manufacturing or Smart Manufacturing. They are designed to encourage the revival of manufacturing. The research and development programs related to manufacturing in the USA focus on key technology assignments, including IoT, big data, data analytics, CPS, system integration, sustainable manufacturing, and additive manufacturing. The fourth industrial revolution responds to changes in the innovative manufacturing environment (Kang et al. 2016). The definition of each vital assignment is as follows:

- IoT refers to embedding sensors and communication equipment in manufacturing machinery and lines.
- Big data and data analytics refer to developing software and systems that can interpret and analyze mass amounts of incoming data.
- Cyber-physical systems and system integration refer to developing mass production systems that are capable of highly efficient and flexible control and customization.
- Sustainable manufacturing refers to developing production systems that can increase resource efficiency and reduce the emission of environmentally hazardous substances through green design, the use of environment-friendly materials, and the optimization of production processes.
- Additive manufacturing refers to the method of applying 3D printing technologies to the manufacture of components and products, which can reduce time and costs for product development and manufacture.

To secure cutting-edge manufacture capability, in June 2016, the American government launched the Smart

Manufacturing leadership Coalition (SMLC), which is a pan-national research and development consortium, for inter-departmental discussions. Twenty-five companies, seven universities, eight consortiums, and one government research institute are currently participating in the program. They are suggesting and performing concrete action plans, such as establishing concepts, technological goals, and roadmaps, as well as assigning roles (Yan Lu, Morris, and Frechette 2016). The National Institute of Standards and Technology (NIST) is an agency of the American Department of Commerce. It performs an essential role in developing Smart Manufacturing technologies, as it is the only government agency that is part of the SMLC. The NIST established the strategies of dynamic production systems and rapid design-to-product through smart manufacture research programs. To achieve the strategies' goals, it suggested three key action technologies, namely decentralized control networks, digital manufacturing, and decentralized machine intelligence. NIST also suggested three key performance indexes for efficiency: agility, asset utilization, and sustainability (Yan Lu, Morris, and Frechette 2016).

### 6.3 Chinese Standard

Like other standards, Chinese standards are popular and play a significant role in Smart Manufacturing. To realize the Chinese national manufacturing strategy for 2025, the Ministry of Industry and Information Technology in China and China's standardization administration published a joint report (China National Standards 2015) titled the "National Smart Manufacturing Standards Architecture Construction Guidance." The Smart Manufacturing standardization reference model in China contains three key dimensions: smart functions, lifecycles, and hierarchy levels.

- Smart functions: from resource elements, system integration, interconnectivity, and information convergence, to new business models.
- Lifecycles: from design, production, logistics, marketing, and sales, to service.
- Hierarchy levels: from devices, controls, plants, and enterprises, to inter-enterprise collaboration.

The key standardization for Smart Manufacturing is to define the reference architecture model for Smart Manufacturing that classifies and position standards in multiple dimension systems, analyzes the status, requirements, and applications of standardization progress. Furthermore, the key purpose of manufacturing standards is to reshape the industrial world with modern trends and practices. The following technologies are key components of a smart factory realized through the roadmap.

- Networked sensors: Data for communication, automated controls, planning and predictive models, plant optimization, health and safety management, and other functions will be provided by large numbers of networked sectors.
- Data interoperability: Seamless exchange of electronic products, processes, and projects.
- Data is enabled through interoperable data systems and used by collaborating divisions or companies, and across design, construction, maintenance, and business systems.
- Multi-scale dynamic modeling and simulation: Business planning and scheduling can be fully integrated with operations through multiscale models that support enterprise-wide coordination and enable large scale optimization across companies and supply chains.
- Intelligent automation: Automated learning systems are vital to Smart Manufacturing, but they must be effectively integrated with human learning and the decision environment.
- Scalable and multi-level cybersecurity: System protection from cyber vulnerabilities (without compromise of functionality) is needed throughout the manufacturing enterprise.

As standards are the paradigm shift to transform the traditional manufacturing methods into smart ones, and without standards it is hard to build any smart system. In next section we present the several standards for the digital manufacturing or Industry 4.0 from different aspects. In today's emerging society where everyone wants to carry his business with high earning and yield, so standards are the paramount importance to fix the various issues at the national and international level.

## 7. Standards at Different Layers of the Smart Manufacturing Ecosystem

It is difficult to build any smart system without standards. Indeed, standards are the pattern that transforms traditional manufacturing methods into smart ones. In this section, we present standards for Smart Manufacturing from different viewpoints such as enterprise, MoM, SCADA, and device level. Nowadays, businesses want to have high earnings and yields. In this context, standards fix various issues at the national and international levels. The

standards at the different layers of Smart Manufacturing are presented in (Yan Lu, Morris, and Frechette 2016). Hereafter, we give an overview of those standards. Although each level describes the various standards. The following Figure 6. and tables are for further details of Smart Manufacturing Ecosystem standards.

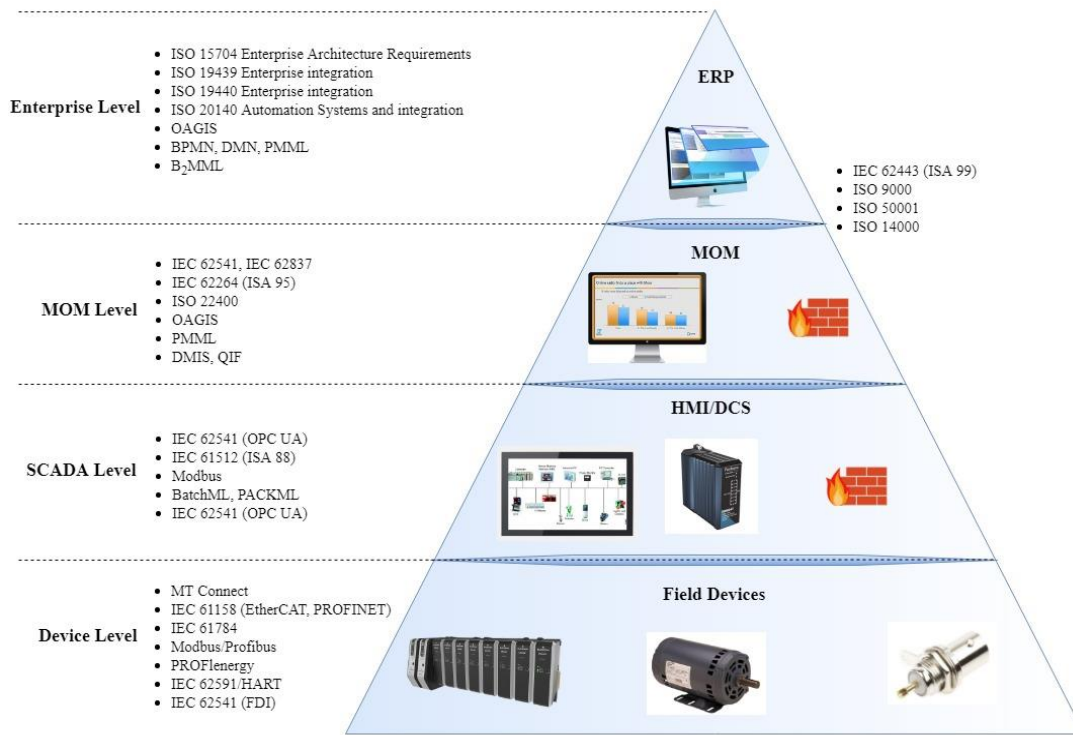


Figure 6. Business level strategies and their standards at different layers in digital Industry

Table 2. Enterprise-Level Standards

Standards		Description
International Standards	ISO 15704	Industrial automation systems — requirements for enterprise-reference architectures and methodologies.
	ISO 19439	Enterprise integration — framework for enterprise modeling and provides a unified conceptual basis for model-based enterprise engineering that enables consistency, convergence, and interoperability of the various modeling methodologies and supporting tools.
	ISO 19440	Enterprise integration — constructs for enterprise modeling and specifies the characteristics of the core constructs necessary for computer-supported modeling of the enterprises conforming to ISO 19439.
	ISO 20140	Automation systems and integration — evaluating energy efficiency and other factors of manufacturing systems that influence the environment.
National Standards	OAGIS	Open applications group integration specification (OAGIS) defines a common content model and common messages for communication between business applications, including application-to-application (A2A) and business-to-business (B2B) integration.
	DMN	Decision modeling notation (DMN) from the objective management group (OMG) provides the constructs that are needed to model decisions to close the gap between business decision design and decision implementation. The DMN is designed to be useable alongside the standard BPMN business process notation.

	PMML	The Predictive Model Markup Language (PMML) is an XML-based file format developed by the Data Mining Group to provide a way for applications to describe and exchange models produced by data mining and machine learning algorithms. It supports common models such as logistic regression and feed-forward neural networks.
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Table 3. MOM-Level Standards

Standards		Description
International Standards	IEC 62264	Enterprise-control system integration — defines the manufacturing hierarchical model and describes the manufacturing operations management domain and its activities, the interface content, and associated transactions within Level 3, and between Level 3 and Level 4 objects. This standard is based on ANSI/ISA-95.
	IEC 62541	OPC Unified Architecture — an industrial M2M communication protocol for interoperability, developed by the OPC Foundation.
	IEC TR 62837	The report on energy efficiency through automation systems provides a framework for the development and adaptation of documents to improve energy efficiency in manufacturing, process control, and industrial facility management.
	ISO 22400	Automation systems and integration — provides key performance indicators (KPIs) for manufacturing operations management, specifies an industry-neutral framework for defining, composing, exchanging, and using KPIs for MOM, as defined in IEC 62264-1, for batch, continuous, and discrete industries.
National Standards	DMIS	Dimensional measuring interface standards provide a standard for the bi-directional communication of inspection data between computer systems and inspection equipment.
	QIF	Quality information framework is a unified XML framework standard for computer-aided quality measurement systems. It enables the capture, use, and re-use of metrology-related information throughout the PLM/PDM domain.

Table 4. SCADA-Level Standards

Standards		Description
International Standard	IEC 61512	ISA-88 — defines the terminology, reference models, and data models (including recipe model) for batch control, as used in the process industries.
National Standards	BatChML	BatchML is an XML implementation of ISA-88.
	PackML	Packaging machine language defines a common approach, or machine language, for automated machines. It was adopted as part of the ISA88 industry-standard in August 2008.

Table 5. Device-Level Standards

Standards		Description
International Standards	IEC 61158	Specifies industrial communication networks such as Fieldbus, including ControlNet and Profibus.
	IEC 61784	Defines a set of protocol-specific communication profiles. It is based on the IEC 61158 series and real-time Ethernet communication profiles that are used in the design of devices involved in communications, factory manufacturing, and process control.
	ISO 11898	Controller area network (CAN) — a serial communication protocol that supports distributed real-time control and multiplexing for use within road vehicles
	IEC 62591	Specifies wireless communication network and communication profiles such as wireless highway addressable remote transducer protocol (HART).
National Standards	MTConnect	Lightweight, open, and extensible protocol designed for the exchange of data from shop floor equipment to software applications, used for monitoring and data analysis.
	IEC/PAS 62030	De facto standard providing serial communications protocol to connect industrial electronic devices. Modbus is often used to connect a supervisory computer with a remote terminal unit





50001, and ISO 14000 standards are related to cross-level standards. The IEC 62541, IEC 61158, and IEC 61508 are related to the interfacing between the four levels. Fig 7 also shows that the different levels have received some standardization. However, they were standardized independently, since there is no clear standard at the interface between the ERP, MOM HMI and field devices layers. There are also no standards about open safety, especially in the field device-level, as mentioned in (Yan Lu, Morris, and Frechette 2016). The OPC UA protocol (IEC 62541) was assigned for the interface between ERP, MOM, HMI/DCS, and field devices. The Ethernet Powerlink and open safety protocols were proposed for the field-device level. The safety protocol (IEC 61508) was assigned to the device-level. Safety has been the major priority for Smart Manufacturing. Open safety is a communication protocol used to transmit information. It is key to the safe operation of machinery in manufacturing lines, process plants, and industrial environments. Open safety is certified according to the IEC 61508 standard. This protocol has been approved by national IEC committees representing over two dozen countries around the world and was released for international standardization in IEC 61784-3.

Summary of discussion, we discussed with details of the standards for each level of Industry4.0 architecture. Proposed standards for interface between the ERP, MOM HMI (IEC 62541) and for field devices layers (IEC 61158, and IEC 61508) from existing pool of standards.

## **8. Future Research Directions**

Future research perspectives for intelligent manufacturing in the Industry 4.0 era are believed to be in the following areas: a generic framework for Industry 4.0, human-machine integration, and smart manufacturing models.

### *8.1 Generic Framework for Industry 4.0*

Given the deep integration of Industry 4.0, a generic framework for intelligent manufacturing is important, since manufacturing science and technology, ICT, and sensor technology will be highly integrated in the future. This generic framework will cover large areas that will be used in different enterprises so that the implementation of intelligent manufacturing can be guided and standardized. Typical technologies such as advanced sensors, wireless communication standards, big data processing models and algorithms, and applications will be placed within this framework. Thus, an intelligent hierarchical architecture will be worked out as a basis for Industry 4.0. One such area is the smart grid, which is designed as an ecosystem in which different elements can be extensively combined in order to work in a highly effective manner (Zhong et al. 2017). In order to fully implement intelligent manufacturing, platform technologies such as networks and the IoT, virtualization and service technology, and smart objects/assets technology should be focused on, since increasing amounts of customized requirements from customers will increase the cost of manufacturing. Platform technology is able to reduce cost by making full use of flexible and reconfigurable manufacturing systems through intelligent design, production, logistics, and supply-chain management. Multiplex platform technology, especially for design and development, will provide a novel solution to address the issue of highly customized products. A more open innovative framework is required to integrate collaborative efforts in manufacturing for additional downstream and upstream activities. Thus, service-oriented concepts for intelligent manufacturing will be key components in Industry 4.0. Figure 7 presents a framework of the Industry 4.0 IMS, in which research topics are categorized into smart design, smart machines, smart monitoring, smart control, and smart scheduling.

#### *8.1.1 Smart Design*

With the rapid development of new technologies such as VR and augmented reality (AR), traditional design will be upgraded and will enter into a “smart era.” Design soft-ware such as computer-aided design (CAD) and computer-aided manufacturing (CAM) is able to interact with physical smart prototype systems in real time, enabled by three-dimensional (3D) printing integrated with CPSs and AR.

#### *8.1.2 Smart Machines*

In Industry 4.0, smart machines can be achieved with the help of smart robots and various other types of smart objects that are capable of real-time sensing and of interacting with each other. For example, CPS-enabled smart machine tools are able to capture real-time data and send them to a cloud-based central system so that machine tools and their twinned services can be synchronized to provide smart manufacturing solutions.

#### *8.1.3 Smart Monitoring*

Monitoring is an important aspect for the operations, maintenance, and optimal scheduling of Industry 4.0 manufacturing systems. The widespread deployment of various types of sensors makes it possible to achieve smart monitoring. For example, data and information on various manufacturing factors such as temperature, electricity

consumption, and vibrations and speed can be obtained in real time.

#### 8.1.4 Smart Control

In Industry 4.0, high-resolution, adaptive production control (i.e., smart control) can be achieved by developing cyber-physical production-control systems. Smart control is mainly executed in order to physically manage various smart machines or tools through a cloud-enabled platform. End-users are able to switch off a machine or robot via their smart phones.

#### 8.1.5 Smart Scheduling

The smart scheduling layer mainly includes advanced models and algorithms to draw on the data captured by sensors. Data-driven techniques and advanced decision architecture can be used for smart scheduling. For example, in order to achieve real-time, reliable scheduling and execution, distributed smart models using a hierarchical interactive architecture can be used.

### 8.2 *Human-machine integration*

Under Industry 4.0, humans and machines will work collaboratively by using cognitive technologies in industrial environments. Intelligent machines will be able to help humans to fulfil most of their work using speech recognition, computer vision, machine learning, and advanced synchronization models. Thus, advanced learning models for machines such as robots are important so that humans and machines develop skills that complement each other under any working conditions. One future research direction is an approach for “human-in-the-loop” machine learning, which enables humans to interact efficiently and effectively with decision-making models. Thus, data-enabled machine learning mechanisms may provide pathways by using human domain expertise or knowledge to better understand the collaboration. For example, traditional machine learning systems or algorithms can be interjected with human knowledge so that a real-world sensing system can help improve human-machine interactions and communications. For example, Festo’s Bionic Learning Network found many applications, such as a learning gripper that used AI for self-learning algorithms and the BionicANT project that used multi-agent systems to enable robots to act in a self-organizing manner and solve a given task as a team. Machine intelligence plays an important role in supporting human-machine collaboration, since machines will be helping with every job, every role, and anything that is done in manufacturing sites where dynamic situations are present (Wan et al. 2017). Safety issues may be a crucial research topic, as machines equipped with intelligent control systems begin to behave and act as humans in real-life manufacturing sites such as workshops. Such machines can easily communicate with workers through self-learning and evolutionary procedures. For example, intelligent human-machine integration for automating design can be realized from ontology-based knowledge management with local-to-global ontology transitions and the epistemology-based upward-spiral cognitive process of coupled design ideation (Yin et al. 2015). Therefore, intelligent human-machine interactions can be implemented within a complex manufacturing environment in order to ultimately achieve manufacturing intelligence in the future.

Intelligent manufacturing applications for entire enterprises or industries are significant in Industry 4.0, in which real-life companies can benefit from cutting-edge technologies. An agent-based framework for IMSs will be a suitable solution to the problem of production planning and scheduling, since manufacturing enterprises may involve many varied elements such as manufacturing process planning and scheduling, workshop monitoring and control, and warehouse management. Agent-based implementation is able to define work-flows and follow manufacturing logics so that the decision-making related to these elements can be effectively facilitated (Zhong et al. 2017). Taking automation in manufacturing systems as an example, multi-agent technologies can be used to parallel-control robots that are enabled by an agent-based architecture with distributed agents, in order to ease the implementation of intelligent manufacturing. Another future implementation of intelligent manufacturing is cloud-based solutions; these use cloud computing and SOA to share or circulate manufacturing resources. Several different cloud platforms will be established to make full use of IMSs so that manufacturing capabilities and resources can provide on-demand services to end-users. Key future research involves manufacturing resources modeling during the Industry 4.0 era, since typical resources with advanced sensors are equipped with intelligence and can react, sense, and even “think,” given different manufacturing requirements or situations.

### 8.3 *Smart manufacturing models*

With the large increase of digital devices carrying RFID and/or smart sensors in manufacturing, enormous amounts of data will be generated. Such data carry rich information or knowledge that can be used for different decision-making situations. Therefore, the effective usage of data not only involves improving manufacturing efficiency, but also drives greater agility and deeper integration with other parties such as logistics and supply-chain management

entities. For example, the chip maker Intel used a data-analyzing approach on its data from manufacturing equipment to predict quality issues. This usage greatly cut down on the number of quality tests and improved the production speed. The data-based model uses 5 TB of machine data per hour to work out the quality predictions. Dynamics in a production system will significantly influence quality and efficiency. Data-driven models are able to make full use of historic or real-time data for system diagnosis or prognosis, based on information or knowledge integration, data mining, and data analytics (Fosso Wamba et al. 2018). For example, a two-stage maintenance framework using a data-driven approach was utilized for degradation prediction in the semiconductor manufacturing industries. In the future, data-based or knowledge-driven models and services will be largely adopted for intelligent manufacturing. One key research area is the integration of cloud services with knowledge management in a platform that is able to provide enterprise services such as intelligent design and manufacturing, production modeling and simulation, and logistics and supply-chain management. This platform will accumulate a vast amount of production data from various manufacturing objects equipped with smart sensors or digital devices, in order to combine human, machine, material, job, and manufacturing logics. An intelligent workshop operation center over the cloud may use self-learning models to build more advanced or intelligent models and algorithms for advanced decision-making in manufacturing systems.

## 9. Conclusions and Future Work

This paper presents the detailed review of the Industry 4.0 or Smart Manufacturing or the fourth industrial revolution. The purpose of this research is to entertain the three challenging questions and proposes the tentative solution to some-how remedies these issues. First: how small and medium enterprises (SMEs) are build and setting-up from conventional manufacturing practices to the smart manufacturing/Industry 4.0? Second: comparative analysis of the key architectures adopted for the Industry 4.0. Third: review, select and suggest the standards from the pool of standard bodies for Industry 4.0. Besides, it is a new paradigm and convergence of cutting-edge ICT and manufacturing technologies. It provides grounds for making effective and optimized decisions through swifter and more accurate decision-making processes. For the realization of Smart Manufacturing, state-of-the-art technologies in various areas, ranging from CPS, cloud manufacturing, big data analytics, IoT, and smart sensors to additive manufacturing, energy saving, and hologram, are being developed and applied to manufacturing sites. As increasing attention is given to Industry 4.0, intelligent manufacturing is becoming more and more important in the advancement of modern industry and economy. Intelligent manufacturing is considered to be a key future perspective in both research and application, as it provides added value to various products and systems by applying cutting-edge technologies to traditional products in manufacturing and services. Product service systems will continue to replace traditional product types. Key concepts, major technologies, and world-wide applications are covered in this study. Future research and applications are highlighted after a systematic review. This research can inform and inspire researchers and industrial practitioners to contribute in advancing the manufacturing industry forward. We hope that the concepts discussed in this paper will spark new ideas in the effort to realize the much-anticipated Fourth Industrial Revolution.

In near future, we will focus on the product lifecycle management and its specific usage in the Industry 4.0 and related applications.

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