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# Smart manufacturing standardization: Architectures, reference models and standards framework

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ABSTRACT

With the development of information & communication technology (ICT), industrial technology and management technology, manufacturing operation pattern and technology are improving quickly. In order to realize economic transformation and get their national competitiveness, American government proposed Re-industrialization and Industrial Internet, German government announced Industry 4.0, and Chinese government published Made in China 2025 national strategy. All of these mentioned strategies have a key topic: smart manufacturing. ISO, IEC, ITU, IEEE, and other international standard development organizations (SDOs) develop sets of international standards related to smart manufacturing. In order to present a systematic standardization solution for smart manufacturing, SDOs of the US, Germany, China and other countries developed their own national standards landscapes or roadmaps. In the paper, the new development of ICT and industrial technology are reviewed firstly. Then, these smart manufacturing architectures are analysed and compared. Thirdly, the reference model for smart manufacturing standards development and implementation is developed. At the end of the paper, a standards framework is provided.

## 1. Introduction

With the development of information & communication technology (ICT), industrial technology and management technology, manufacturing pattern and technology are improving quickly. Two historical processes, informatization and industrialization, are promoted mutually.

As shown in Fig. 1, because of different indoctrination levels, different countries are facing different challenges of informatization. Based on technical advantages, developed countries try to keep or resume their manufacturing competitiveness. Since newly industrialized countries and developing countries' industrialization process is accompanied with the informatization process, it is neither feasible nor necessary for these countries to follow the traditional development pattern (i.e. realizing industrialization first and then informatization). Newly industrialized countries and developing countries hope to grasp tremendous historic opportunity which is brought by the ICT rapid development.

In the context of informatization and industrialization, some developed and developing countries announced their national manufacturing strategies to support their economic transformation and national competitiveness.

- The United States published *A Framework for Revitalizing American Manufacturing* in December 2009 [1] and *National Network for Manufacturing Innovation: A Preliminary Design* in January 2013 [2]. Re-industrialization, the third industrial revolution, industrial internet, smart manufacturing are key concepts of national manufacturing strategies of the United States.
- Germany published *Recommendation for Implementing the Strategic Initiative INDUSTRIE 4.0* in April 2013 [3]. Now, Industry 4.0 is a hot topic discussed and researched by governments and industrial enterprises all over the world, in which Internet of Things (IoT), Cyber-Physical Systems (CPS) and smart manufacturing are the key concepts.
- Chinese government announced *Special Action Plan for Deep Integration of Informatization and Industrialization (2013–2018)* in Aug. 2013 [4] and *Made in China 2025* in May 2015 [5]. Integration of informatization and industrialization (iI&I), smart manufacturing and industrial internet are placed in important positions in Chinese national strategic plans.
- Japan announced the Industrial Value Chain in June 2015 [6]. A

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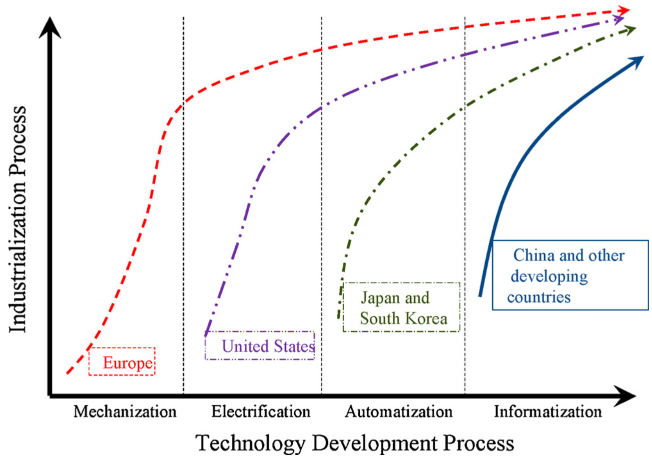



**Fig. 1.** Industrialization process with technology development processes [8].

new organization, Industrial Value Chain Initiative (IVI), has been set up.

- The Government Office for Science and Department for Business, Innovation & Skills of UK sponsored the Foresight project and published *The Future of Manufacturing* serial reports in October 2013 [7]. The foresight project developed a long-term picture for the UK manufacturing sector between 2013 and 2050.

Above mentioned strategies include different terms: Industry 4.0, smart manufacturing, industrial Internet, intelligent manufacturing, and so forth. Although some literatures discuss differences of these terms [9], in the paper, we do not distinguish the difference among these terms. Based on comparative studies [10,11], all of these terms share the same connotation and can be concluded into one key topic: smart manufacturing.

Manufacturing is the multi-phase process of creating a product out of raw materials. Smart manufacturing aims to take advantages of advanced information and manufacturing technologies to enable flexibility in physical processes to address a dynamic and global market [12]. Because smart manufacturing naturally has features of information technology, manufacturing (industrial) technology and their integration, it can be considered as one of implementation paths of iI&I.

Faced with the current complicated international and domestic economic situation and trends, the iI&I with smart manufacturing is a critical factor related to survival and long-term sustainability of manufacturing enterprises. In order to support manufacturing industry transformation and update, standardization is the important part of smart manufacturing strategies all over the world.

Standards are the building blocks that provide for repeatable processes and the composition of different technological solutions to achieve a robust end result. With standards, business owners may be able to adopt technologies and innovations more easily. Also, standards raise innovations and can protect them, providing a sustainable environment for smart manufacturing, which, to be specific, means standards make the goals through improve the reliability of the system, relevance of the market and the security of the investment.

Without the support of standards, the process of implementing smart manufacturing will be rough. It may also be costly and cause overwhelming waste of manpower and material resources due to the repetition of research and surveys. Standards allow people to work on the basis of the previous work conducted by experts. So without standards, new comers in a certain industry may have huge difficulty in carrying out their work. Especially, during the process of informatization, standards are the key of effectiveness of information exchanging, sharing and integration [13]. Kim, Lee and Kwak make an investigation of M2M (machine-to-machine) and IoT standards and patents, and conclude that standards serve as a driver of technological convergence. They also find related technology or system architectures lead the development of standards, which serve as a critical factor in the process of creating a new path for catch-up firms [14,15].

In order to realize the significance of the standardization, the paper firstly reviews the development of technologies and smart manufacturing, and then compares main smart manufacturing architectures. The reference model for smart manufacturing standards development and implementation is developed later. Finally, a standards framework is proposed [8].

## 2. Smart manufacturing and related standardizations

In the past 40 years, ICT develops very quickly and it is integrated with manufacturing activities deeply. There are several dimensions to help us to understand manufacturing technology improvement as well as ICT.

- Computing centre is transferring from machine oriented, to application oriented, and then to enterprise-oriented computing.
- Integration scope is extended from single computer usage, to department application and integration with LAN, to enterprise application and integration with WAN, to inter enterprises application and integration with the Internet, and then to enterprise network collaboration and supply chain network integration [16].
- Enterprise infrastructure is changing from mainframe, to client / server (C/S), to browser / server (B/S), to SOA (service-oriented architecture) and then cloud computing [17].
- The capability of enterprise information system, which evolves from office automation system (OA), to management information system (MIS) [18], to material requirement planning (MRP), to manufacturing resource planning (MRPII), to enterprise resource planning (ERP), and then to collaboration manufacturing / business and supply chain management, is increasing [16].
- Computing aided designing tools have emerged to CAD (computer aided design), CAE (computer aided engineering) [19], CAM (computer aided manufacturing) [20], CAPP (computer aided progress planning) [21], PDM (product data management), PLM (product lifecycle management), collaboration simulation, virtual reality (VR) [22] and so forth.
- Service Oriented Architecture (SOA) [17], cloud computing [23], wireless sensor network and smart technology, mobile network [24], IoT [25,26], semantic web, big data [27], 3D printing technology, CPS [28], artificial intelligence and so forth, these new emerging technologies are integrated with manufacturing more and more deeply and quickly.
- Manufacturing patterns transform from craft manufacturing, mass production, computer integrated manufacturing (CIM), lean production [29–31], agile manufacturing [32], next generation manufacturing (NGM), to smart manufacturing, Industry 4.0 and industrial Internet. Including total quality management (TQM) [33], business process re-engineering (BPR) [34], management technologies are also developing quickly.
- Industrial / manufacturing technology is also developing quickly. New equipment, new material, new production process and new energy technology make many breakthroughs. For instance, 3D printing (additive manufacturing) technique is a new manufacturing method, which is the convergence of new equipment technology, material technology and ICT.

Smart manufacturing converges information technology, industrial / manufacturing technology, management technology and human/organization to push a rapid revolution in the development and application of manufacturing intelligence. It will fundamentally change features of manufacturing.

- It will change products inventing, manufacturing, shipping and

selling methods.
- It will improve worker safety and protect the environment.
- It will keep manufacturers competitive in the global marketplace.

Smart manufacturing stands at the junction of industrialization and informatization. It embodies integration of information technology revolution, industrial (manufacturing) technology revolution, and management technology revolution. Smart manufacturing will take new capabilities and core competences to manufacturing enterprises and their countries. Therefore, smart manufacturing needs systematic solutions and methodologies, as well as its standardization.

In order to standardize different aspects of ICT, industrial technology and their integration, standard development organizations (SDOs) develop sets of standards [35]. These SDOs include:

- ISO/TC184 automation systems and integration. ISO/TC184 develops standards in the field of automation systems and their integration for design, sourcing, manufacturing, production and delivery, support, maintenance and disposal of products and their associated services. Its areas of standardization include information systems, automation and control systems and integration technologies. Its SC1 is physical device control, SC4 is industrial data, SC5 is interoperability, integration, and architectures for enterprise systems and automation applications.
- IEC/TC65 industrial-process measurement, control and automation. IEC/TC65 develops international standards for systems and elements used for industrial-process measurement and control concerning continuous and batch processes. Its WG10 is security for industrial process measurement and control - network and system security. WG16 is digital factory. WG19 is life-cycle management for systems and products used in industrial-process measurement, control and automation. AHG3 is smart manufacturing framework and System architecture. JWG21 is smart manufacturing reference model(s) which is linked to ISO/TC184.
- ISO/IEC/JTC1 information technology. ISO/IEC JTC1 develops international standardization in the field of information technology, which includes the specification, design and development of systems and tools dealing with the capture, representation, processing, security, transfer, interchange, presentation, management, organization, storage and retrieval of information. JTC1 is the standards development environment where experts come together to develop worldwide ICT standards for business and consumer applications. Its WG7 is sensor networks, WG9 is big data, WG10 is Internet of things, SC25 is interconnection of information technology equipment, SC27 is IT security techniques, SC31 is automatic identification and data capture techniques, SC32 is data management and interchange, SC38 is cloud computing and distributed platforms, SC41 is Internet of things and related technologies.

Some industrial organizations, joint committees or working groups are also related to smart manufacturing standardization, such as ISA (International Society of Automation), IEEE (Institute of Electrical and Electronics Engineers), OneM2M (standards initiative for machine to machine communications and the Internet of things), IEC/SEG7 (smart manufacturing), ISO SMCC (smart manufacturing coordinating committee), and so forth [36].

These SDOs developed some basic standards for smart manufacturing. For instance, IEC/ISO 62264 *Enterprise - Control System Integration* (from ISA95) presents a multiple layers framework for enterprise and control system integration, which includes Levels 0, 1, 2 Batch, Continuous and Discrete Control, Level 3 Manufacturing Operations & Control, Level 4 Business Planning & Logistics [37]. The multiple layers framework is widely called the manufacturing pyramid. IEC/ISO 62264 is the factual international standard of manufacturing execution system (MES). MES is the most important information system for smart manufacturing systems implementation and integration. However, Kannan et al. point out there are gaps between commercial MES applications and industrial standards from the viewpoint of Industry 4.0 [38]. In the context of Industry 4.0, plenty of standards are facing revision.

Some industrial organizations are also developing smart manufacturing related technology and standards. For instance, Object Management Group is cooperating with International Council on Systems Engineering (INCOSE) to develop SysML (system modelling language). Model Based Systems Engineering (MBSE) and SysML are powerful tools for large scale complex systems analysis and design, including smart manufacturing systems [39]. OneM2M is developing standards of machine-to-machine and IoT, which are foundations of smart manufacturing [13].

As shown in Fig. 1, because developed and developing countries stand in different developing stages, some countries published their own standards landscapes and roadmaps.

- National Institute of Standards and Technology (NIST) of the United States published *Current Standards Landscape for Smart Manufacturing Systems* [40].
- DIN, DKE VDE of Germany published *German Standardization Roadmap Industry 4.0* [41].
- Ministry of Industry and Information technology of China (MIIT) and Standardization Administration of China (SAC) published a joint report *National Intelligent Manufacturing Standards Architecture Construction Guidance* [42].
- Based on Germany-Japan cooperation, Platform Industrie 4.0, Robot Revolution Initiative and Standardization Council Industrie 4.0 jointly published *The Common Strategy on International Standardization in Field of the Internet of Things/Industrie 4.0* [36].

All above mentioned standardization landscapes and roadmaps share same principles:

- Respect to the standardization activities of international SDOs [36];
- Focus on systems and system of systems integration;
- Find standardization blank areas and take actions;
- Take full consideration of their industrialization and informatization developing stages.

Because the United States has a developed and powerful industrial foundation, NIST forms a smart manufacturing ecosystem with related standardization architecture for the United States. Its principles are consistent with the progress from computer integrated manufacturing (CIM), agile manufacturing [43,44], next generation manufacturing (NGM) [45], to collaboration manufacturing [16]. The ecosystem architecture covers almost all aspects of a manufacturing system from different viewpoints of businesses and management.

Germany also has a developed and powerful industrial foundation. Industry 4.0 tries to embed knowledge to equipments, and update devices and production systems continuously through CPS and IoT. Keeping the leading position in high-end manufacturing industries is the starting point for Germany to put forward industry 4.0.

Principles and technology of lean production embodies the systematic consideration of Japanese manufacturing. Through improvement of enterprise culture and staff, manufacturing enterprises can improve their performance. Quality management theory and system provide the key methodology for Japanese Industrial Value Chain Reference Architecture [46].

China is facing more complex situations. Researchers conclude that most Chinese manufacturing enterprises are located in Industry 1.5 to 3.0. Few outstanding enterprises can try to implement Industry 4.0. Therefore, Chinese strategies are manifold. Integration of industrialization and informatization (iI&I) is the core of Chinese smart manufacturing implementation strategy.

## 3. Smart manufacturing architectures

Architecture is a description (model) of the basic arrangement and connectivity of parts of a system (either a physical or a conceptual object or entity) [47]. Architectures are widely used to describe top structures and internal relationships of complex systems. In order to develop a smart manufacturing solution and push a systematic standardisation, architectures are developed by different industrial organizations and SDOs.

- Smart Manufacturing ecosystem (SME) [40], developed by NIST;
- Reference Architecture Model Industrie 4.0 (RAMI4.0) [48], developed by Industrie 4.0;
- Intelligent Manufacturing System Architecture (IMSA) [42], developed by MIIT and SAC;
- Industrial Value Chain Reference Architecture (IVRA) [46], developed by IVI;
- Industrial Internet Reference Architecture (IIRA) [49], developed by industrial internet consortium (IIC);
- Framework for Cyber-Physical Systems (F-CPS) [50], developed by Cyber-Physical Systems Public Working Group, Smart Grid and Cyber-Physical Systems Program Office, and Engineering Laboratory, published by NIST;
- Internet of Things Architectural Reference Model (IoT-ARM) [51], developed by IoT-A project.

As shown in Fig. 2, based on the collaboration manufacturing management model [16] of ARC Advisory Group and the hierarchical model of ISO/IEC 62264, NIST describes the SME that encompasses manufacturing pyramid with three dimensions – product, production, and enterprise (business).

- Product. The product lifecycle is from design, process planning, production engineering, manufacturing, use & service, to EOL & recycling. And the information flows and controls along the product lifecycle are concerned a lot.
- Production. The production system lifecycle is from design, build, commission, operation & maintenance, to decommission & recycling. These lifecycle phases are mainly about an entire production facility including its systems.
- Business. The supply chain cycle is from plan, source, make, deliver to return, which mainly addresses the functions of interactions between supplier and customer.
- Manufacturing pyramid. This dimension is based on the IEC/ISO 62264 model - enterprise level, manufacturing operations management (MOM) level, supervisory control and data acquisition (SCADA) level, device level and cross levels, which is the vertical integration of machines, plants and enterprise systems.

Based on SME, the existing standards have a reference model to be classified and the standard landscape could be derived. These current standards related to smart manufacturing are classified and arranged into some standards groups along the four dimensions. However, those standards are not classified by the lifecycle phases of those dimensions. NIST classified them by functions within each dimension:

- Product. Standards are classified into five categories - Modelling Practice, Product Model and Data Exchange, Manufacturing Model Data, Product Category Data, and Product Lifecycle Data Management. Modelling practice standards define basic data about both 2D and 3D models. Product model and data exchange standards define the information to achieve data exchange between different vendor's CAX software. Manufacturing model data standard are mainly needed as Numerical Control programing language, which addresses how a product are manufactured from a design. Product category data and lifecycle data define data about products in a vendor-neutral way.
- Production. Standards are classified into Production System Model Data and Practice, Production System Engineering, O&M, and Production Lifecycle Management. Production system model data and practice standards is much like standards of modelling practice in the product dimension, which define information models for

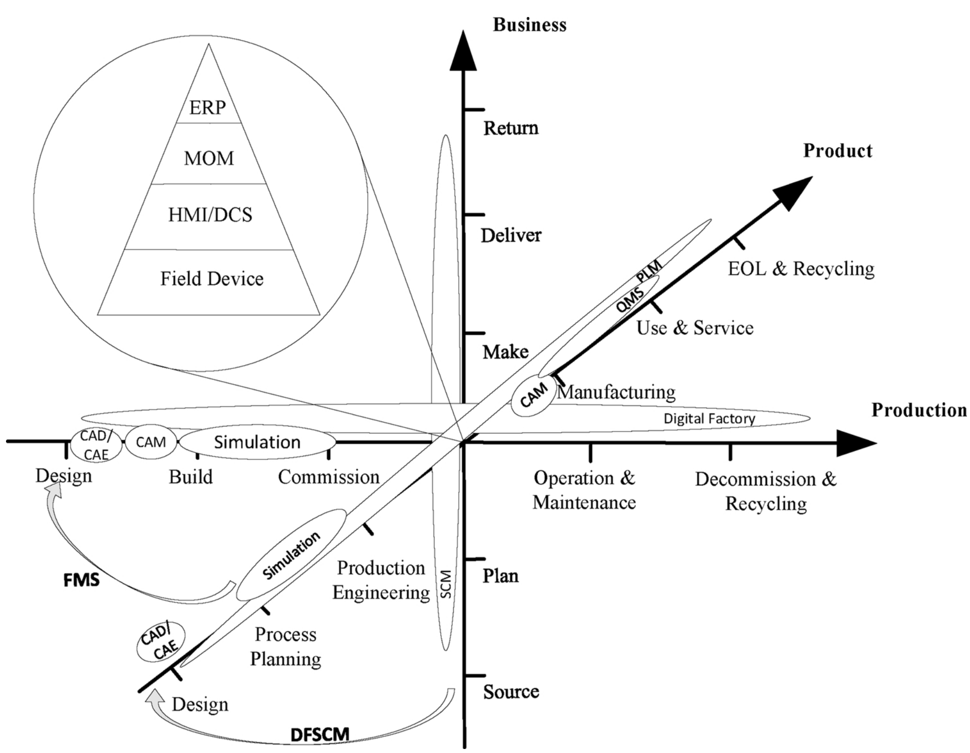



**Fig. 2.** Idea of SME according to NIST [40].

factory and production system design, for the production machine can be regarded as a product here. Product system engineering standards help to achieve interconnections between different disciplines. Production lifecycle management standards are about to handle the data generated along the production process and to achieve the integration, sharing and exchanging of them. O&M standards define functions related standards along the O&M lifecycle such as data processing, communication and monitoring etc.
- Business. Three sets of manufacturing-specific standards critical for integration are highlighted: APICS Supply Chain Operations Reference (SCOR), Open Applications Group Integration Specification (OAGIS), and MESA's B2MML.
- Manufacturing pyramid. The classification of the standards of the manufacturing pyramid is the same as the ecosystem, for the hierarchy of the pyramid is based on the IEC/ISO 62264 and its functions. Enterprise level standards are mainly about functions of the enterprise such as decision design and decision implementation. MOM level standards refers to applications controlling plant level operations. SCADA and device level standards are shop floor standards, which describe the control systems such as HMI, PLC and field components and their communication protocols. The cross-level standards are standards may be used cross all the levels, such as system security, quality management and energy management.

The existing standards are classified in the way above. However, there must be some requirements to decide whether a certain standard can be associated within this landscape. The NIST points out that to identify a standard as within scope, the standard must contribute to a capability. And the key smart manufacturing enabling capabilities are classified into four categories including productivity, agility, quality and sustainability by NIST. The productivity is the ratio of output to input, which can be broken down further to material and energy efficiency and so on. Agility means the ability to reacting quickly and effectively to changing markets to make more profits. Quality is about the capability of the products meeting design specifications. The example of applying this requirement of capability is that, the reason for why the standards about CAD, CAM, and CAx can be identified within the scope of modelling practice in the product development dimension is because these standards can improve engineering efficiency greatly and then the manufacturing system agility and product quality can be enhanced. Freitag and Zelm develop a similar lifecycles model with related information systems when they research Industry 4.0 and service lifecycle standardisation [52].

SME points out that current standards have not cover all areas of smart manufacturing. Al-Qaseemi et al. also point out that lack of standardization is the challenge and issue of IoT architecture [53].However, through the ecosystem and the standard landscape derived from the ecosystem and the capability model, new standards opportunity such as cyber security and intelligent machine communication standards can be easily analysed for which ecosystem dimension they belong to and which capability they could support.

Reconsidering the idea of SME shown in Fig. 2, dimensions of Product, Production and Business belong to the same technical field, management. The ecosystem emphasizes application of ICT in real manufacturing activities. Product lifecycle, production process and business process are in the same time dimension and dependent to each other. In the ecosystem architecture, it is very hard to see important position of industrial technology in smart manufacturing, such as 3D printing, intelligent robot, new material, and so forth. The ecosystem architecture only describes ICT application systems, such as CAD, CAM and SCM. The improvement of enterprise infrastructure cannot be found in the architecture, as well as cloud computing, big data, IoT, CPS, digital twin [54] and so forth. Therefore, NIST's smart manufacturing standardization mainly considers application fields.

The core idea of RAMI4.0 is shown in Fig. 3, which includes three dimensions to define the domains of industry 4.0.

- Layers: from asset, integration, communication, information, functional, to business. It includes asset layer representing the real, physical world and also a virtual map of the physical installation of a system.
- Life cycle & value stream: from development to maintenance/usage which is defined by IEC 62890. The difference between the "type" and instance is that, when an idea, a concept, or a thing, etc. remains a plan, it's a "type" and when it is available as a real and usable object, it becomes instance.
- Hierarchy levels: from product, field device, control device, station, work centres, enterprise, to connected world defined by ISO/IEC 62264 and IEC 61512.

Standards situation analysis, standard requirements analysis, and standard application analysis are discussed based on the reference model shown in Fig. 3. In accordance with this reference architecture model, the existing standards, existing models and new models should be incorporated within it. And characteristics, semantics and ontologies are required. Except for the system architecture model, reference models of instrumentation and control functions, the technical and organizational processes and reference models of life cycle processes are recommended.

Standards requirements are analysed in the aspect of reference model, and there are some other aspects of the standardization landscape:

- Fundamentals: standards about the use of common modelling and description techniques such as terms and modelling languages.
- Non-functional properties: standards about non-functional properties such as safety, security and IT-security, reliability and robustness and interoperability etc.
- Development and engineering: standards about the auxiliary and ancillary processes such as transparent and seamless database and development tools for the entire product life cycle and industrial location management etc.
- Communication: standards about industrial communication systems are needed such as line-based and radio-based communication and network management and topology etc.
- Addictive manufacturing: standards about 3D printing.
- Human beings in industry 4.0: standards about human beings such as further develop standards and specifications for people-friendly work design, concepts for a functional division of work between human being and machines and design of the interaction between them.
- Standardization process: the standardization process also needs standards to support it. The research directions could be open source development, formalization of stipulation, categorization of standards and exchange of documents etc.

Industry 4.0 has not a standards framework to cover all aspects of smart manufacturing and connect all related standards to present a solution for smart manufacturing implementation. Mazak and Huemer develop a standards framework for value networks in the context of Industry 4.0. However, their standards framework only covers standards of Business Operational View (BOV) related standards and Functional Service View (FSV) related standards, including REA (Resource-Event-Agent business ontology, ISO 15944-4), ISA95 (IEC/ISO 62264), B2MML (the Business To Manufacturing Markup Language), UMM (UN/CEFACT's Modeling Methodology, UN/EDIFACT, the United Nation's Centre for Trade Facilitation and Electronic Business), CCTS (Core Components Technical Specification), XML and Web Services [55]. Weyer et al. also analyse the crucial challenges of Industry 4.0 standardization, especially for highly modular, multi-vendor production systems [56]. Weyer's problem is a typical integration issue which needs systematic standards.

In order to prompt the integration progress of informatization and

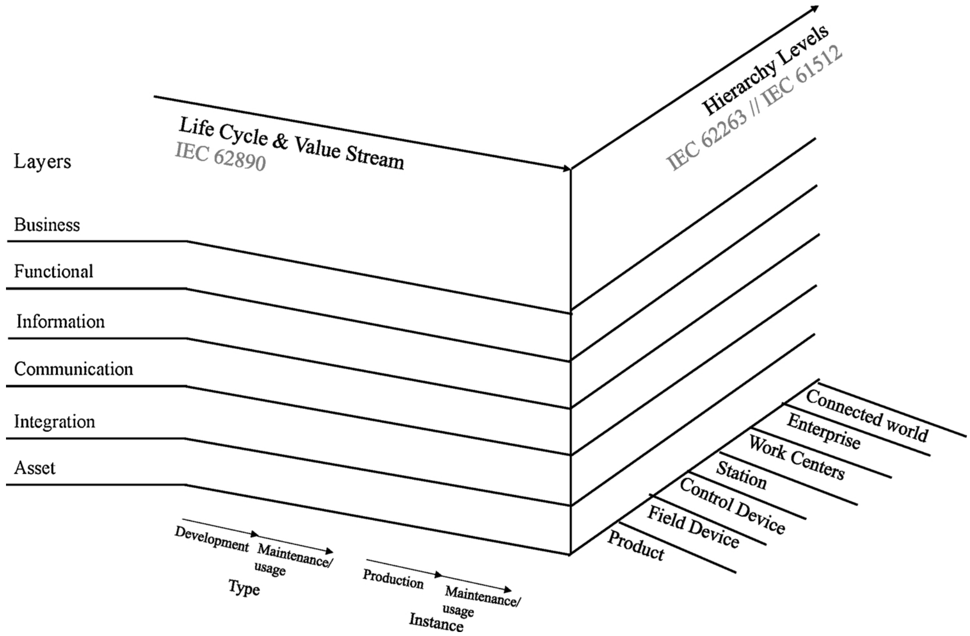



**Fig. 3.** Idea of RAMI4.0 [48].

industrialization of manufacturing industries in China, Chinese government envisaged a national strategy named Made in China 2025. Ministry of Industry and Information technology of China (MIIT) and Standardization Administration of China (SAC) published a joint report *National Intelligent Manufacturing Standards Architecture Construction Guidance* [42], providing reference model, terminology, evaluation indicators, and technology standards for intelligent manufacturing. The report announces that standardization should be taken as the top priority on the way from traditional manufacturing to smart manufacturing.

Intelligent manufacturing is named as the Chinese Industry 4.0 [57]. The main contribution of the corresponding report is the establishment of a three-dimensional Intelligent Manufacturing System Architecture (IMSA) shown as Fig. 4. According to the model, the scope of every smart manufacturing related technology can be determined in terms of dimensions of Life Cycle, System Level, and Smart Functioning. For instance, the scope of industrial robot within the model is presented in the building block formed by resource factors, equipment, and manufacture of Fig. 4, indicating that industrial robot technology affects

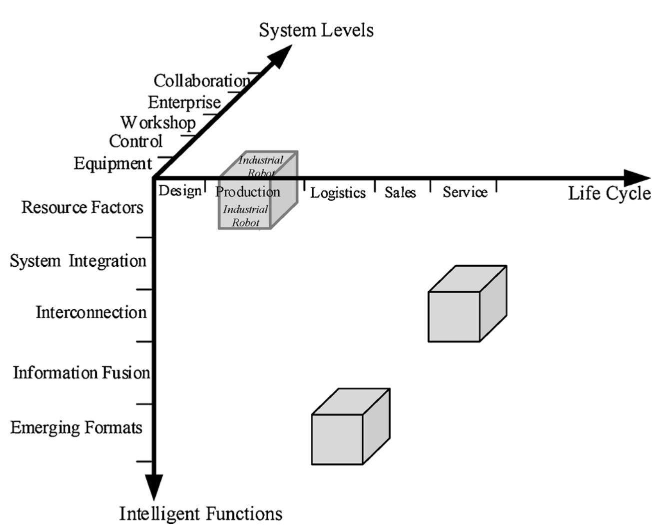



**Fig. 4.** Idea of the IMSA [42].

production process within the product lifecycle dimension, belongs to device and control level within the system level dimension, and can be seen as a resource for performing smart function.

In IMSA, a landscape of intelligent manufacturing standardization architecture, shown as Fig. 5, is proposed in assistance to standards classification. The landscape totally covers groups of five basic standard types, key technology standard types, industrial application standard types.

*National Intelligent Manufacturing Standards Architecture Construction Guidance* takes a first step in revealing the picture of standardization process in the area of smart manufacturing by providing a basic landscape of different categories of standards needed to be studied for smart manufacturing. In fact, standardization of smart manufacturing in China is still in its infancy and there is much should be investigated in a broader and deeper extent, that is:

- The compatibility and integration between standards of different domains requires deeper investigation.
- Scenarios of standardization process of smart manufacturing across various area of industry should have been developed.
- An evaluation framework used to assess the capability in terms of smart manufacturing implementation should have been developed to assist enterprises sketching out roadmaps to the transformation to smart manufacturing.

As shown in Fig. 6, Industrial Value Chain Reference Architecture (IVRA) observes smart manufacturing units from 3 views:

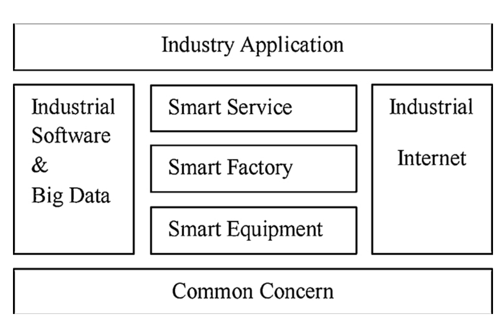



**Fig. 5.** Landscape of intelligent manufacturing standardization architecture.

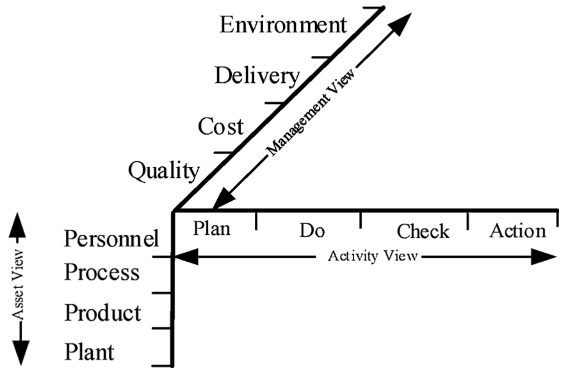



**Fig. 6.** Idea of IVRA.

- Asset view. The view shows assets valuable to manufacturing enterprises. Four classes of assets (personnel, process, product and plant) are distinguished.
- Activity view. The activity view is composed of the cycle of "Plan", "Do", "Check" and "Action", which is the core methodology of total quality management and business process continuous improvement.
- Management view. The management view shows targets of management. Quality, cost, delivery accuracy, and environment are included.

From IVRA, we cannot see detailed technology related to smart manufacturing. IVRA points out a manufacturing enterprise shall integrated personnel, process, product and plant, which are objects of enterprise management. Comparing with other architectures, IVRA points out enterprise operating management targets (performances) and presents the methodology for management improvement.

In 2012, GE proposed the concept Industrial Internet. In April 2014, GE, IBM, Cisco, Intel and AT&T started the Industrial Internet Consortium (IIC). In June 2015, IIC published Industrial Internet Reference Architecture (IIRA) and in Jan. 2017, IIC published the Industrial Internet of Things – Volume G1: Reference Architecture. As shown in Fig. 7, IIRA includes 3 dimensions: Viewpoints, Lifecycle Process and Industrial Sectors. Management fields are the core consideration of IIRA.

The development of smart manufacturing architectures has aroused worldwide attention, and there are several papers compare and research architectures mentioned above. Takahashi, Ogata and Nonaka use 4 aspects to compare these architectures and models: logical, physical, lifecycle and comprehensive [58], whose goal is to develop a Unified Reference Model for smart manufacturing, which follows the framework of UML and SysML. Papazoglou and Heuvel propose an architecture and knowledge-based structures for smart manufacturing networks [59]. The structure focuses on smart manufacturing system components and their relationships, which is a technical realization scheme. Mohsen et al. investigate the IIRA and RAMI4.0's commonalities, limitations and architectures in order to identify the existing technological gaps and make some recommendations for next-generation enterprises [60]. And also, many researches focus on IoT, which is one of the enabling technologies of smart manufacturing. Jasmin et al. compare several IoT-Platforms on the marked and reference architecture represented within them and finally introduced an IoT reference architecture and defined components involved in [61]. Cavalcante et al. compare two IoT reference architectures and discusses important issues for future [62]. Torkaman discusses ITU_T standard IoT reference architecture and also explore four other reference architectures: IoT-A, WSO2, Korean and Chinese perspectives, whose characteristics and capabilities are compared together [63].

Based on comparative analysis we can conclude that the construction of all these architectures is based on following principles:

- Decomposition. All architectures are described as multi dimensions diagrams. Every dimension shows one important aspect of smart manufacturing. For instance, SME includes 4 dimensions (business, product, production and manufacturing layers). RAMI4.0 includes 3 dimensions (layers, life-cycle & value stream, hierarchy levels). Some architectures further point out building blocks among different dimensions. For instance, in IMSA, Production in the dimension Life Cycle, Resource Factors in the dimension Intelligent Functions, and Equipment in the dimension System Levels form the building block Industrial Robot.
- Focalization. Not all elements and concepts of smart manufacturing are included in these architectures. All architectures focus on their own core concepts. For instance, SME only includes layers of enterprise—control system integration, and life cycles of business, production and product. IVRA emphasizes the important role of P (Plan), D (Do), C (Check), A (Action) cycle, which comes from total quality management.
- Strategic consistency. These architectures embody related national manufacturing strategies. SME embodies application areas of smart manufacturing. IMSA emphasizes new technical areas, such as PLC,


**Fig. 7.** Idea of IIRA.

industrial robot, which need further research and development investment. The lack of core technologies has always been a short board for the development of Chinese manufacturing.

As discussed above, smart manufacturing is the convergence of information technology, manufacturing (industrial) technology and management technology, and aims to take new capabilities and core competences to manufacturing enterprises. The developments of information technology, industrial technology and management technology, or domains of information technology, industrial technology and management technology can position elements of smart manufacturing with its standardization accurately.

Although above analysed architectures share some common ideas and similar concepts / elements, it is necessary to develop a general architecture and reference model of smart manufacturing and its standardization.

- A generalized architecture and reference model are needed to link the above-mentioned architectures together to realize interoperation among these architectures and models.
- In above-mentioned architectures, standards are located on every dimension. How to develop and use standards cover two or three dimensions, especially in the SME, has not discussed in detail.
- There are different viewpoints for standards development and implementation, how to combine them together is a big challenge.
- For a manufacturing enterprise, it is necessary to accept and apply a standards framework as a whole to support their smart manufacturing program. Therefore, how to describe standards clusters as a system is required.

Summarising the above discussions on various smart manufacturing architectures, as well as frameworks of IoT, CPS and so forth, we can get the result as shown in Table 1.

Currently, we are facing three technological revolutions: industrial technological revolution, information technological revolution and management technological revolution.

- Information technology is developing in different layers and directions. Information systems are coupled tightly with design process. From this viewpoint, CAD, CAE, CAM, CAPP, PDM/PLM are integrated into digital mock-up [64]. Infrastructure transforms from C/S, B/S, SOA to cloud computing. Database technology improves from local database, distributed database, cloud data storage, to big data cloud storage. Network technology develops from LAN, WAN, Internet, mobile Internet, to IoT. These directions are all important for smart manufacturing.
- Industrial / manufacturing technology is also developing quickly and supports smart manufacturing. Currently, new equipment, new manufacturing process techniques, new energy and new material get great achievements. For instance, 3D-print involves new print device, new materials and new information applications.
- Management technology is also developing quickly [65]. SME, RAMI4.0, and so forth all consider management processes from different viewpoints. Product lifecycle, production lifecycle, and supply chain are described in these architectures. Management layers are also included in these architectures. New manufacturing patterns are also springing up.
- The target of smart manufacturing implementation is to achieve new capabilities and core competences. IVRA emphasizes personnel improvement and enterprise culture development. Time, quality, cost, and environment is defined as core management performance indicators by IVRA. In SME, the key smart manufacturing enabling capabilities are classified into productivity, agility, quality and sustainability.

As shown in Fig. 8, core viewpoints of iI&I are defined based on above analysis. Smart manufacturing covers fields of industrial fields, information technology fields and management fields. At the same time, smart manufacturing tries to improve performances of enterprises. Therefore Fig. 8 has 4 dimensions: industry, information, management and human/organization. The 4 dimensions also show technology development and revolution directions.

As mentioned above, in the context of smart manufacturing, every dimension can be decomposed into several sub-dimensions. All of these sub-dimensions present detailed technology development directions. Sub-dimensions shown in Fig. 8 can be extended as necessary.

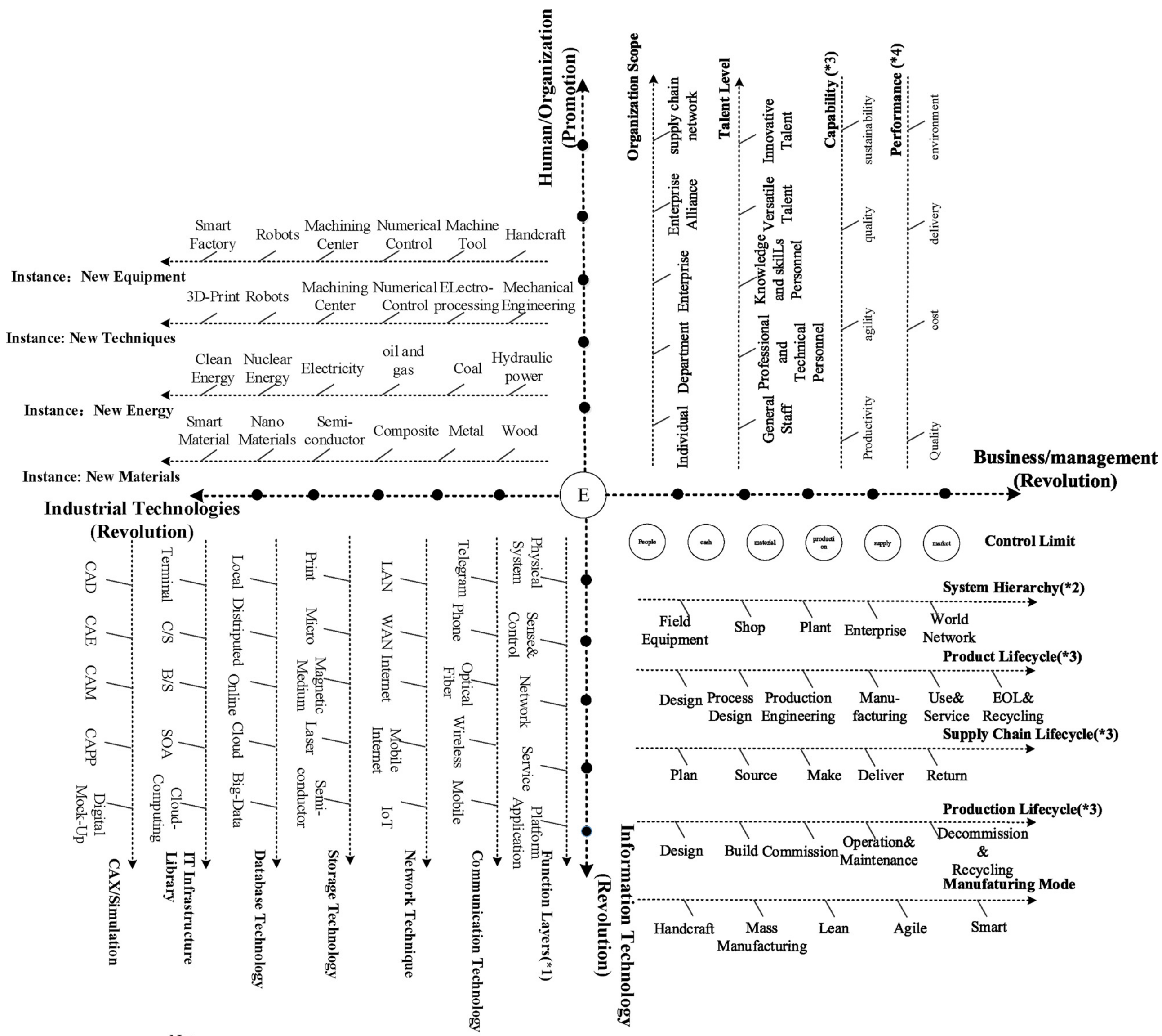
Different from SME, RAMI4.0, IVRA and IIRA, Fig. 8 embodies the situation of most developing countries. Because their manufacturing enterprises locate in Industry 1.5 to Industry 3.0, these countries are integrating the two progresses, industrialization and informatization.

## 4. Smart manufacturing standardization reference model

For a manufacturing enterprise, how to use smart manufacturing technology (industrial technology, information technology and management technology) to link manufacturing processes together is the core consideration. Enterprise lifecycle and hierarchy are two suitable dimensions indexes.

**Table 1**
Dimensions and sub-dimensions of smart manufacturing architectures and reference models.

| Dimension | Sub-dimensions | SME | RAMI4.0 | IMSA | IVRA | IIRA | F-CPS | IoT-ARM |
|---|---|---|---|---|---|---|---|---|
| Business / Management (domains, technology revolution) | System Hierarchy | x | x | x | x | x | | |
| | Product Lifecycle | x | x | x | x | x | x | x |
| | Business (Supply Chain) Lifecycle | x | x | x | x | x | x | x |
| | Production Lifecycle | x | x | x | x | x | x | x |
| | Manufacturing Mode Development | | | | | | | x |
| Industrial Technology Revolution | New Equipment | | x | x | x | | | |
| | New Manufacturing Process Techniques | | x | x | x | | x | |
| | New Energy | | | | x | | | |
| | New Materials | | | | x | | | |
| Information Technology Revolution | Function Layers | x | x | x | | | x | x |
| | Communication Technology Development | | x | x | x | x | x | x |
| | Network Technique Development | | x | x | x | x | | x |
| | Data Storage Technology Development | | | | | x | | x |
| | Database Technology Development | | x | x | | | | x |
| | IT Infrastructure Development | | x | x | x | x | | x |
| | CAX / Simulation Technology Development | x | x | | | | | |
| Human / Organization Promotion | Organization Management Scope | x | x | | | | | |
| | Human Resource Talent Levels | | | | x | | | |
| | Capability / Performance | x | | | x | | | |




Note:
*1: refers to Reference Architecture Model Industrie 4.0
*2: refers to ISO62264
*3: refers to Smart Manufacturing ecosystem, by NIST
*4: refers to IVRA

**Fig. 8.** Core viewpoints of iI&I.

Based on SIMA reference architecture Part 1 Activity model [66], which divides the manufacturing process of an enterprise into Design Product, Engineering Manufacture or Product, Engineer Production System, Produce Products, and Manage Engineering Workflow. The information systems relationship along research, development, and manufacturing whole lifecycle is shown in Fig. 9, in which we can see main activities of research, development, and manufacturing, as well as ICT's supporting to these activities.

- For R&D activities, CAD, CAE, and CAPP are involved. CAD, CAE, CAPP and CAM are step by step interconnected and integrated. PDM/PLM is implemented to integrate all design applications together. [67].
- For manufacturing activities, from physical layer, MES layer to business layer, multiple layers of the manufacturing pyramid shall be integrated [37].
- For business operation activities, there are four information systems: ERP, SCM, CRM, and PLM. Some additional information systems, such as BI (business intelligence), are integrated with the four systems [16].

The process and lifecycle of Fig. 9 combines product, production and business processes of SME. It also embodies lifecycles of RAMI4.0 and IIRA.

However, when dividing the smart manufacturing by functional activities, some universal integration technology and fundamental supporting environment techniques are implied. Through extracting the enabling technologies and fundamental environment technology and associating technologies to functional activities, a model which shows the supporting relationships between techniques can be derived, and it's shown in the Fig. 10. However, all above mentioned architectures have no definite description of information technology. Lack of core industrial and information technology is always a big challenge of China and other developing countries. Bujari, Furini et al. describe a similar framework of IoT architecture, which includes 4 bottom-up layers: Objects, Communication, Platform and Application [68].

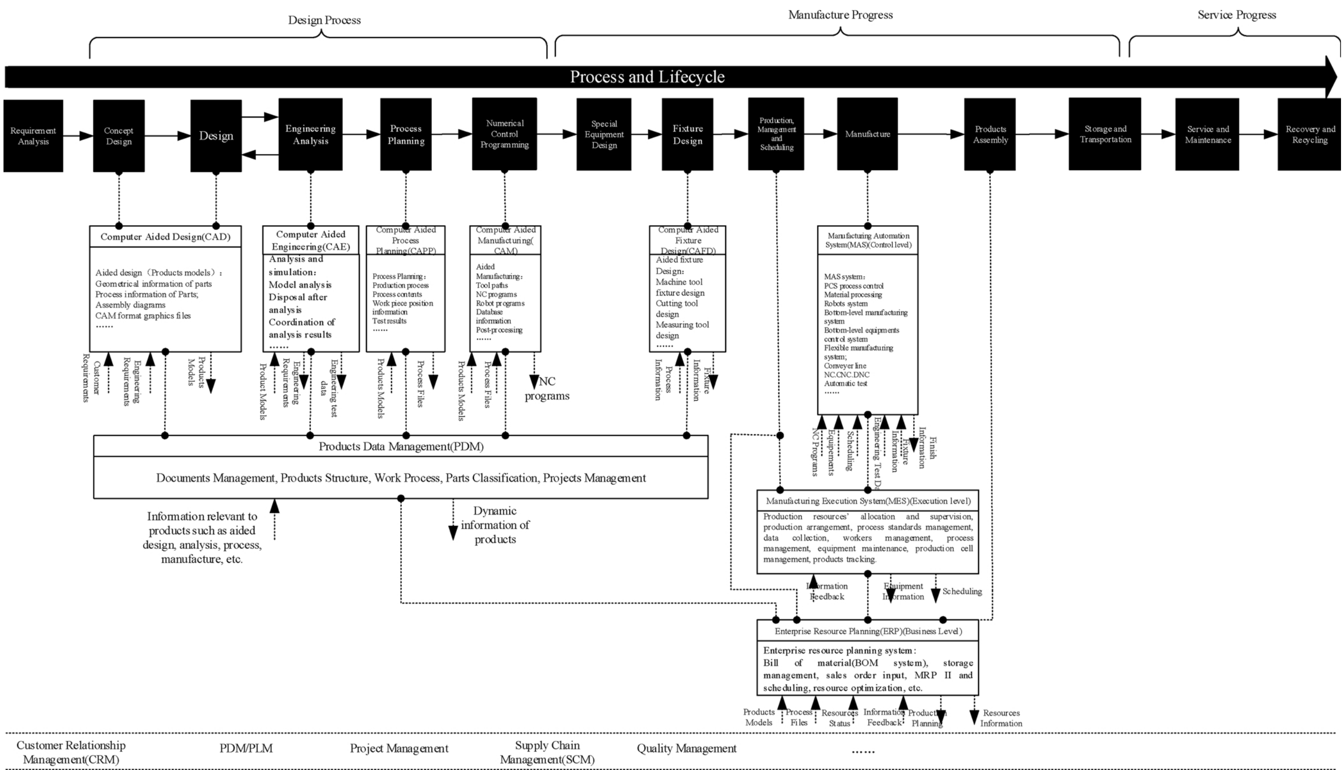



**Fig. 9.** Information systems relationship along R&D & manufacturing whole lifecycle.

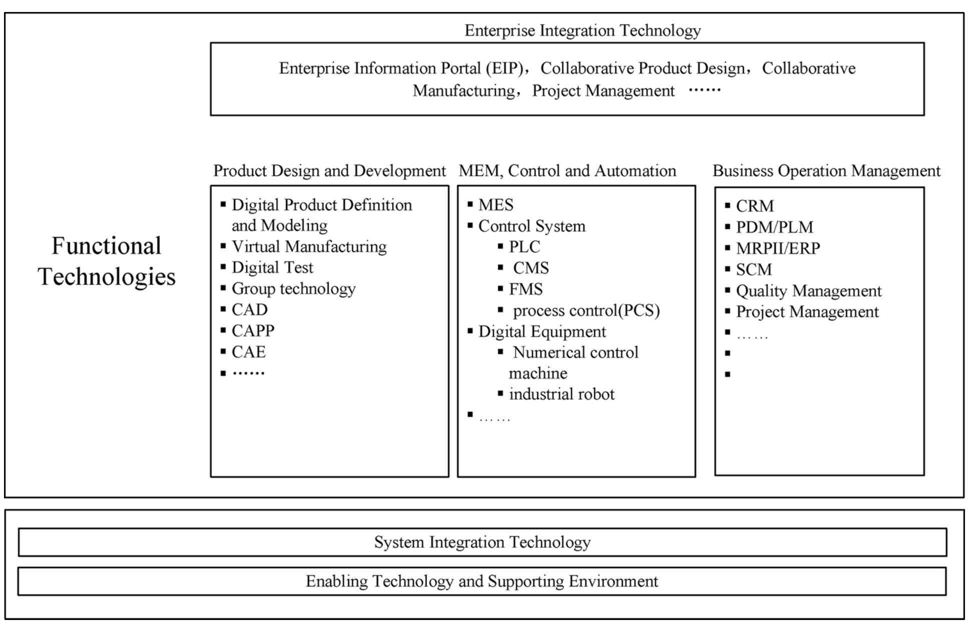



**Fig. 10.** Hierarchical decomposition of smart manufacturing technologies.

Information systems shown in Fig. 10, such as CAD/CAE, SCM, CRM, are also shown in SME. Choi, Jung, Kulvatunyou and Morris analyse technologies and standards for smart manufacturing systems, and present a summary of related standards [69].

Here is the detailed description about each part of the model shown in Fig. 10.

- Functional technologies: supporting certain business process and function. They use all kinds of enabling technology to accomplish related business activities, which have direct relations with functional divisions of an enterprise. Usually, they are combined with commercial application systems such as CAD, CAM, CAE and CAPP [70].
- System integration technology: supporting the interconnection, communication and interoperation among functional technologies [71].
- Enabling technology and supporting environment: relating to hardware and software. They are enabling technology to develop functional technologies and support system integration, which including computer graphics, operating systems and network protocols etc [72]. Ponnusamy and Rajagopalan present a survey on IoT protocol standards [73]. Furtherly, Trappey et al. review essential

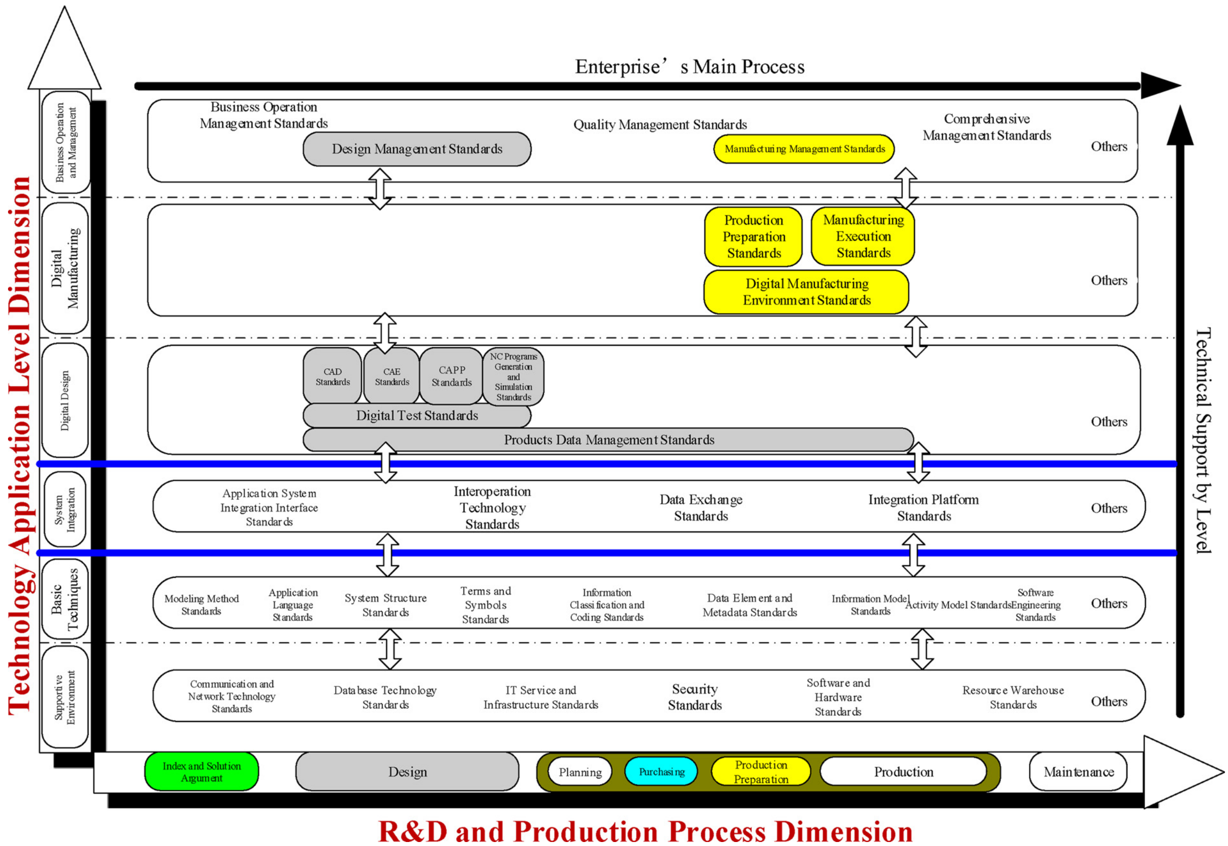



**Fig. 11.** Smart manufacturing standardization reference model.

standards and patent landscapes for IoT, they form a multi layers, tree style standards framework. [74].There is tremendous amount enabling technology standards. Trappey et al. believe IoT with its standards is a key enabler for Industry 4.0.

However, models shown in Figs. 9 and 10 cannot describe relations among different technologies, and cannot provide further guide for the application of these technologies with related standards. Therefore, a more effective smart manufacturing standardization reference model (SMSRM) is required.

In order to guide smart manufacturing implementation and integration, it is necessary to analyse and describe elationship among technologies. However, technologies related to smart manufacturing are various, numerous and fast updating, and they are also different in their developing process and background of application. This situation makes relationships among technologies complicated. To express these relationships clearly, a high dimensional architecture is required, which, however, is impractical. The reasonable approach is to pick up less but important dimensions to construct the SMSRM.

From viewpoints shown in Fig. 8, SMSRM shall consider about requirements of enterprise collaboration and integration, and realize following two kinds of integration:

- From bottom level automation system, through manufacturing execution system, to decision supporting. All layers of an enterprise shall be integrated, and then the integrated system shall be extended to integrate from suppliers to customers (the whole value chain), and realize inter enterprises collaboration. IEC/ISO 62264 defines the multi layers manufacturing Pyramid, which is the important component of SME and RAMI4.0. It is also a sub-dimension in Fig. 8.
- Because informatization relates to multiple enterprise business fields, including research, development, production, service, decision and so forth. SMSRM shall consider the whole business / value chains. SME, RAMI4.0, IMSA and IIRA all introduce kinds of lifecycles and processes. Fig. 8 presents another kind of description of these processes and progresses.

Therefore, the analysis dimensions SMSRM can be defined into two aspects:

- Technology application layers;
- Life cycle and value stream.

There are natural supporting relationships between technology fields. For instance, the CAD and CAE techniques are the core techniques in the field of designing, and, however they are commonly used in the manufacturing field, which can be regarded as the techniques in designing fields supporting the manufacturing techniques. Through the further research, fundamental technology and supporting environment, system smart design technology, manufacturing technology, business operation and management technology have these supporting relations. Computer-aided design and manufacturing all need the support of the fundamental technology and supporting environment, manufacturing techniques need the support of the design techniques, intelligent management will use the techniques of the digital manufacturing, and when those functions are needed to be integrated, the integration techniques are needed. So, the first dimension is divided as the business supporting techniques, which includes smart design technology, manufacturing technology, business operation and management technology, system integration techniques, and basic techniques and fundamental environment.

Along the dimension of the Life cycle and value stream, the product design and manufacturing whole life cycle is considered and the main activities are divided as solution argument, design, plan, purchase, production preparation, production, use and maintenance.

Analysing an enterprise from the aspects of the organization,

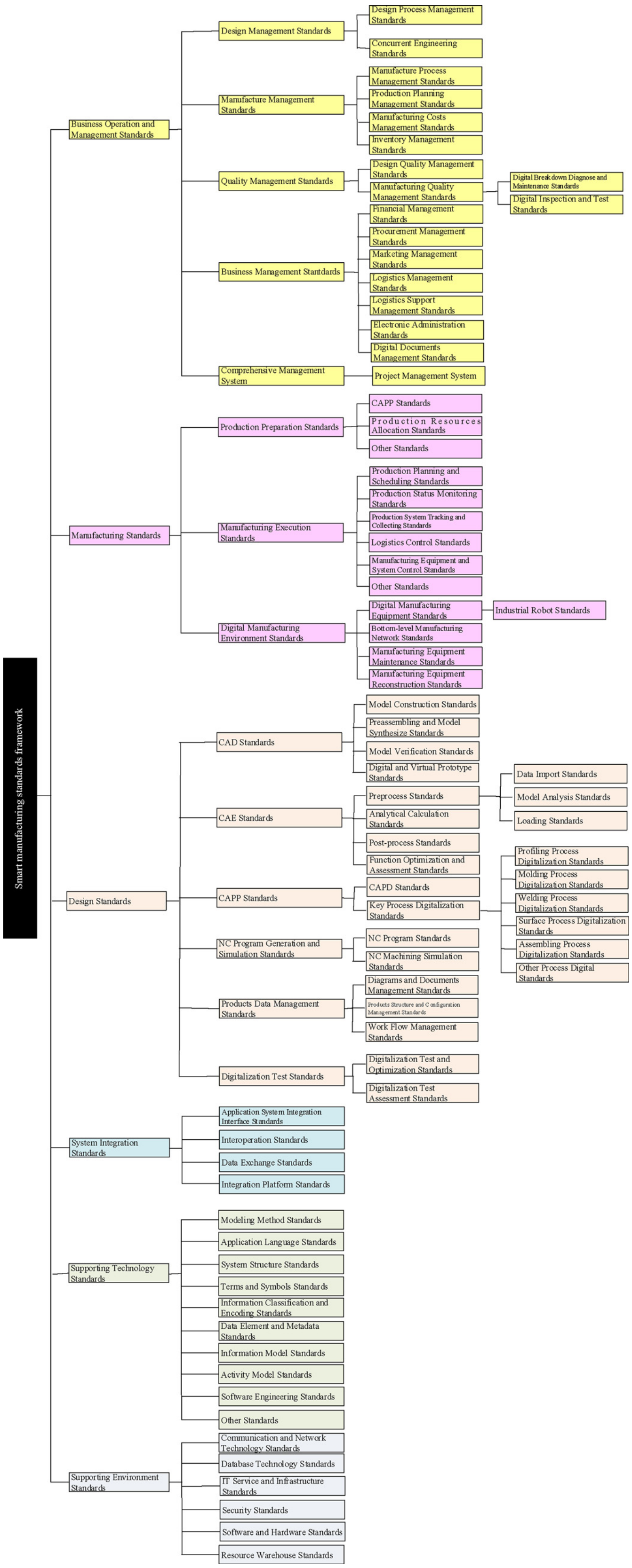



**Fig. 12.** Smart manufacturing standards framework.

function, information, resource and business and process is more comprehensive. In the above given architectures, the dimension of the techniques application layers can partly demonstrate information about function and organization, the dimension of the life cycle and value stream can demonstrate information of process and business, and the relations between the application of different layers can demonstrate the relations of the information flow between them. This architecture has a stable structure.

Integration technologies have great impact and significance of realizing the integrated operation between techniques which are from different types and fields and realizing information benefits. Generally speaking, according to the difference of the realization methods, way and degree of the integration, current integration techniques can be classified as system integration interface technology, interoperability, data exchange technology, and the integration platform technologies, etc. Integration technologies are used in functions related techniques in all levels and, also, they are supported by fundamental techniques and environment.

To apply those mentioned above techniques of all levels, and to accomplish the integrated operation of them to achieve the ICT's advantage and benefit, the related fundamental techniques are required. For instance, enterprise modelling methods and enterprise reference model technology are needed when analysing an enterprise, designing, planning and implementing system integration, and knowledge and technology about data element and metadata are required when achieving the information exchange among systems. There are many technologies likewise, and the upper level techniques and those fundamental techniques own many-to-many relations. To sum up, the main techniques of the basic techniques level are modelling method, application language, system structure, terms and symbols, information classification and coding, data element and metadata, information model, activity model software engineering and etc. In SME, ISO15704, 19439, 19440 20140, OAGIS, BPMN, DMN, PMML and B2MML are placed in the top-most level of manufacturing pyramid. These standards are also components of MBSE and system of systems engineering, which are main developing directions of systems engineering technology [75].

The implementation of information system in an enterprise is usually in a gradual process, which make an enterprise implementing single application (such as automation equipment, or some management systems) one by one and step by step. These systems are always not integrated and thus form lots of so-called automation isolation islands. Technologies of the fundamental environment level are significant and indispensable, which includes communication and network technology, database technology, IT service and infrastructure, IT security, software and hardware and resource warehouse and etc. Developments of these technologies can be found in sub-dimensions of information technology of Fig. 8.

In order to guide standardization activities, SMSRM shall also consider following ideas:

- The decomposition of techniques used by business operation and management is not based on current information systems (i.e. ERP, PLM, SCM, CRM and so forth), but based on management fields, which include design management, manufacturing management and business management. Thus, it can avoid focusing on commercial information systems and keep the stability of standards framework. Application problems of information systems are classified into the combined management.
- Integration techniques are not located among functional technologies. For instance, they are not classified as 3C integration, PDM & ERP integration. They are classified as integration interface, interoperability, integration platform and so forth based on the common properties of integration techniques.
- Manufacturing process is divided into production preparation and manufacturing excursion, supported by smart manufacturing environment.

Fig. 11 is the resulting SMSRM.

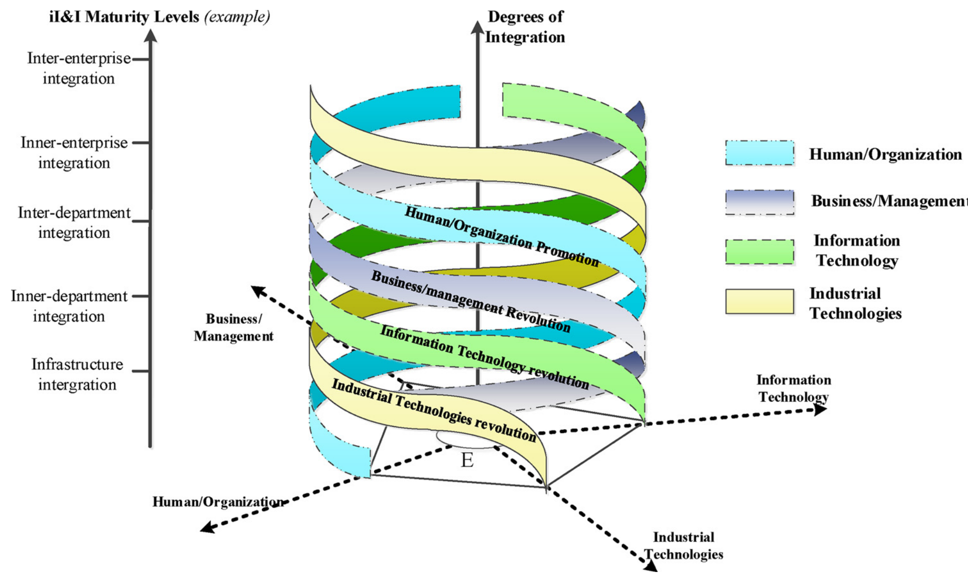



**Fig. 13.** iI&I reference architecture.

## 5. Smart manufacturing standard framework

Based on the SMSRM, the smart manufacturing standards framework can be derived by the methodology as following:

- To derive the basic structure elements according to the application domain decomposition of technologies (ICT, industrial technology and management technology).
- To formulate the basic framework in two dimensions: technology application layers and Life cycle / value stream.
- To locate the elements technology in the domain, integration technology, basic technology and support environment in the framework, and then determine the basic technical standards.
- To build relevant standards according to those technologies.
- To generate the detail branches iteratively.

However, to be sure, as technical system (IT product and industrial equipment) standards are concerned and used by specialized hardware and software system developers. When enterprises choose a certain technical system of a vendor, they choose the related standards. Because implementation of technical systems in an enterprise is usually in a gradual model, which always lead to automation isolations. Therefore, technologies of the fundamental environment level are significant and indispensable. They are communication and network technology, database technology, IT service and infrastructure, security, software and hardware and resource warehouse and etc.

Although we pointed out that the standards reference model should be correspond to the smart manufacturing architectures and reference models, for the SMSRM can be easier to understand and operate, a one-dimensional simplified model is needed. So, the smart manufacturing standards framework can be derived, which is shown in Fig. 12.

Specifically, it includes the following several main parts:

- Smart design standards: the group of standards are expanded along the order of design activities, supported by data management standards. The standard framework decomposition does not follow the classification of design subjects.
- Smart production standards: the group of standards are expanded based on working process and technical supporting.
- Business operation and management standards: the group of standards are focused on management activities for design and production. ERP, SCR, CRM, MES, these commercial applications are not used as standards categories. Their implementation standards are discussed in combined management standard group.
- System integration standards: the group of standards relate to common technologies that integrate systems of different domains. They are classified based on technical types but integration software.
- Fundamental technologies and supporting environment standards: the group of standards includes standards on common supporting technologies, such as infrastructure, database, meta data technology and so forth.

## 6. Summary and conclusion

Smart manufacturing is a systematic technology, which relates to ICT, industrial technology and management technology. Smart manufacturing system is a huge scale complex system. Standardization is a powerful tool to push the development and implementation of smart manufacturing technologies.

NIST, DIN, MIIT&SAC and so forth published standards landscapes, standardization roadmaps, or standardization construction guidance for smart manufacturing. Currently existing standards are arranged in related architectures. Based on results of comparing and analysis, the paper develops a reference model for smart manufacturing standards development and application. A smart manufacturing standards framework is also developed.

Based on the developed standards framework, manufacturing enterprises have a guidance in recognizing, organizing and implementing existing smart manufacturing standards. At the same time, technology and standard researchers shall focus on those blanks in the standards framework.

The paper also conclude that smart manufacturing is currently standing on the junction point of ICT revolution, manufacturing (industrial) technology revolution and management technology revolution, smart manufacturing is a realization path of iI&I. Because iI&I with smart manufacturing is a long developing progress, with the development of information technology, industrial technology and management technology, enterprise performance will improve continuously, and iI&I with smart manufacturing will spiral up. Fig. 13 is the reference architecture of iI&I, in which ICT, industrial technology, and management technology interact with each other and push enterprise performances improvement.

In Fig. 13, the four spirals come from the four dimensions in Fig. 8 which embody the interaction of ICT development, industrial technology development, management technology development and enterprise performances improvement. The interaction is also the driving force for smart manufacturing and related standardization.

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