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Smart Manufacturing: Past Research, Present Findings, and Future Directions

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Today, the manufacturing industry is aiming to improve competitiveness through the convergence with cutting-edge ICT technologies in order to secure a new growth engine. Smart Manufacturing, which is the fourth revolution in the manufacturing industry and is also considered as a new paradigm, is the collection of cutting-edge technologies that support effective and accurate engineering decision-making in real time through the introduction of various ICT technologies and the convergence with the existing manufacturing technologies. This paper surveyed and analyzed various articles related to Smart Manufacturing, identified the past and present levels, and predicted the future. For these purposes, 1) the major key technologies related to Smart Manufacturing were identified through the analysis of the policies and technology roadmaps of Germany, the U.S., and Korea that have government-driven leading movements for Smart Manufacturing, 2) the related articles on the overall Smart Manufacturing concept, the key system structure, or each key technology were investigated, and, finally, 3) the Smart Manufacturing-related trends were identified and the future was predicted by conducting various analyses on the application areas and technology development levels that have been addressed in each article.

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1. Introduction

Since the industrial revolution that started in the UK in the middle of the 18th century with the steam-engine development, through the mass production system in the early 19th century thanks to the commercialization of the electricity, and to the development of ICT (Information and communication technology) and introduction of automation system in the late 20th century, the manufacturing industry has been building innovative advances that could possibly be called revolutionary. Currently, the advances in ICT technologies have repeatedly progressed in various fields, including H/W (hardware) and S/W (software), and may bring a renaissance or a new revolution to the manufacturing industry. Smart Manufacturing may have the driving force of this new revolution. It is a collection and a paradigm of various technologies that can promote a strategic innovation of the existing manufacturing industry through the convergence of humans, technology, and information. While lean manufacturing focused on cost saving through waste elimination during the 80s and 90s, Smart Manufacturing is a future growth engine that aims for a sustainable growth via management and improvement of the existing major manufacturing factors, such as productivity, quality, delivery, and flexibility based on technology convergence and various elements over societies, humans, and environment. NIST (National Institute of Standards and Technology), which is an agency of the U.S. Department of Commerce, defines Smart Manufacturing as "fully-integrated and collaborative manufacturing systems that respond in real time to meet the changing demands and conditions in the factory, supply network, and customer needs."[1] In other words, it means that the active manufacture-based technologies and systems that can respond to complicated and diversified situation of manufacturing field in real time. Advanced manufacturing countries, such as Germany and the U.S., have already been developing technologies in various fields to realize Smart Manufacturing over the past few years. The major technologies are IoT (Internet of Things), CPS (Cyber-Physical System), cloud, etc. These technologies were developed as cutting-edge ICT technologies, and they have been applied to various fields such as manufacturing, health, building management, etc. Smart Manufacturing can be successfully realized through a balanced development and application of those major key technologies. For this purpose, the current level needs to be checked by analyzing the research and development status of the total concept while each technology in the perspective of successful realization of Smart Manufacturing, as well as future directions in the aspects of technology development and applied strategies, need to be suggested accordingly.

In this paper, the past and present levels of Smart Manufacturing were analyzed by investigating the existing related studies, technologies, and articles, and then the future technology development directions were suggested. The policies related to Smart Manufacturing in Korea were analyzed based on the cases of Germany and the U.S., as they are very active in developing related technologies. Key technologies related to Smart Manufacturing were found and the articles related to those technologies were investigated. The future research directions for the technologies related to Smart Manufacturing were suggested after analyzing the current trends.

2. Composition of Analysis Process

This chapter describes the investigation and analysis method used in this paper to understand the past and present trends and technology levels of Smart Manufacturing. The overall procedures were as shown in Fig. 1 (1) survey and review national strategies and policies, (2) classify data and select core technologies, (3) organize data related to core technologies, and (4) final analysis and discussion.

In further detail, the Industry 4.0-related data of Germany, NIST or SMLC (Smart Manufacturing Leadership Coalition) related data of the U.S., and the policies and research plans propelled by MOTIE (Ministry Of Trade, Industry and Energy) or MSIP (Ministry of Science, ICT and Future Planning) of Korea were reviewed to select core technologies. The studies and data related to the selected core technologies were summarized and organized based on keywords, factory applications, and engineering processes. Time series analysis and correlation analysis were performed on the organized data to analyze research status levels, application areas of each technology, such as a system, equipment, or a factory, in the aspect of infrastructure, and the targeted steps of each technology on a factory development process. The areas with relatively low level of current technology and the areas with high correlation of each technology were also summarized. Based on this, the past and present technologies related to Smart Manufacturing were discussed, and the future directions were suggested. The targeted articles in this paper are largely divided into two. The first consisted of the policies or strategic technology data of major countries, such as Germany, the U.S., and Korea, which are strategically driving Smart Manufacturing. The second consisted of studies and reports dealing with the technologies related to Smart Manufacturing. The range of the studies and reports was from highly related to Smart Manufacturing to general manufacturing application of each core technology of Smart Manufacturing. The articles from 2005 to 2015 were used.

3. Global Trends of Smart Manufacturing Technology

In this chapter, the policies and research trends of advanced manufacturing countries, such as Germany and the U.S., were summarized along with the policies and research plans of Korea that are mainly from MOTIE and MSIP. Through this, the key technologies needed to realize Smart Manufacturing were identified, and the studies and reports for the related technologies were summarized.

3.1 Government Programs

3.1.1 Germany

The German government announced Industry 4.0 to establish smart factories that are the ultimate realization of Smart Manufacturing, and it is a combined project involving the private sector, government, and academia. The Industry 4.0 concept was first announced at the 'Hannover Messe 2011' that was held in Germany. The final report on Industry 4.0 specified that it creates new values that have not been seen before, constructs new business models, and resolves various social problems by linking the things inside and outside a factory and services through the communication networks based on CPS, IoT and IoS (Internet of Services).[2]

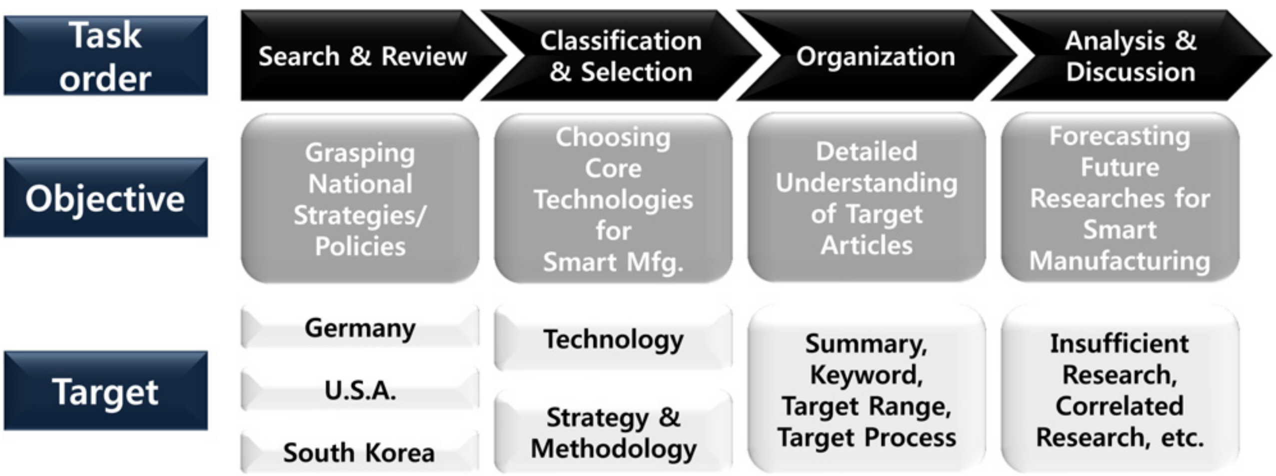

Fig. 1 Procedure of review and analysis

Figs. 2-4 show reference architectures and diagrams for the basic concept of Industry 4.0. Fig. 2 shows the link of IoT and IoS around a smart factory based on CPS. Fig. 3 shows more concrete architecture, which consists of IoT that secures connectivity at a factory site, service platforms that link IoT and IoS while performing CPS functions, IoS that links applications to business processes, and applications for each area.

Fig. 4 is an example reference architecture for a CPS platform that corresponds to the key component of a smart factory. The integration of the existing systems or platforms such as MES (Manufacturing Execution System), ERP (Enterprise Resource Planning), and CRM (Customer Relationship Management) and the construction of Data-backbone effectively manage complex systems and provide various functions that can be utilized in the applications area.

Reports mentioned that IoT, IoS, and CPS must be established to integrate these existing complex systems, and that various IT technologies, modeling, simulations, big data, cloud computing, sensors, and smart energy technologies were required. In addition, Industry 4.0 is being propelled not only for the realization of smart factories, but also in the following 8 assignments including innovations in overall conditions, such as personnel and laws.[2]

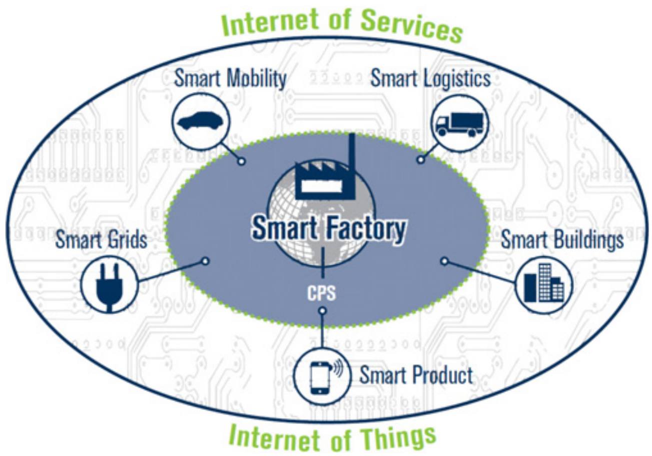

Fig. 2 Industry 4.0 and smart factories as part of the IoT and IoS[2]

- Standardization and reference architecture
- Managing complex systems
- A comprehensive broadband infrastructure for the industry
- Safety and security
- Work organization and design
- Training and continuing professional development
- Regulatory framework
- Resource efficiency

3.1.2 The U.S.

The U.S. is aggressive in budgeting research and development, and executing programs for manufacturing, which is also called an advanced manufacturing or Smart Manufacturing, a high technology in an effort to expand the revival of manufacturing. The research and development programs related to manufacturing in the U.S. focus on key technology assignments, including IoT, big data, data analytics, CPS, system integration, sustainable manufacturing, and additive manufacturing to respond aggressively to the innovative manufacturing environment change called the fourth industrial revolution. The meaning of each key assignment is as follows.

• Internet of Things: Embedding sensors and communication equipment in manufacturing machineries and lines.

• Big Data and Data Analytics: Developing software and systems that can interpret and analyze mass incoming data.

• Cyber-physical System and System Integration: Developing mass production systems that are capable of highly efficient and flexible real-time control and customization.

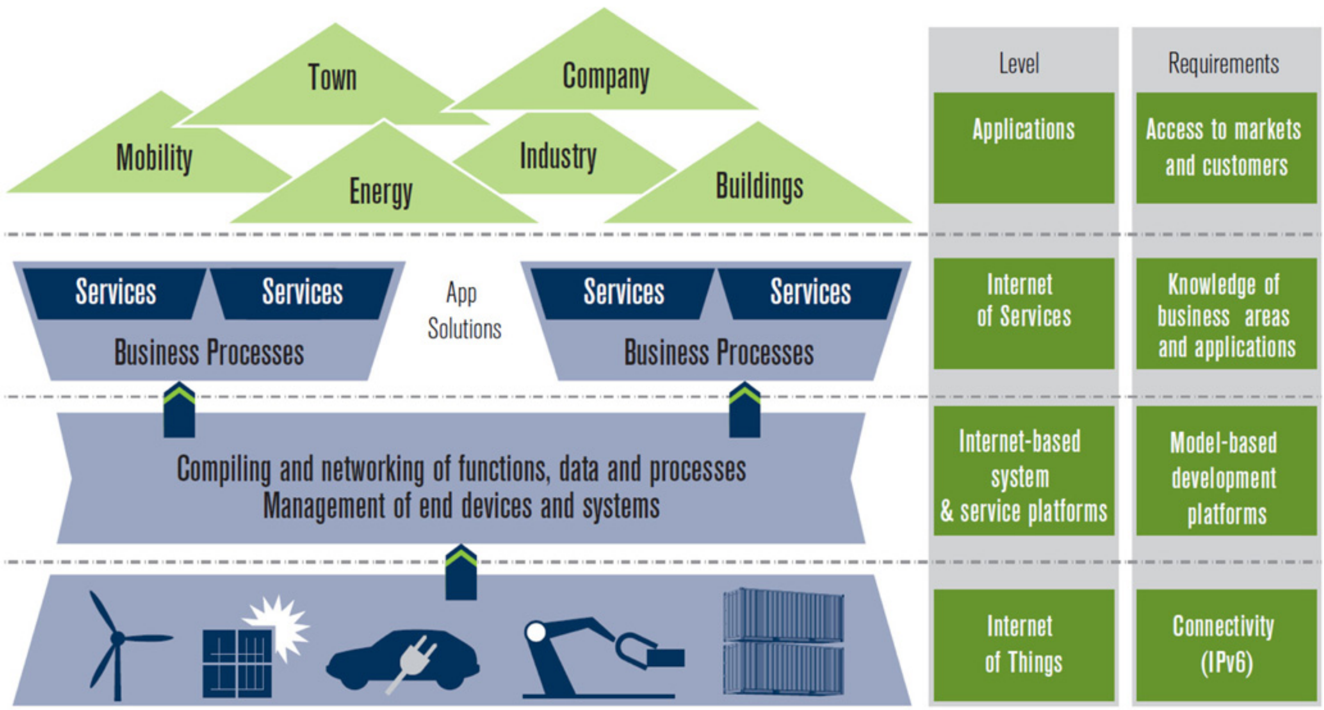

Fig. 3 Reference architecture for connecting IoT and IoS[2]

• Sustainable Manufacturing: Developing production systems that can increase resources 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: The method of applying 3D printing technologies to the manufacture of components and products, which can reduce time and cost for product development and manufacture.[3]

In an effort to secure cutting-edge manufacture capability, the government launched SMLC, which is a pan-national research and development consortium, for inter-departmental discussions. Currently participating are 25 companies, 7 universities, 8 consortiums, and 1 government research institute. They are suggesting and performing the concrete action plans, such as concept establishment, technological goals, a roadmap, and role assignment.

Fig. 5 is a diagram of a Smart Manufacturing platform. The goal of the platform is for the innovation of cutting-edge manufacture and

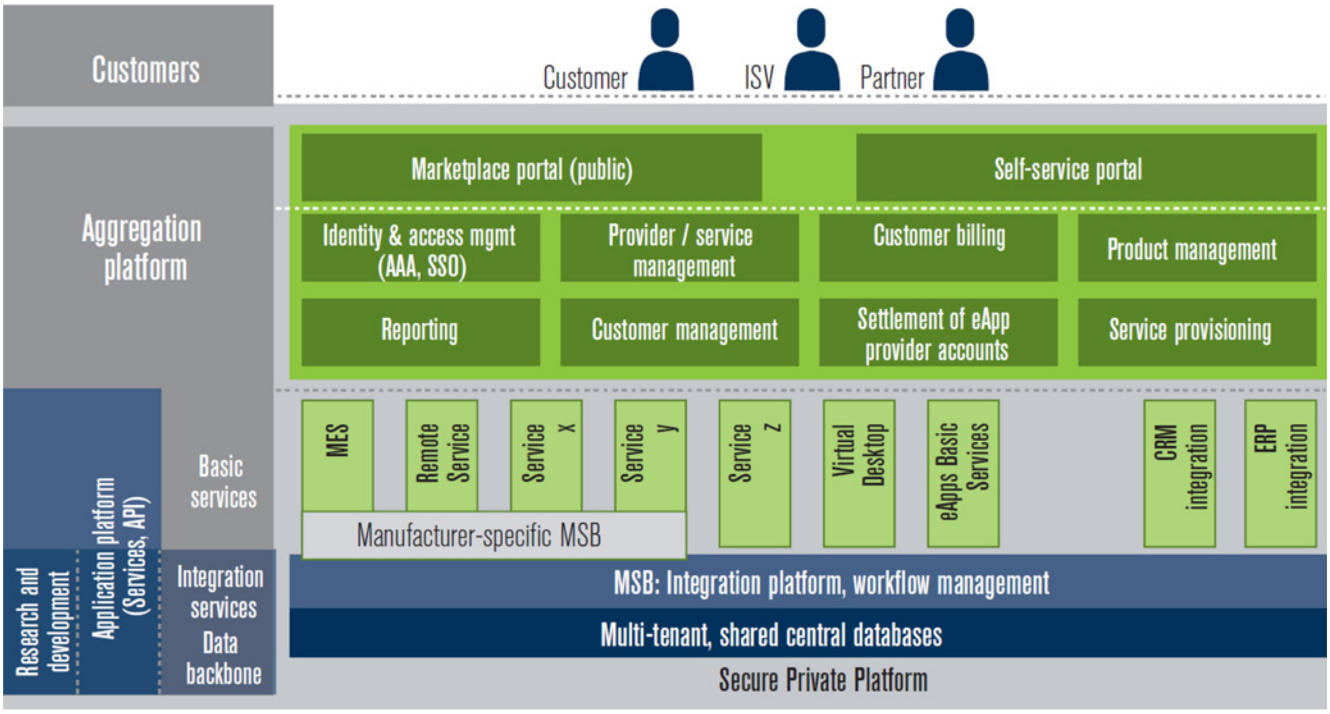

Fig. 4 Example reference architecture for a CPS platform[2]

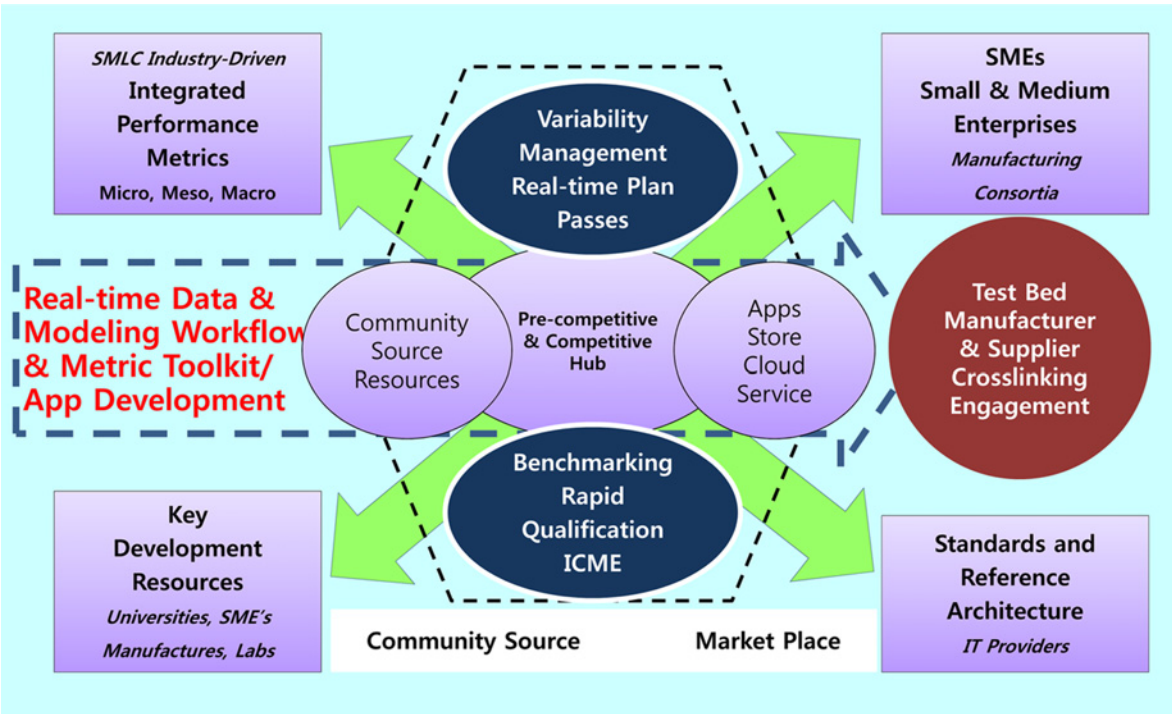

Fig. 5 Smart manufacturing platform[105]

collaboration. Table 1 shows an action roadmap composed of 10 work packages for the efficient achievement of Smart Manufacturing realization. The roadmap mainly consists of modeling, simulation, data collection and management, enterprise-wise integration, education, and training. The contents are conceptually similar to the goals of 8 assignments in Germany.

The key technologies of a smart factory realized through the roadmap are summarized as follows.

• Networked sensors: Data for communications, 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 product, process, and project data is enabled through interoperable data systems 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 via 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 SM but they must be effectively integrated with human learning and decision environment.

• Scalable and multi-level cyber security: System protection from cyber vulnerabilities (without compromise of functionality) is needed throughout the manufacturing enterprise.[3,4]

NIST is an agency of the U.S. Department of Commerce and it is performing an essential role in developing Smart Manufacturing technologies as the only government agency that beongs to SMLC. NIST established the strategies of dynamic production system and rapid design-to-product through smart manufacture research programs. It suggested 3 key action technologies, namely, decentralized control network, digital manufacturing, and decentralized machine intelligence, in order to achieve the strategies. NIST also suggested 3 key performance indexes, namely, agility, asset utilization, and sustainability, in terms of efficiency. NIST is operating 4 Smart Manufacturing research programs and sub projects as shown in Table 2.[5]

Table 1 Ten priority action for smart manufacturing[3]

<table>
<tr><td colspan="4">Industrial community modeling and simulation platforms for smart manufacturing</td></tr>
<tr><td>Create in community platforms (networks, software) for the virtual plant enterprise</td><td>Develop next generation toolbox of software and computing architectures for manufacturing decision-making</td><td>Integrate human factors and decisions into plant optimization software and user interface</td><td>Expand availability of energy decision tools (energy dashboards, automated data feedback systems, energy ‘apps’ for mobile devices) for multiple industries and diverse skill levels</td></tr>
<tr><td colspan="4">Affordable industrial data collection and management systems</td></tr>
<tr><td colspan="2">Establish consistent, efficient data methods for all industries (data protocols and interfaces, communication standards)</td><td colspan="2">Develop robust data collection frameworks (sensors/data fusion, machine and user interfaces, data recording and retrieval tools)</td></tr>
<tr><td colspan="4">Enterprise-Wide integration: business systems, manufacturing plants, and suppliers</td></tr>
<tr><td>Optimize supply chain performance through common reporting and rating methods (dashboard reports, metrics, common data architecture and language)</td><td>Develop open platform software and hardware to integrated and transfer data between small and medium enterprises (SMEs) and original equipment manufacturers (OEMs) (data sharing systems and standards, common reference architectures)</td><td colspan="2">Integrate product and manufacturing process models (software, networks, virtual and real-time simulations, data transfer systems)</td></tr>
<tr><td colspan="4">Education and training in smart manufacturing</td></tr>
<tr><td colspan="4">Enhance education and training to build workforce for smart manufacturing (training modules, curricula, design standards, learner interfaces)</td></tr>
</table>

Table 2 Smart manufacturing research programs and projects of NIST[5]

Programs	Sub projects
Smart manufacturing system design and analysis	Reference structure Modeling methodology Real-Time data analytics Performance assurance
Smart manufacturing action plan and control	Execution management Wireless platform Digital thread Equipment maintenance diagnosis Cyber security Interoperability
Robot system for smart manufacturing	Performance evaluation framework of robot system Collaboration performance of robot system Agility of robot system Interoperability and integration of robot system
Measurement science of additive manufacturing	Specialization of material for additive manufacturing Qualification verification of material/process/component for additive manufacturing Real-Time control of additive manufacturing process System integration for additive manufacturing

3.1.3 Korea

Korea is also driving the development of Smart Manufacturing-related technologies similar to the Industry 4.0 of Germany and the national strategies related to Smart Manufacturing in the U.S. The departments that support major technology development projects are operating roadmaps with slightly different characteristics, but they are gradually moving toward establishing and driving integrated strategies that go beyond the departmental barriers. Table 3 shows major strategies and detailed assignments for promoting the smart innovation of manufacturing. The 8 Smart Manufacturing technologies, which correspond to the second assignment in the table, refer to CPS, Energy Saving, Smart Sensor, Additive Manufacturing (3D Printing), IoT, Cloud, Big Data, and Hologram.

Table 3 The 4 strategies and 13 assignments of Korea for the manufacturing innovation 3.0

4 strategies	13 assignments
Smart manufacturing proliferation	Distribute proliferate smart factories Develop 8 smart manufacturing technologies Reinforce manufacturing soft power Promote production facility sophistication investment
Representative new industry creation for a creative economy	Early visualization of smart convergence products Develop and commercialize 30 intelligent materials components Promote private sector R&D and investment
Smart innovation of local manufacturing	Activate the manufacturing business through a creative economy innovation center Realize smart locally based industrial complexes Promote locally specialized smart new industries
Business reorganization and innovation base creation	Promote spontaneous business reorganizations by the companies Improve regulatory systems for the convergence of new products Anticipatory training of the personnel to support manufacturing innovation

Table 4 Smart manufacturing propulsion strategies and assignments of Korea (MOTIE, as of 2014)

4 strategies	8 assignments
Create convergence of new manufacturing	Process innovation based on IT SW Create a convergence growth engine
Strengthen the key capabilities of the main industries	Enhance material and component Boost manufacturing soft power
Manufacturing innovation base enhancement	Supply customized personnel sites Leap to the Northeast R&D hub
Promote overseas expansion	Expand and utilize FTA Maximize summit diplomacy results

Table 5 Major projects related to smart manufacturing supported by MSIP

Projects	Project contents
Development and construction of CSF testbed	Build a test bed to apply, verify, and commercialize the new manufacturing service model combined with the key technologies for CSF realization Develop systems for CSF technology, product, and system verification and certification
Development of the evaluation model for the application of CSF	Apply CSF technologies to manufacturing sites to suggest and expand Korean manufacturing innovation model and create successful models
Development of open FaaS IoT service platform for mass personalization	Develop open-type FaaS (Factory as a Service) technologies that assist various individual manufacturing demands of start-up companies in ICT convergence smart factories
Development of modeling & simulation cps platform technology based on cyber-physical manufacturing equipment	Develop modeling/simulation technologies linked to CPS-based cyber-physical manufacturing equipment for an optimal equipment control through linkage among manufacturing resources in a customized multi-product production environment
Development of worker-oriented AR Smart helmets based on CSF platform	Develop worker-oriented smart helmets that enable the management of sensing data of workers and AR (Augmented Reality), and CSF platform-linked technologies for productivity, quality, and industry safety improvement
Development of process reference model standards for manufacturing service support and manufacturing intelligence	Develop manufacturing service reference models through CPS and ICBM technology convergence, reference models for intelligence processes, and information model standards
Establishment of infrastructure for IoT open platform-based development and verification	Establish IoT open platform-based development assistance systems to strengthen the competitiveness of small and middle companies through the reduction of IoT product and service development period and cost saving
Establishment of Infrastructure for ICT converged manufacturing services	Establish ICT convergence manufacturing system verification test beds and proliferation bases for nurturing creative small and middle manufacturers through ‘manufacturing servitization’
Establishment of bases for commercializing creative and emotional devices	Establish bases for assisting an entire commercialization period of smart devices and products to strengthen product development capabilities of small, middle, and venture companies, improve productivity, and promote the commercialization of developed technologies

3.1.3.1 Smart Manufacturing Propulsion Strategies of MOTIE

In 2014, MOTIE announced the 'manufacturing innovation 3.0' for a new leap of Korean manufacturing, which is similar to the Industry 4.0 of Germany. This meant the change of the main manufacturing strategy from the existing assembly and device-oriented industry to the innovation of leading a new convergence industry. Table 4 shows manufacturing propulsion strategies and assignments by MOTIE. The basic directions of the government include creating a new added value in manufacturing through IT SW convergence, securing competitive advantage, and generating an environment for companies to lead the manufacturing innovation.

3.1.3.2 Smart Manufacturing Propulsion Strategy of MSIP

MSIP is supporting research and development activities related to Smart Manufacturing based on the information research infrastructure construction project and CSF (Connected Smart Factory) project. Table 5 shows major projects of MSIP related to Smart Manufacturing, including the CSF project. The 6 detailed projects of CSF project and 3 information research infrastructure construction projects are aiming to develop technologies related to Smart Manufacturing in each area. The key technology development projects are mainly focused on manufacturing data linking technology through the IoT technology, based on ICT technology, CPS modeling & simulation technology, and wearable device technology that supports AR (Augmented Reality), among others.

3.2 Classification of Core Technology for Smart Manufacturing

As aforementioned, Germany, the U.S., and Korea are running various programs and projects related to Smart Manufacturing. They selected key technology areas, and they are the leaders in technology development. They are also strategically approaching non-technical areas, such as expansion of related infrastructure and establishment of various systems. The common key technologies of the three countries were classified and selected as shown in Fig. 6, as the main purpose of this paper is to analyze technical trends related to Smart Manufacturing. In the case of Korea, the strategic parts, such as the construction of infrastructure, were ruled out from the selection as it clearly selected 8 manufacturing technologies. As for Germany and the U.S., the technologies with similar concepts were considered and selected even though they were not expressed in the same words.

The key and representative technologies selected for Smart Manufacturing include CPS, IoT, cloud computing (cloud manufacturing), big data, additive manufacturing (3D printing), sensors, energy saving, and holograms. These coincide with the 8 key technologies of Korea. The current status of Smart Manufacturing-related technologies was analyzed, and the future was predicted in this study through the investigation and review of the studies and data related to these representative technologies.

4. Literature Survey

In this chapter, the main research contents, keywords, application areas, and steps of the aforementioned 8 key technologies, as well as the conceptual and technical approaches and structures of Smart Manufacturing, were summarized in a technical perspective. As aforementioned, there are many existing studies on the algorithms and methodologies of each technology; therefore, the articles in this chapter are mainly studies focused on perspective of Smart Manufacturing. The studies of each technology were conducted simultaneously in many cases, as they all dealt with Smart Manufacturing. As a result, the studies regarding the overall concept and technology of Smart Manufacturing were initially reviewed and summarized in this paper, and then the articles on each key technology. In the case of parallel studies, a summary was conducted based on a more essential one.

4.1 Vision, Concept, Direction, and Technology of Smart Manufacturing

First, the various conceptual and technical studies were conducted

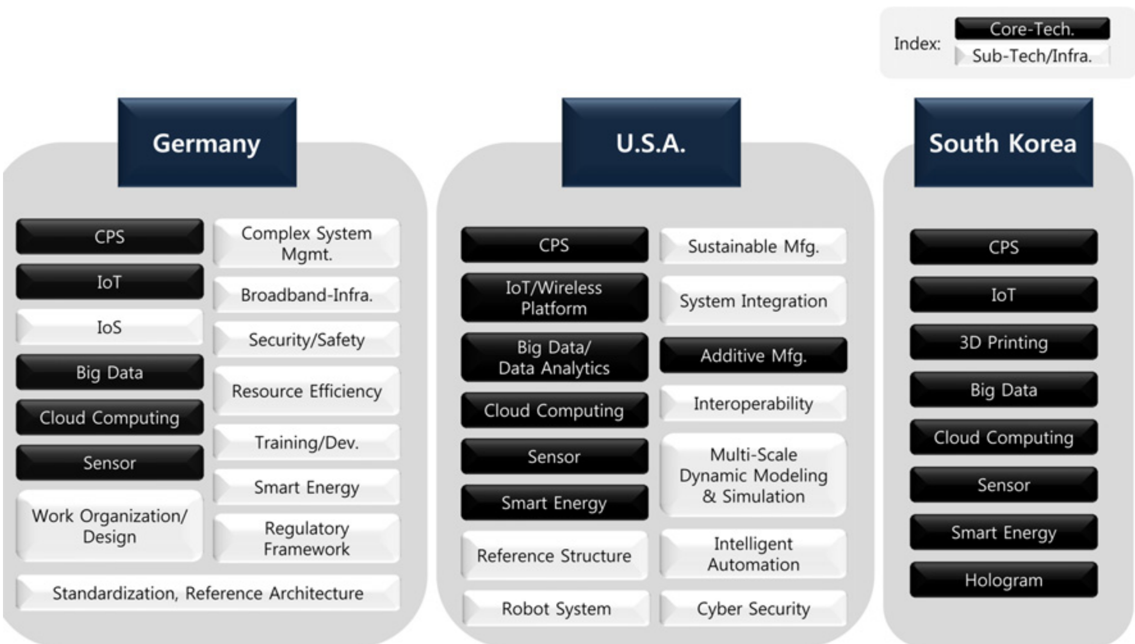

Fig. 6 Classification and selection of core technology for smart manufacturing

on the Industry 4.0, Smart Manufacturing, or smart factory. These studies mainly contain what the challenges are to be expected, how and what technologies need to be researched and developed, and what strategies are required to realize Smart Manufacturing.

Blanchet et al. explained the major concepts and key technologies on Industry 4.0 as the fourth revolution in their strategy report.[6] Industry 4.0 could be realized through cloud computing, big data, 3D printing, smart sensors, as well as CPS, and a similar concept was established by Wang et al. through a framework that supported vertical and horizontal integration of systems.[7] Anderl is showing the effects of Industry 4.0 through manufacturing objects that carry information directly, process and condition monitoring, and use cases such as additive manufacturing.[8]

On the other hand, Brettel et al. suggested forecasts on the research areas, such as CPS, by performing clustering analysis on the existing related studies regarding the three areas that are closely associated with Industry 4.0, i.e. (1) individual production, (2) horizontal integration in collaborative networks, and (3) end-to-end digital integration, and by finding the correlations between the detailed technologies.[9]

Various studies on the definition, realization process, approaches, and examples of Smart Manufacturing were also conducted. Choi et al. suggested an approach for Smart Manufacturing realization through a system-based phased application of digital manufacturing.[10] Radziwon et al. made the following definition of a smart factory after investigating the existing literature. "A Smart Factory is a manufacturing solution that provides such flexible and adaptive production processes that will solve problems arising from a production facility with dynamic and rapidly changing boundary conditions in a world of increasing complexity. This special solution could, on the one hand, be related to automation, and understood as a combination of software, hardware and/or mechanics, which should lead to the optimization of manufacturing, thereby resulting in the reduction of unnecessary labour and waste of resource. On the other hand, it could be seen in a perspective of collaboration between different industrial and non-industrial partners, where the smartness comes from forming a dynamic organization."[11]

Lucke et al. defined the process of realizing a smart factory as the steps of definition, challenge assignment recognition, realization technology acquisition, and functional architecture application. They specifically defined challenge as (1) identification, (2) localization, (3) status knowledge, (4) update of Smart Manufacturing system, (5) support for different queries, (6) integration of heterogeneous information, and (7) real-time characterized reaction. Meanwhile, they defined realization technology as (1) embedded system, (2) (wireless) communication technology, (3) automatic identification (auto-ID) technologies, (4) positioning technologies, (5) federation platform, (6) situation recognition, and (7) sensor fusion. They suggested a model that applied a smart factory to the functional architecture of a manufacturing company based on these definitions.[12]

Zuehlke introduced the technical elements about equipment, communication, sense, control, and management systems via the SmartFactory^{KL} case. It is described that the characteristics of Factory-of-Things, wherein the basic characteristics of IoT were applied to a factory, in the perspectives of technology, structure, plan, stability, security, and humans.[13] Ivanov et al. developed a dynamic model and algorithm for a short-term supply chain scheduling in a smart factory as applied researches of Smart Manufacturing,[14] while Choi et al. suggested a strategic plan and a systematic design for the efficient implementation and application of the virtual factory.[15]

4.2 Cyber-Physical System

Cyber-Physical Systems (CPS) are systems of collaborating computational entities which are in intensive connection with the surrounding physical world and its on-going processes, providing and using, at the same time, data-accessing and data-processing services available on the internet.[16-18] The application areas of CPS are widely ranged from aerospace, automotive, chemical processes, civil infrastructure, energy, and transportation to manufacturing. In the area of manufacturing, CPS is a key technology for realizing Smart Manufacturing, and it is being studied in close relationship with such technologies as cloud, IoT, and big data. Lee et al. defined the 5C architecture for realizing CPS as (1) smart connection level, (2) data-to-information conversion level, (3) cyber level, (4) cognition level, and 5) configuration level. They also defined the detailed attribute information and conditions according to each level.[19]

The CPS researches in the manufacturing area are still in the initial stage, and most studies are focused on modeling, conceptualization, and utilization plans rather than on realization. Dworschak and Zaiser described the utilization plans of CPS in the perspective of manufacturing workmanship, and automation and tools in the perspective of a worker who uses them.[20] Seiger et al. suggested a metal model-based object-oriented workflow language for modeling and formalizing processes on CPS in heterogeneous and dynamic environments.[21] Monostori explained that CPPS (Cyber-Physical Production Systems) is an applied version of CPS to the manufacturing area with various root technologies, and suggested technologies, such as context-adaptive and autonomous systems, that require research and development.[22]

The researches for monitoring and controlling the manufacturing sites and processes through CPS put emphasis on the association with the existing system such as SCADA (Supervisory Control and Data Acquisition). Genge et al. suggested and constructed an experimental framework of CPS. This framework is divided into the physical layer that is composed of actuators, sensors, and hardware devices, and the cyber layer that is composed of all information, communication devices, and software. It shows the association PLC (Programmable Logic Controller) and SCADA.[23] Wang et al. proposed a system architecture with connected heterogeneous network subsystem for the joint operations of control and communication.[24]

The studies with further approaches to Smart Manufacturing mostly suggested CPS models and frameworks linked to cloud, IoT, and big data, etc. Niggemann et al. suggested cognitive reference architecture for the CPS based on the data collected and analyzed in real time through IoT and big data, and performed case studies in various areas.[25] Similarly, Lee et al. also suggested a CPS model based on big data.[26] Wan et al. suggested CPS as a more evolved and intelligent M2M (machine-to-machine) concept in the IoT architecture base.[27] Lu summarized threats that may arise in a perspective of CPS security and the related technical studies.[28] Colombo et al. described SCADA/DCS-related or SOA (Service Oriented Architecture) based industrial CPS through the IMC-AESOP approach.[29,30]

The studies on CPS are regarded in the early stage as seen, but they are making advances. The researches being performed are closely related to cloud, IoT, and big data, which are major key technologies of Smart Manufacturing.

4.3 Cloud Manufacturing

Cloud manufacturing (CM) is the cloud computing technology that is applied to the manufacturing area, and it is considered as an innovation of the existing manufacturing paradigm similar to Smart Manufacturing. Wu et al. defined CM as follows: "Cloud Manufacturing is a customer-centric manufacturing model that exploits on-demand access to a shared collection of diversified and distributed manufacturing resources to form temporary and reconfigurable production lines that enhance efficiency, reduce product lifecycle costs, and allow for optimal resource loading in response to variable-demand customer generated tasking."[31] In order to realize CM simultaneously with Smart Manufacturing, it will require defining various elements, such as conceptual requirements, key technologies, environment, clear vision, and strategic approach. The following studies are offering various related backgrounds.

Wu et al. analyzed the current status of CM and technical trends, and suggested future research directions in the perspectives of (1) automation and control, (2) business model, (3) information and resource sharing, (4) distributed system simulation, and (5) cost estimation.[32] A model with an applied CM concept to its design and manufacturing, a system architecture, and scenario-based studies were conducted accordingly.[33-37] Similarly, Zhang et al. developed a prototype and constituted a platform architecture for CM with resource layer, resource-perception layer, resource virtual access layer, manufacturing cloud core service layer, transmission network layer, and terminal application layer.[38]

The researches on CM were conducted mainly for technology elements and architecture design. Tao et al. suggested an architecture of a cloud manufacturing service system linked with cloud computing and IoT, and analyzed the correlations between each technology.[39] Karnouskos suggested cloud service-based architectures from production site levels to business levels.[40] He and Xu summarized key technologies for CM as (1) the existing manufacturing systems and technologies, (2) cloud computing, (3) IoT, (4) virtualisation, (5) service-oriented technologies, and (6) HPC (High-Performing Computing), and described the key services that need to be realized accordingly.[41]

The various studies related to CM environment or systems were also carried out. Luo et al. suggested the multidimensional information of manufacturing capability in a CM system as a concept composed of the four elements, i.e. resource, task, process, and knowledge. They studied a methodology of describing the concept through ontology, fuzzy information, and dynamic behavior, among others.[42] Laili et al. developed models and algorithms for Optimal Allocation of Computing Resources (OACR) under a clouding manufacturing environment.[43] Wang developed a service-oriented system based on the internet and the web that performed machine availability monitoring and process planning.[44] Wang et al. constructed ontology that provided semantic modeling and description of various tasks on CM, and suggested a framework that is perfect by the semantic similarity algorithm.[45] Pisching et al. studied the service-composition of the CM linked to CPS and IoT under the concept of Industry 4.0.[46]

4.4 Big Data Analytics

Big data generally means a data set that is inappropriate to be used by traditional data process methods due to their wide range, complex structure, and size. Therefore, technical and special systems, and methodologies, such as analysis, capture, data curation, search, sharing, storage, transfer, visualization, and information privacy, are required to perform predictive analytics, extract value from data, and seldom to a particular size of data set, among others. The realization of Smart Manufacturing requires effective visualization, analysis, and sharing of various data arising from product development and manufacturing system engineering processes to manufacturing sites to be utilized for predictions and modeling.

Lee et al. summarized the changing trends of big data environment in manufacturing services and the readiness of smart predictive informatics tools for big data management in the perspective of Industry 4.0 realization. They stressed that the self-awareness and self-maintenance of a machine must be achieved in an IoT-based CPS environment, and that the decision support analytics for machine health awareness analytics and self-maintenance based on self-learning knowledge base were required to be developed and applied.[47] A research that collected data from various layers that constituted manufacturing systems in a CPS environment and extracted major data from the big data using algorithms, such as (1) signal processing, (2) feature extraction, (3) health assessment, (4) performance prediction, and (5) fault diagnosis, of a predictive analytics such as Watchdog Agent® was also conducted.[48] The results were applied to industrial robots and virtual batteries.[26] Shahbaz et al. suggested conceptual methodologies and platforms for various techniques, such as statistical techniques, neural network, decision trees, and genetic algorithm, to be adequately utilized on a product manufacturing life cycle.[49] Shao et al. introduced decision guidance methodology that used SPAF (Sustainable Process Analytics Formalism) developed by NIST.[50]

Many studies suggested big data analytics as a solution for various manufacturing problems. Ündey et al. suggested an approach that performed real-time monitoring and control in hierarchical levels of observation level, and batch level through process mining among data mining methodologies in biopharmaceutical manufacturing industries.[51] Meidan et al. performed a project that assisted decision-making by converting synthesized fab data to actionable knowledge in semiconductor manufacturing industries. The project recognized and predicted the key factor of a cycle time by building MLDM (Machine Learning and Data Mining) based on the SNBC (Selective Naïve Bayesian Classifier) and conditional mutual information maximization for feature selection.[52] Similarly, Bagchi et al. analyzed data of a semiconductor fab by using technologies such as data mining, process trace data analysis, stochastic simulation and production optimization through a research project of IBM. They improved production efficiency through better planning and resource scheduling.[53] Gröger and Mitschang conducted researches on indication-based and pattern-based manufacturing process optimization, as novel data mining approaches provided through the Advanced Manufacturing Analytics

Platform.[54] Çiflikli and Kahya-Özyirmidokuz suggested a way to detect isolated machine breakdowns of carpet manufacturing through a decision tree.[55] Shin et al. proceeded to conduct a research that performed the (1) identification of manufacturing data to be analyzed, (2) design of a functional architecture for deriving analytic models, and (3) design of an analytic model to predict the sustainability performance, particularly the power consumption, through big data infrastructure for power consumption efficiency in manufacturing industries. They developed a prototype system through MapReduce, HDFS (Hadoop Distributed File System), and a machine-learning tool.[56] A research that visualized the big data related to the logistics of a shop floor via RFID (Radio Frequency IDentification) linked with cloud manufacturing was conducted in the perspective of Smart Manufacturing realization.[57]

4.5 Internet-of-Things

IoT means networks of electricity, software, sensors, network connectivity, and embedded ‘things’ or physical objects. It collects or exchanges data.[58] IoT makes objects sensed or controlled through a network infra,[59] supports integration between physical real world and computer-based systems, and brings various effects such as improved productivity or economy in manufacturing.[60-64] IoT collects or exchanges data acquired from smart sensors, enables bid data analytics, and realizes CPS and CM. It is a core technology for the realization of Smart Manufacturing, and it is currently being researched. The report by Löffler and Tschiesner on IoT and the future of manufacturing is predicting the future of manufacturing and the physical world, which is becoming an information system where physical objects equipped with IoT technologies, i.e. embedded sensors and actuators, are connected with each other through internet protocol and wired or wireless networks. The report specifically addressed the actual innovation and application of logistics systems, the convergence of processes and devices, and the integration of supply chains.[65] Da et al. described the four major layers of the architecture for IoT, such as (1) sensing, (2) networking, (3) service, and (4) interface, through researches on IoT technologies in the industries, and discussed the future research issues, such as standardization, information security, and privacy protection.[66] Bi et al. analyzed the effects of IoT for the Enterprise System (ES) of modern manufacturing industries in terms of IT technologies, such as (1) ubiquitous computing, (2) RFID, (3) wireless sensor network, and (4) cloud computing.[67]

As for the researches on systems regarding the actual IoT realization, Dias et al. explained the platforms for the integration of systems, such as the PLC system and SCADA in the IoT environment based on SOA and DPWS (Device Profile for Web Service).[68] Guinhard et al. suggested an SOA-based IoT, i.e. processes and system architectures, in which developers and business process designers can query, select, or use real world services.[69]

Furthermore, case studies and application studies for the application of IoT technologies to industries, or studies directly related to CM and Smart Manufacturing were performed. Tao et al. classified and mapped services and manufacturing resources of CM for the access and intelligent perception to various manufacturing resources, and suggested the system architecture composed of 5 layers (application, service, network, perception, and resource) that included the technical elements of IoT.[70] Zhang et al. conducted researches on real-time manufacturing information capturing through the sensor-embedded manufacturing resources and the IoMT (Internet of Manufacturing Things) architecture based on RTMIIS (Real-Time Manufacturing Information Integration Service) that supported interoperability.[71] Butala et al. designed and developed a distributed agent-based system for virtual monitoring and control of a 3-axis CNC (Computer Numerical Control) milling machine, in which the process status and 3D model of a machine could be checked in real time in a web-interface environment.[72]

4.6 Smart Sensor

As aforementioned, the most important technology at the device or hardware level in realizing IoT, CM, CPS, and Smart Manufacturing is the sensor technology because the sensor is the most basic technology for collecting and controlling data in real time. In this chapter, the sensors applied to manufacturing, and the articles focused on network technologies were mainly reviewed rather than the technologies of the sensor itself.

The star network (single point-to-multi point), mesh network, hybrid star-mesh network are the architectures of a wireless network that connects sensors, and such standards and technologies, such as the IEEE802.11x, Bluetooth (IEEE802.15.1 and .2), IEEE802.15.4, ZigBee, and IEEE1451.5, are the physical wireless communication technologies.[73] They may have different applicability according to the nature of a manufacturing environment that accompanies complexity and much noise as they have different characteristics. Zhuang et al.[74] and Flammini et al.[75] suggested mathematical methods to solve problems, such as network instability, in building sensor networks for factory automation, and conducted researches on the effective use of the sensors in manufacturing sites by using TEDS (Transducer Electronic Data Sheets), a standardized sensing data structure related to manufacturing, and RTE (Real-Time Ethernet), a communication interface that supported real-time data exchange. Chi et al. developed CPLD (Complex and Programmable Logic Device), and a smart sensor interface that could process numerous different data in real time through a core controller.[76] Meanwhile, a research that integrated sensor node-oriented or RFID/Auto-ID device-oriented networks through agent-based smart gateway was conducted. In the study, a system that exchanged manufacturing-related data in real time with SO (Smart Object) formed by each manufacturing resource, communication of agents via a SOA-based system, and a smart gateway that supported ‘plug & play’ was constructed.[77,78]

Based on the researches that utilized smart sensors, Lee et al. conducted researches on a wireless sensor network based on self-coordination and CMMS (Computerized Maintenance Management System) for extending the lives of manufacturing assistance utilities, such as motors and water pumps, by checking the white noise, illegal vibration, and high temperature based on smart sensor and wireless network technologies.[79] Wright et al. built a sensor-based wireless network on a manufacturing site, and conducted a research that monitored the condition of a milling machine through the network.[80] Kortuem et al. developed a sensor-based vibration monitoring system that could identify risk elements, such as vibration, during work for the safety and health of workers.[81]

4.7 Applied and Additional Technologies

As aforementioned, the technologies of CPS, cloud manufacturing, IoT, big data analytics, and smart sensors are very essential in realizing Smart Manufacturing. These technologies affect each other when applied, thus interoperability is considered more important than any other technologies. Meanwhile, additive manufacturing, energy saving, and holograms are more of applied levels or additional technologies than the above 5 technologies. However, they are also important in terms of the perfection or versatility of Smart Manufacturing. These three technologies are reviewed in this chapter.

4.7.1 Additive Manufacturing (3D Printing)

Additive Manufacturing (AM) is a way to convert a 3D model, such as a CAD file, into a physical object by bonding or joining materials through light, ultrasonic vibration, laser, and electron beam. It has different characteristics, according to the materials or bonding methods.[82] The realization of it through a cutting-edge technology is the 3D printing technology. Additive manufacturing started as a rapid prototyping technology that realized the product ideas of design engineers in 1980s, and now it is being used not only for prototyping, but also for making complete products, thanks to the advances in materials and lamination technology.[83] Various related studies are now under way. Huang and Leu classified additive manufacturing into 7 types according to lamination method, materials, and attributes of related manufacturers and machines. They are now applying the technology to various areas, including aviation, vehicles, clothing, and biomedical. They predicted that the technology will go toward the integration with CNC machining in the future.[84] Wong and Hernandez[85] and Huang et al.[86] also looked back on the history of technological developments related to additive manufacturing through their review papers, and mentioned that finishing process should not be demanded through increased precision in the future. They mentioned that additive manufacturing has advantages, as compared to the existing manufacturing methods in (1) material efficiency, (2) resource efficiency, (3) part flexibility, and (4) production flexibility, and has weakness in (1) size limitation, (2) imperfection, and (3) cost. They also mentioned the problems with energy and environment. Berman presented the characteristics and advantages of 3D printing, and compared it with the existing manufacturing methods in terms of mass customization.[87] The application or case studies of additive manufacturing include an application study for manufacturing electronics,[88] a study on the new DFM approach for the convergence of machining and additive manufacturing,[89] a study on the ontology-based META model for composable and reusable additive manufacturing processes,[90] and a study on data schema for the management of additive manufacturing processes.[91]

4.7.2 Energy Saving

Energy saving is also an important element for the realization of Smart Manufacturing. Various studies have been performed on the energy saving of manufacturing, including FEMS (Factory Energy Management System), in which BEMS (Building Energy Management System) of construction was converted and applied to manufacturing, and the studies on efficiency increased through energy consumption monitoring and analysis. Seow and Rahimifard modeled the energy flow of a manufacturing system in the perspective of a 'product', and conducted a study that utilized energy consumption data at the levels of 'process' and 'plant'. They also developed a decision making assistance tool based on a simulation model through Arena™.[92] Vijayaraghavan and Dornfeld conducted a study that automated the monitoring and analysis on the energy consumption of a machine tool about a manufacturing system based on metalworking and machining.[93] Duflou et al. reviewed the methods and techniques that enhanced the efficiency of energy and resources for different scale levels of a manufacturing system, and identified the major measures.[94] The studies on the methodology and system that modeled, simulated, and analyzed the flow of energy were similarly conducted by Herman et al.,[95] Rahimifard et al.,[96] and Herman and Thiede.[97] In the meantime, Weinert et al. developed a system that predicted and planned energy consumption based on the Energy Block methodology, in which the specific energy consumption depending on the operational conditions of production equipment was expressed as production operation.[98] Mouzon et al. developed dispatching rules by the circumstances to minimize energy consumption of manufacturing equipment and an optimization algorithm.[99] As for FEMS, Katsutomo et al. defined the KPI for energy saving, and developed factory inspection services and engineering services performed by energy-saving diagnostic experts.[100] Endo et al. conducted a study that increased energy efficiency by quantifying operational condition of equipment according to energy consumption and equipment behavior through the visualization technique, which analyzed the correlation between productivity and energy, applied to FEMS.[101]

4.7.3 Hologram

Hologram is one of the visualization methods along with VR (Virtual Reality) and AR (Augmented Reality). It is the sophistication stage of the Smart Manufacturing-related technologies. However, most studies are currently focused on VR or AR, and there are only a few studies on the hologram itself in manufacturing. Hetzler et al.[102] and Schillke et al.[103] applied the U.S. patent on the manufacture of optical elements using a hologram. While VR in basic standard by rendering is focused on tangible models, AR is a technology that can be applied directly to manufacturing sites, and it can conform to the real-time nature of Smart Manufacturing. The studies on the application of AR to manufacturing mostly applied it to design and manufacturing steps. According to Nee at al., the application of AR requires hardware, such as (1) display equipment like Head-Mounted Display (HMD), handheld devices, and projectors, (2) User tracking equipment, and (3) haptic and force feedback equipment, and software that support fiducial marker tracking such as (1) Computer Vision (CV)-based tracking and registration algorithm, (2) ARToolKit, and osgART, among others, (3) BRIEF, and SIFT, that support natural feature tracking, and (4) Parallel Tracking and Mapping (PTAM). Various applications depending on purposes and properties are available as libraries or platforms. They are generally being applied to design, robotics, factory layout planning, system maintenance, CNC simulation, and assembly design and operation planning in collaboration environment.[104]

5. Analysis and Discussion

5.1 Analysis

In this chapter, the trends and development status of the key technologies related to Smart Manufacturing were identified and summarized based on the aforementioned literature. The past was reviewed, the present was identified, and the desirable future was suggested in terms of each technology or overall Smart Manufacturing. For these purposes, the following analysis was performed.

First, Time-series analysis was performed on the overall Smart Manufacturing concept or each key technology to identify research and development trends according to different viewpoints. Second, the applications described in each article were classified as factory (overall), process and machine, and infrastructure in terms of smart factory realization. Third, the application ranges of each technology on an engineering work process were also classified as overall, design & construction, and operation and maintenance. Fourth, the implementation levels were classified as strategic approach, system (methodology) design, and proof-of-concept and case application to identify the development status of the technologies mentioned in the articles. Finally, the keyword and key technology suggested in the articles were analyzed to identify the correlation between the key technologies of Smart Manufacturing.

Fig. 7 shows the chronological flow of the published literature on each technology, as well as the overall Smart Manufacturing concept. Most technologies were dramatically increased in 2014. This is because it was not long that Smart Manufacturing and Industry 4.0 appeared as topics and the literature survey could not count the unpublished literature in 2015. Moreover, technologies, such as the hologram and smart sensor, were decreasing in trends. This is because these technologies have been actively researched for themselves and not published in the literature directly related to Smart Manufacturing, and the scope of the survey in this study is limited to the literature that is highly associated with Smart Manufacturing.

Fig. 8 shows the distribution of the application area of the overall Smart Manufacturing concept and 8 key technologies obtained through the literature survey of each article. The overall Smart Manufacturing concept, CPS, and cloud manufacturing were applied to the entire areas

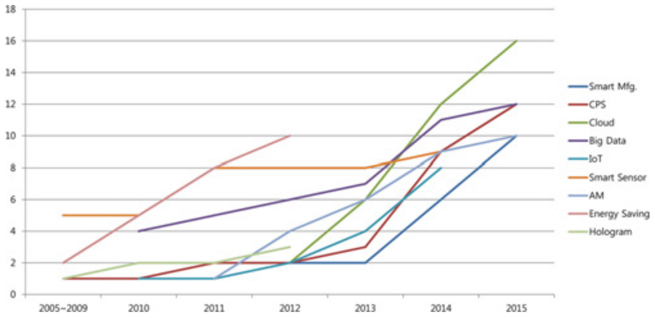

Fig. 7 Time-Series analysis result

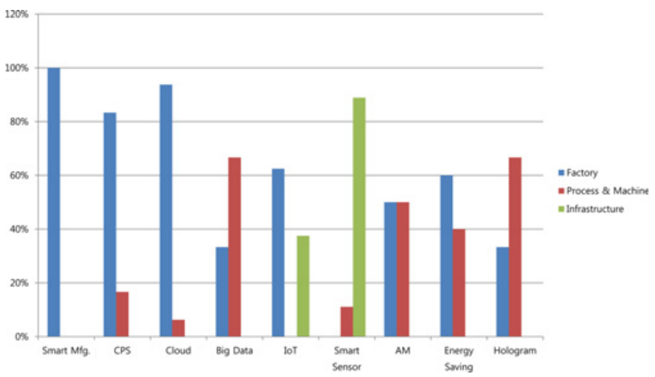

Fig. 8 Distribution of the application area of each technology

including factory, i.e. process, and machine. Big data and hologram had relatively high proportion in process or machine. Smart sensor and IoT were high in infrastructure. Additive manufacturing had similar distribution in factory, and process and machine. It was confirmed that smart sensors and IoT were constructed in the infra-system of manufacturing sites for utilization as the key technologies that support Smart Manufacturing, and the big data directly handles more information through developing and applying technologies, which is related to process and machine. Meanwhile, additive manufacturing is a paradigm itself or sometimes a process technology, thus it had similar distribution in factory, and process and machine. CPS and Cloud Manufacturing are technologies that cover Smart Manufacturing, and represented a high proportion, mainly, in factory.

The distribution of the applicable processes from the surveyed articles is shown in Fig. 9. The high proportion of the design and construction of a manufacturing system was accounted for by the articles on additive manufacturing. As for the operation, management, and maintenance process of a constructed manufacturing system, big data and IoT had relatively high proportion. Smart sensors were evenly distributed in the two processes. The others were applied mainly to the overall process. As each technology can be widely applied to the development and operation processes of various manufacturing systems due to their characteristics, systematic and strategic approaches from clear requirement analysis to the realization of Smart Manufacturing are required to successfully introduce and apply the corresponding technology. Furthermore, the reason that the big data had the above results was that the related studies on the big data were mainly performed based on the cases of constructed factories. The related elements of big data, however, must be considered when a new manufacturing system is developed or constructed.

Fig. 10 shows the development levels of each technology that has been addressed in the articles. The levels were classified into three, namely, conceptual or strategic approach, system or methodology design, and case application through technology implementation or proof-of-concept. As seen in Fig. 10, many technologies overall are still at the concept establishment step of the strategic level, or at the methodology and system design step, while some of them are applied to cases. Smart sensor and energy saving were actively researched and applied to the manufacturing areas regardless of Smart Manufacturing. They are now being researched mainly in terms of commercialization. It was estimated that the strategies for the development of each

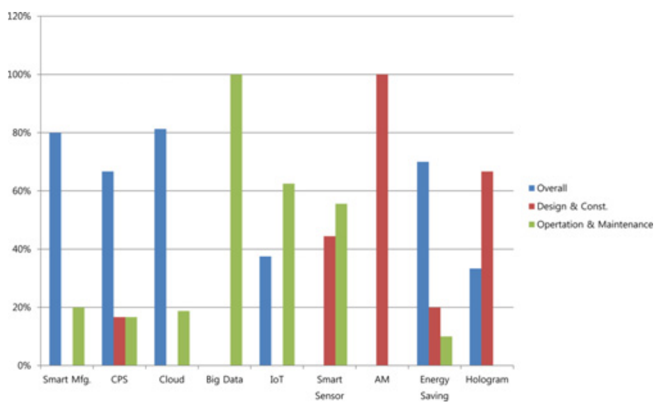

Fig. 9 Application process distribution of each technology

technology must be accompanied by the related researches and developments for the realization of Smart Manufacturing. Asymmetric development of technologies may adversely affect the development of the other technologies. The ground for this argument can be found in the following analysis.

Table 6 shows the summary of keywords that appeared in the articles on Smart Manufacturing-related technologies. CPS, cloud, big data, IoT, and smart sensors as the key technologies for Smart Manufacturing were found to have a close relationship with the other technologies, as mentioned in chapter 4. On the other hand, the additional or applied technologies, such as additive manufacturing, energy saving, and hologram, are not closely associated with the aforementioned 5 technologies. Therefore, the successful realization of Smart Manufacturing requires an environment or roadmap, in which the 5 key technologies are strategically developed, and then the remaining 3 technologies can be developed accordingly.

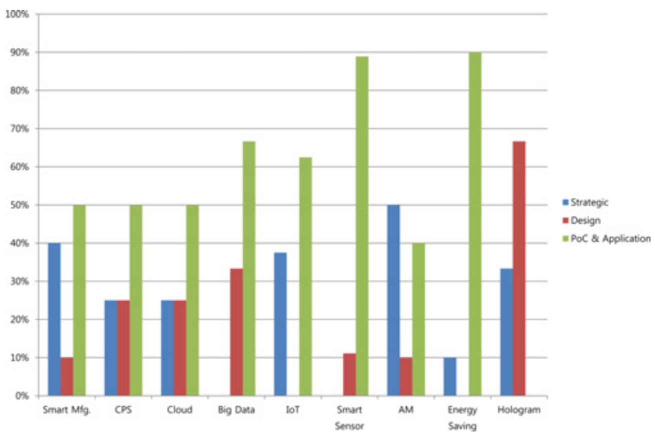

Fig. 10 Development level distribution of each technology

Table 6 Technology-Related keywords

Technology	CPS	Cloud
Keywords	Cloud	Distributed system
	SOA	IoT
	Big data	SOA
	IoT	IoS
	Monitoring & control	Monitoring
	Security	Semantic modeling
	SCADA	CPS
	DCS	Virtual enterprise
	Sensor network	∘∘
Technology	Big data	IoT
Keywords	CPS	RFID
	Predictive Manufacturing	Industrial informatics
	Energy consumption	SOA
	Soft-Sensors	CPS
	Real-Time monitoring	Cloud manufacturing
	Cloud manufacturing	Sensor network
	RFID	Real time Manufacturing Information
		Web-Services
	∘∘	∘∘
Technology	Smart sensor	AM
Keywords	Real-Time system	Rapid prototyping
	IoT	3D printing
	SOA	Digital manufacturing
	Machine monitoring	
	CPS	
Technology	Energy saving	Hologram
Keywords	Monitoring	Augmented reality
	Simulation	Virtual reality

Technically, a methodology on linking the rest technologies must be discussed in the key technology development step. Studies must be carried out to identify the interoperability and problems on interfaces.

5.2 Discussion

5.2.1 Past and Present

Smart Manufacturing is a new revolution and paradigm of the manufacturing industry. It is rapidly developing in terms of the integrated concept, application method, and key technology. The existing manufacturing technologies ranging from digital manufacturing, virtual manufacturing, and advanced manufacturing to sustainable manufacturing have been converged with ICT before the advent of Smart Manufacturing. Smart Manufacturing-related technologies have also been individually developed or in conjunction with other technologies. In the cases of IoT, smart sensors, and big data, the studies were mostly on machines or processes in the past. This was mainly due to the shortage of networks, data process systems, and methodologies that supported fast data exchange in a complicated environment, wherein the entire manufacturing system must be in complete control in real time. The gradual development of hardware and software technologies, however, provided grounds for processing various and complicated information in real time.

IoT and smart sensors are both developing gradually, and extending their application from homes and buildings to manufacturing industries. The grounds for a smooth analysis and process of big data collection through this extension are being provided. CPS and cloud manufacturing, which are constructed based on these element technologies, are developing in conjunction with the existing manufacturing systems or IT technologies. In the case of CPS, it is gradually expanding from machine-oriented to the entire manufacturing system. It constitutes a digital twin connecting manufacturing sites to cyber-models through the development of modeling and simulation technologies, and the connection of SCADA and DCS. At the same time, it is providing technical grounds for cloud manufacturing that is based on SOA. Meanwhile, the diversification of materials, the development of lamination technology, and the precision of 3D printing machines are moving toward supporting the application of 'mass customization' through additive manufacturing. The introduction of the systems, such as FEMS, is heading toward supporting sustainable manufacturing through energy saving, while the application of VR and AR technologies are supporting more tangible engineering works based on a CPS environment through the convergence of manufacturing systems and hologram technologies.

5.2.2 Future

Despite the consistent development of the related key technologies for the realization of Smart Manufacturing, there are still many issues to be considered in terms of research, development, and commercialization. Although each key technology is being improved through research and development, versatility and practicality need to be addressed rather than individuality when considering integration and flexibility. In the case of technologies, such as CPS and big data, which were previously applied to other areas, they must be applied considering the characteristics of manufacturing and developed in the direction of meeting the characteristics and requirements of various businesses in the manufacturing industry. For this purpose, the construction of the key algorithms that constitute the technologies, methodologies, and systems is important. However, a strategic approach is required on how and what effects will be obtained through the actual application and utilization, as well as how they are verified.

The following need to be considered accordingly. Currently, many legacy systems are being used in manufacturing sites and engineering work processes. They also have different process systems and data structures. As many studies related to Smart Manufacturing are still carried out in terms of the conceptual approach, design step, or manufacturing sites, future studies need to address the application strategies for Smart Manufacturing in terms of Product Lifecycle Management (PLM) according to each life cycle step, including plan, design, manufacture, operation, and maintenance, and develop the assisting models and systems. As a result, reference models and application guidelines are required for the application of key technologies at each life cycle step, while standard models and services in terms of interoperability for connection to the existing heterogeneous legacy systems must be constructed. In addition, a system that can apply new technologies and conduct verifications flexibly, according to the levels of each key technology, manufacturing systems, and the maturity of IT-based technologies, must be prepared. The system will be the ground for assisting vertical and horizontal integration in terms of business processes, as well as manufacturing systems.

Furthermore, Smart Manufacturing must be able to create not only the effects in the economic indicators, such as cost saving and productivity increase, but it must also be able to create new values that can constantly contribute to societies. The revolution of the existing manufacturing industry was focused mainly on the aspect of effectiveness. This caused many problems due to the lack of human and society-oriented thinking. Smart Manufacturing will not only be able to simply construct intelligent systems through convergence with cutting-edge IT technologies, but it will also be able to develop as a continuous growth engine for manufacturing with human and society-oriented philosophy through ‘sustainable development’.

6. Conclusions

Industry 4.0 or Smart Manufacturing is the fourth industrial revolution. 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.

In this paper, the past and present Smart Manufacturing-related technologies were identified, while the future of Smart Manufacturing with its development directions was suggested. A survey mainly based on the articles in the perspective of Smart Manufacturing or on the eight related technologies applied to manufacturing was conducted. The trends of the five major key technologies and three additional or applied technologies were identified, while various analyses were performed.

In conclusion, the most important issues for the realization of Smart Manufacturing are technically the interoperability, along with the development of technologies themselves and the necessity to develop an integrated technology, and strategically a system that supports technology development and application according to the purposes, levels, and steps of application for developing and introducing practical technologies. The realization of Smart Manufacturing, which is applied not only to some processes and factories, but also to an entire enterprise or supply chain, and the confirmation of its various effects will be possible in the future.

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