IX. Engineering Management

1 Engineering Research Fronts

1.1 Trends in top 10 engineering research fronts

In the field of engineering management, the fronts of global engineering research mainly include the following ten parts: (1) research on sustainable development in the Industry 4.0 era, (2) construction management driven by machine vision, (3) resilience of the infrastructure systems, (4) application of big data in remote health monitoring systems, (5) effect of high-speed railway networks on urban development, (6) description of shared socioeconomic pathways and their expansion, (7) building information modeling (BIM) and safety management, (8) analysis and research on the Internet of Energy (IoE), (9) logistic trading and shipping management under the Belt and Road, and (10) research on blockchain alliance of energy exchange. Their core papers are shown in Table 1.1.1 and Table 1.1.2. Of these, research on sustainable development in the Industry 4.0 era, construction management driven by machine vision, and resilience of the infrastructure systems are the key fronts. Their development situations and future trends are detailed below.

(1) Research on sustainable development in the Industry 4.0 era

Industry 4.0 was first proposed by Germany as the development strategy for future manufacturing, which is essentially the digitalization of industrial production. It is the intellectualized transformation of the traditional manufacturing industry by closely combining it with information and communication technology (ICT) and Cyber-Physical Systems (CPS). Industry 4.0 is regarded as the fourth industrial revolution marked by high digitalization, networking, and self-organization of machines following the previous three industrial revolutions, namely, the application of steam engines, large-scale electrified production, and automatic production based on information technology. The core goal of Industry 4.0 is intelligent manufacturing and its core feature is interconnection, representing a new intelligent production model towards "Internet + manufacturing." Furthermore, Industry 4.0 is an interactive embeddedness of the new generation of ICT and

Table 1.1.1 Top 10 engineering research fronts in engineering management

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Research on sustainable development in the Industry 4.0 era	22	486	22.09	2017.2
2	Construction management driven by machine vision	17	424	24.94	2016.6
3	Resilience of the infrastructure systems	28	691	24.68	2017.3
4	Application of big data in remote health monitoring systems	33	703	21.30	2016.1
5	Effect of high-speed railway networks on urban development	34	771	22.68	2015.4
6	Description of shared socioeconomic pathways and their expansion	20	789	39.45	2016.6
7	BIM and safety management	8	100	12.50	2017.1
8	Analysis and research on the IoE	6	143	23.83	2017.0
9	Logistic trading and shipping management under "the Belt and Road"	9	107	11.89	2017.6
10	Research on blockchain alliance of energy exchange	5	108	21.60	2017.6

Table 1.1.2 Annual number of core papers published for the top 10 engineering research fronts in engineering management

No.	Engineering research front	2013	2014	2015	2016	2017	2018
1	Research on sustainable development in the Industry 4.0 era	0	0	1	4	7	10
2	Construction management driven by machine vision	0	0	0	9	6	2
3	Resilience of the infrastructure systems	0	0	0	0	21	7
4	Application of big data in remote health monitoring systems	4	2	5	4	11	7
5	Effect of high-speed railway networks on urban development	2	8	9	7	6	2
6	Description of shared socioeconomic pathways and their expansion	2	8	9	7	6	2
7	BIM and safety management	0	0	0	1	5	2
8	Analysis and research on the IoE	0	0	1	1	1	3
9	Logistic trading and shipping management under “the Belt and Road”	0	0	0	2	0	7
10	Research on blockchain alliance of energy exchange	0	0	0	0	2	3

industrial manufacturing technology as well as an intelligent combination of the virtual and real worlds. It reflects the profound evolution of human–machine relationships and socially-networked organizational patterns. The advancement of Industry 4.0 has brought about the rapid increase of output and efficiency, the dramatic reduction of production and human costs, and has put forward new requirements for the production mode, value chain, industrial form, business model, and management promotion of traditional engineering management. Providing the corresponding ecological capabilities of the platform and establishing a complete application ecology and business ecology are especially key to the next stage because the interoperability between different applications has become a bottleneck as the platform technology matures and the application in different industrial scenarios become increasingly abundant. The global Industry 4.0 tide indicates that the manufacturing industry will return to the strategic focus of all countries in the future and will become an important engine for global economic growth, exerting profound effects on the distribution of international industrial labor and value division, and the restructuring of globalization.

(2) Construction management driven by machine vision

Machine vision is the realization of human visual functions in computers—perceiving, recognizing, and understanding the three-dimensional scene of the objective world, and realizing the acquisition, processing, and analysis of digital images. Compared with sensing technology such as radio frequency identification (RFID), global position system (GPS), and ultra wideband (UWB), machine vision can provide more abundant image and video information without wearing sensors. With the development of camera sets and the maturity of deep learning algorithms, machine vision has been widely used in the field of construction, particularly in safety surveillance, productivity analysis, and defect detection of large infrastructure facilities (roads, bridges, tunnels, etc.). In the construction process, the risk identification and surveillance based on machine vision during construction are a hotspot of research. Traditional construction relies on periodic manual inspection which is time- and labor-consuming and cannot achieve full-time monitoring, while automated monitoring based on machine vision can improve safety management. Currently, the research on machine vision often relies on extracting feature information by using algorithms, but it fails to achieve a high degree of semantic understanding of scenes. In addition, because deep learning algorithms often require a large number of data training models, the lack of an open graphics database greatly restricts the further development of machine vision technology.

(3) Resilience of the infrastructure systems

The infrastructure system refers to the network of engineering facilities providing basic services for social production and residents’ lives, including electric power, natural gas, transportation, water feed and drainage, communication, and other related systems. In recent years, the risk of failure of these systems caused by natural disasters, climate change, and rapid urbanization has increased year by year; in addition, these systems are interrelated, causing the internal failure of a single system to spread among the different systems, causing simultaneous damage to multiple systems. This seriously affects the economy of cities and even the whole countries and people's lives. In the 2010s, many countries or regions, such as the USA, Europe, Canada, and Australia, have proposed protection plans for their infrastructure systems. Resilient infrastructure systems, which are systems that can maintain certain basic functions during and restore normal functions soon after disasters, have become the objective of active construction in many countries. Evaluating and improving the resilience of infrastructure systems have been research hotspots for the interdisciplinary international fronts such as urban planning, civil engineering, and industrial engineering.

(4) Application of big data in remote health monitoring systems

With the iterative development of information technology, remote health monitoring systems are becoming the highlight of information analysis in the field of health. For residents, especially for patients in remote or mountainons areas, remote health monitoring systems have improved the health service geography and economic reachability, enabling in-charge doctors to analyze medical and health data of service targets and put out high-quality services while saving health funds. In the field of medical health, the application of big data technology is becoming the consensus of health development. Health and medical big data are a "mine of inexhaustible gold" and will provide a new impetus for high-quality development of health services. Generally speaking, remote health monitoring systems mainly include a health information acquisition module, a monitoring terminal module for processing the health information, and a remote medical service platform module, wherein, data acquisition and transmission are the keys of the whole system. Along with the application of 5G technology, remote health monitoring systems will face larger development opportunity. Building cloud-based regional health big data platforms and using remote health monitoring systems can facilitate the interaction among hospitals, doctors, patients (and their families), and medical devices; they can provide patients with more accurate diagnostic suggestions and better personalized treatment solutions; they can help realize the closed-loop of user health management and directly drive basic health bodies to conduct intelligent medical health management services. Currently, as the application of health big data is still under exploration and the remote health monitoring systems are not yet mature, the difficulties and hotspots of research mainly include intelligent integration of health data, construction of health big data platforms, construction of health management closed loops, interaction of the data from multiple medical institutes, and health data exploitation technology.

(5) Effect of high-speed railway networks on urban development

In recent years, the high-speed railway construction represented by China has been developed greatly, having a significant effect on urban social economies and spatial structures, bringing new opportunities as well as new challenges to urban sustainable development. As a research topic, the fast and convenient high-speed railway network can promote inter-city exchange of economic elements, optimize geographic space layout, reconstruct urban space connections and drive the growth of city clusters. Globally, the current research has construed the internal link between high-speed railway and urban as well as inter-city spatial structures from the perspective of traffic accessibility, connectivity, and station location; revealed the action mechanism of high-speed railways on urban development and urbanization quality based on economic structures, population flow, environmental protection, and residents' behaviors; evaluated the alternative effect of high-speed railways, aviation and other traffic tools; analyzed the interactive interface among different traffic modes; and built convenient and efficient transportation systems inside and outside cities. In addition, the current research has provided the key concerns: to optimize high-speed railway networks, and to promote urban transformation and development; to optimize the layout of the high-speed railways and promote their balanced construction in urban areas; to consummate the construction of high-speed railways and guide the healthy competition of cities; to avoid high-speed railway development mode oriented by quantitative growth of cities and short-term benefit; to co-develop comprehensive operation systems by different departments under the background of big data and artificial intelligence (AI) and realize a seamless connection of high-speed railways, aviation, and common railways; to incorporate the design and site location of high-speed railways into urban development strategies strengthen the selection and design of high-speed railway stations, and construct an organic link with the local ecological, economic, and social cultural environments.

(6) Description of shared socioeconomic pathways and their expansion

The concept of shared socioeconomic pathways (SSPs) is the new scenario framework for the research of land utilization–ecological environment–climate change system and it can describe the development trend of future societies and reveal the co-relation and internal logistics between climate change and socioeconomic elements. The SSP framework takes into account six key elements for building the future socioeconomic scenario, namely, population, human development, economy and lifestyle, policies and mechanism, technology, and environment and natural resources. The SSP framework includes five pathways, i.e., the sustainable development pathway (SSP1), intermediate pathway (SSP2), regional rivalry pathway (SSP3), disequilibrium pathway (SSP4), and development pathway dominated by fossil fuels (SSP5). According to the framework scenarios of SSP, current scholars, in China and abroad, have conducted predictions, research and driving factor analysis on population, economy, energy, greenhouse gas emission, and urbanization levels by comprehensively using models in different scales and scopes all over the world. Such models include the population–development–environment analysis (PDE) model, Cobb–Douglas economic prediction model, integrated appraisal model (IAM), computable general equilibrium (CGE) model, GLOBIOM and IMPACT model, global change appraisal model (GCAM), and future land utilization simulation (FLUS) model. The hotspots of the research in recent years have been researching SSP multi-element coupling mechanisms based on land resource utilization and analyzing the dynamic changes of lands in the different pathways. The SSP is part of the new scenario framework being used in the field of climate change research, and it aims to provide basic data for the research on climate change effects, risks, adaption, and alleviation. Additionally, it illustrates different pathways for possible future socioeconomic development and provides references for the selection of relevant climate change countermeasures and realization of sustainable development.

(7) Building information modeling (BIM) and safety management

The prevention of major accidents and injuries have become the focus of all industries. Due to severe situations of occupational health and safety, the management of the engineering construction sector has always been a concern in the world. Along with the development of AI and ICT, exploring and analyzing the applications of ICTs and intelligence methods in building design, engineering design, and the construction service sector, safety management, in particular, is the current research front. Building information modeling (BIM) is deemed as one of the most valuable methods for improving safety management. Based on information of a project process from design, construction, and operation coordination, the BIM technical method can construct the integral digital integration process flow related to safety management (process visualization, simulation optimization, interactive coordination, etc.). Along with the constant promotion of the application of BIM technical methods in the engineering sector, technical methods of BIM+others have emerged, such as RFID/GIS positioning technology, virtual reality (VR), augmented reality (AR), eye tracker technology, cloud computing, and machine vision method; and the issues related to safety management have further deepened. The key issues for the hotspots of research on BIM and safety management include the following: the BIM automatic safety review method, 3D–*n*D engineering safety simulation and analog analysis methods, safety management information control method integrated with other technologies, BIM and image/data-based engineering safety risk scenario analysis method, etc. BIM has pushed forward the change of data-driven management models and technical methods. Researching BIM and other technical methods is rather significant to information consolidation, visualization, sharing, delivery, integration, and computing in the process of engineering construction, and to scientific issues of engineering whole-process safety management such as effect characteristics, change rules, and control requirements, and the whole-life safety and management of current construction engineering projects.

(8) Analysis and research on the IoE

With the stress of energy marketization and a development mode for a green economy, sustaining social development demands higher requirements of energy systems in view of energy safety, environmental pollution, and climate change. As a new industrial form, the IoE is an important approach for pushing forward the energy revolution and improving energy utilization efficiency. The IoE, a new energy system deeply integrated by the energy system with a core of electric power and the Internet based on electronic information technology, has realized the two interconnections, i.e., the multi-energy physical interconnection and the data interconnection with transparent energy and resources. Although the IoE is still being defined, with the close coupling with renewable energy, natural gas, and traffic networks and other systems, it has become the new focus of current international scientific research and industrial development. Currently, the research hotspots of technical innovation of the IoE include construction of the general structure and standard system, construction of the networking and inter-operational model, modeling simulation and analysis technology development, operation and control equipment research and manufacturing, and construction of security systems. Due to high systematicness and complexity, the IoE requires consolidated planning and top designs. In the future, the IoE needs to be more open in energy types, users, standards, and interfaces, and to have richer applications, realizing multi-energy interconnection and multi-user interconnection. Along with the maturing of scientific technologies and consummation of relevant policies, the IoE will play an important role in energy production, transmission, consumption, storage, conversion, and other links of energy exchange and supply chains.

(9) Logistic trading and shipping management under the Belt and Road

As China is entering the center of the world stage gradually, the Belt and Road Initiative has been initiated. Along with the deepening and promotion of this initiative, the basic significances of logistical channels have been expressed. As an economic bond for surrounding countries or regions, it has realized the coordinated development of the regional economy. This initiative has grown rapidly due to its adaptation to world economy development rules, but it has also challenged logistical risk management. The logistics channel of “the Belt and Road” is important in realizing strong traffic. The research on the improvement of influence and competitive power of the logistics industry of China, the elevation of the sector’s standards to regional and even international standards, and the promotion of the internationalization of logistical standards are the development directions in the future; moreover, the logistics sector shall consummate the construction of the talent supply chain, establish the cultivation system of organization and technology professionals to cultivate talents who can connect with international organizations and surrounding countries, incorporate the construction of talent output channels to the key points of research, meet international demand dynamically, and realize the innovative development of the talent supply chain, which is the research direction in the future. The logistics channel is not only for material circulation, but also bears the opportunities to develop China’s trade. The construction of a “traffic–trade” corridor mode is an important direction. For realizing the closed-loop development of corridor economies targeted at coordinated and innovative development of “logistics, trade, and industries”, promoting the deep application of big data and Internet of Things (IoT) to forge a “supply chain of data” and realize comprehensive optimization is the future feasible direction. In addition, as geopolitics, exchange rates, ecology, and other factors challenge the the Belt and Road Initiative, how to warn the risk through changes of surface features and realize the logistics, trade, and shipping risk management under the Belt and Road as per the decision-making system with fast response is another direction to take.

(10) Research on blockchain alliance of energy exchange

With the evolution of the commercial society, the organizational structure of centralized exchanges with third parties at the core has exposed three problems, i.e., privacy disclosure, high cost, and unclear ownership. With the development of computer technology, the distributed database has become the key to decentralization. Blockchain, a distributed data management technology, can change the way of managing exchange participants from centralized control to distributed collaboration. The multi-party sharing mechanism enables the participants to form blockchain alliances that can access, maintain, and share databases. Auditing and tracking the credits of the database updaters has improved the security of exchange and information sharing. With the development of green and shared economies, the traditional business model of energy enterprises no longer adapt to the demand of the contemporary low-carbon economy, incurring a transformation in the energy sector led by energy enterprises and users. Energy departments apply blockchain technology to provide a distributed energy system so that energy supply contracts can be transmitted directly between producers and consumers. The combination of blockchain technology and energy departments has resulted in abundant energy exchange applications, such as the application of blockchain technology in management of energy enterprise capital, energy user, energy network supply chain, renewable energy power generation, and energy sharing. Improving the computing, storage, and processing capacities of blockchain and determining cross-sector open standards when the blockchain technology provides more channels for capital operation and exchange management of energy departments is of great significance to the deep commercial application of blockchain technology in the field of energy, and it is an important research direction of the future.

1.2 Interpretations for three key engineering research fronts

1.2.1 Research on sustainable development in the Industry 4.0 era

The sustainable development of engineering in the Industry 4.0 era mainly focuses on four typical areas: global industrial development strategy, system framework and key technologies, coupling with circular economies, and construction industrialization.

(1) Global industrial development strategy

The concept of Industry 4.0 was first proposed by the German Federal Ministry of Education and Research and the Federal Ministry of Economy and Technology in 2013, aiming to improve the competitiveness of the German industry. The proposal of Industry 4.0 has triggered a new round of industrial transformation competition all over the world. Many countries have put forward their own re-industrialization strategies. In the era of big data, cloud computing, and mobile interconnection, it is necessary to upgrade enterprises by combining intellectualization and industrialization to break through the existing growth bottleneck in productive forces.

The USA announced its National Strategic Plan for Advanced Manufacturing and proposed the Industrial Internet to improve production efficiency and create the future of the digital industry through machine interconnection, software, and large data analysis. The UK launched The Future of Manufacturing strategy to promote the sustainable development of society and the economy by focusing on a high-value manufacturing industry and adopting individualized low-cost products, production redistribution, and digitization of the manufacturing value chain. The European Union (EU) issued the “Factories of the Future” program to support the research, development, and innovation of advanced production technologies, and it further launched the “Digital Single Market” strategy to improve the usability of digital goods and services, foster a prosperous environment for digital networks and services, and create the European digital economy and society with potential long-term growth. Japan has formulated The Fifth Science and Technology Basic Plan. It plans to build a new super-intelligent society through the integration of cyberspace and real space and the creations of new industries and services. China has promulgated “Made in China 2025,” which includes accelerating the deep combination of the new generation of information technology and manufacturing industries, promoting intelligent manufacturing, strengthening the basic industrial capacity, improving the level of comprehensive integration, and promoting industrial transformation and upgrading. The research strand on the development strategies of global industries is mainly based on a policy research perspective, and covers relevant topics such as the core concepts, comparison analysis, strategic choice and path optimization, implementation methods, support system, open cooperation, management change, influence on the sustainable development of national and global societies and economies, and so on.

(2) Industry 4.0 framework, key technologies, and development evolution

Industry 4.0 is a complex engineering system with different objects and subjects. Its objects include the techniques, process, and automation under different standards in the industrial field, as well as information, communication, and Internet technology in information field. The Reference Architecture Model Industrie 4.0 (RAMI 4.0) illustrates Industry 4.0 in three dimensions: product life cycle and value chain, full-level industrial system, and capability level of CPS. RAMI 4.0 defines new standards and a technical framework and points out the direction for enterprises to deploy new infrastructure, apply new technologies, and exploit new standards. The framework of Industry 4.0 exhibits the basic model of transformation from a centralized to a decentralized enhanced control, and the goal is to establish a highly flexible production model with individualized and digitalized products and services.

Currently, the development of Industry 4.0 focuses on four main aspects: 1) Intelligent factories based on intelligent, networked production systems and networked distributed production facilities; 2) Intelligent production based on emerging technologies such as production logistics management, human–computer interaction, and 3D printing technology; 3) Intelligent logistics which integrates demand and matches services with demand based on the IoT, logistics network, and the Internet; 4) Intelligent services based on multi-faceted information technology applications and diversified cross-platform satisfaction of customer demands. The key technologies of Industry 4.0 include the IoT, cloud computing, industrial big data, industrial robots, 3D printing, knowledge task automation, network security, VR, and AI.

Successful implementation of Industry 4.0 involves three affinitive areas of action: digital sovereignty, interoperability, and sustainability. Digital sovereignty is the freedom of market participants to make decisions and participate in fair competition. It mainly touches upon digital infrastructure, security, and technological progress. Interoperability is the key element of the digital business process in Industry 4.0. It mainly involves standards and integration, regulatory framework, distributed systems, and AI. Sustainability covers economic, environmental, and social sustainability, and mainly includes employment and education, social participation, and climate change.

(3) Coupling between Industry 4.0 and circular economies

The development of Industry 4.0 is reconstructing the traditional economic system. The widespread application of intelligent technology could make economic systems more conveniently and harmoniously embedded into the material cycle process of natural ecosystems and realize the ecologization of economic activities. Typical Industry 4.0 and circular economy coupling models are based on the regenerate, share, optimize, loop, virtualize and exchange (ReSOLVE) framework. The five main steps are as follows: 1) Select an approach to ReSOLVE; 2) Identify suitable Industry 4.0 technologies; 3) Adopt sustainable operation management (SOM) decisions; 4) Develop cooperation in the supply chain; 5) Create performance indicators and small and achievable targets. Its core idea is to integrate and optimize the design-based and process-based methods to achieve the cyclic utilization of materials throughout a product life cycle, which would make Industry 4.0 the key enabling factor of a circular economy. The coupling between Industry 4.0 and circular economies involves technological, social, and business paradigm changes. Relevant research topics include an evaluation system of circular economies in the context of Industry 4.0, extended producer responsibility (EPR), green supply chain, zero-waste cities, source control schemes, pollutant process control, benign interference methods, key ecological link technology, etc.

(4) Construction Industry 4.0

As an important subdivision sector in Industry 4.0 era, construction industrialization has attracted much attention in the field of engineering management. Construction Industry 4.0 refers to the informationization and industrialization of the construction industry. It embodies the revolutionary transformation from the traditional manual operation to the building automation mode, from centralized to decentralized enhanced control and governance mode, and to a highly flexible production mode of individualized and digitalized construction products and services. The essence of construction industrialization in the Industry 4.0 era is to reconstruct a heterogeneous and customized construction industry through data flow automation technology with homogeneous and large-scale costs. It also reflects the change from economies of scale to economies of scope. Its goal is to achieve sustainable development of construction products in energy saving, environmental protection, and value maximization in whole-life cycles by technology chain integrating, industrial chain reengineering, and value chain upgrading. There are two important strands in the research of sustainability of construction industrialization in Industry 4.0: BIM and prefabricated construction. Being the core technology platform in construction industry, the integration of BIM and Industry 4.0 will promote the subversive revolution of the construction industry. BIM provides accurate building information, continuous digital records, and a collaborative work platform, which ensures the refined, intelligent, and green management in the whole-life cycle of construction products. Prefabricated construction is a breakthrough innovation of the construction mode. With standardized design, factory production, prefabricated constructing, all-in-one decoration, information management, and intelligent application, prefabricated construction could greatly help the construction industry to realize sustainable development. Highlighted research topics include policy support mechanism, management models, diversified governance, design technology systems, important green and integration technology, collaborative innovation network, cultivation of human resources, and so on.

The research on the sustainable development of engineering in the Industry 4.0 era is still in its infancy.

The number of core papers published has increased rapidly over the past three years. Germany, the USA, and France are the top three countries that have published the largest number of core papers related to sustainable development of engineering in the Industry 4.0 era (Table 1.2.1), while Sweden, Germany, and Brazil are the top three countries with the largest number of citations per paper (Table 1.2.1).

According to the collaboration network among major countries or regions producing core papers (Figure 1.2.1), a close cooperation network does not exist yet, but the network shows some preliminary regional characteristics. Sporadic collaborations exist between the USA and Asia, and similar ones exist between Germany and France, as well as France and Brazil.

Berlin University of Technology, Friedrich-Alexander University Erlangen-Nurnberg, and Montpellier Business School are the top three institutions that have published the largest number of core papers (Table 1.2.2). Based on the cooperation network chart of the institutions producing core papers (Figure 1.2.2), a close cooperation network does not exist, but the network also shows some preliminary regional characteristics which are consistent with the distribution of the country or region. China is still in a leading position.

Table 1.2.1 Countries or regions with the greatest output of core papers on "research on sustainable development in the Industry 4.0 era"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Germany	6	27.27%	195	40.12%	32.50
2	USA	4	18.18%	50	10.29%	12.50
3	France	4	18.18%	85	17.49%	21.25
4	Brazil	3	13.64%	75	15.43%	25.00
5	China	2	9.09%	17	3.50%	8.50
6	South Korea	2	9.09%	22	4.53%	11.00
7	Japan	1	4.55%	7	1.44%	7.00
8	Italy	1	4.55%	4	0.82%	4.00
9	Spain	1	4.55%	3	0.62%	3.00
10	Sweden	1	4.55%	33	6.79%	33.00

Table 1.2.2 Institutions with the greatest output of core papers on "research on sustainable development in the Industry 4.0 era"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Tech Univ Berlin	2	9.09%	97	19.96%	48.50
2	Friedrich Alexander Univ Erlangen Nurnberg	2	9.09%	30	6.17%	15.00
3	Montpellier Business Sch	2	9.09%	22	4.53%	11.00
4	Beijing Inst Technol	1	4.55%	7	1.44%	7.00
5	Doshisha Univ	1	4.55%	7	1.44%	7.00
6	Univ Texas Dallas	1	4.55%	7	1.44%	7.00
7	UFSCar Fed Univ Sao Carlos	1	4.55%	14	2.88%	14.00
8	Sapienza Univ Rome	1	4.55%	4	0.82%	4.00
9	Univ Tuscia Viterbo	1	4.55%	4	0.82%	4.00
10	Fraunhofer Inst Reliabil & Microintegrat	1	4.55%	10	2.06%	10.00

The USA, Germany, and China are the top three countries that have published the largest number of citing papers related to the sustainable development of engineering in the Industry 4.0 era (Table 1.2.3), while University Johannesburg, University Nova Lisboa, and Berlin School of Economic & Law are the top three institutions that have published the largest number of citing papers (Table 1.2.4).

1.2.2 Construction management driven by machine vision

With the development of signal processing theory and computer technology, people began to try to use cameras to obtain environmental images and convert them into digital signals, so that computers could extract environmental information through one or more images. The computers' main tasks are image processing, pattern classification, and

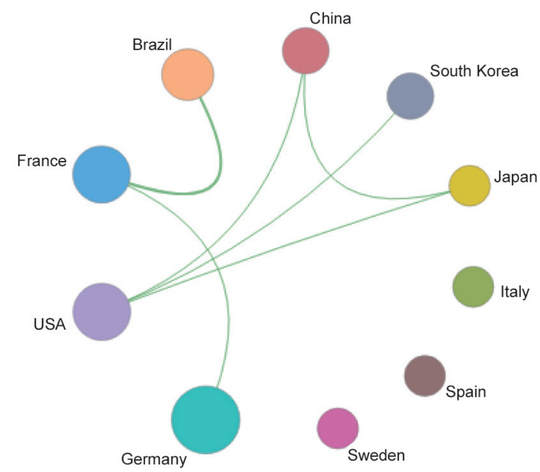

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of "research on sustainable development in the Industry 4.0 era"

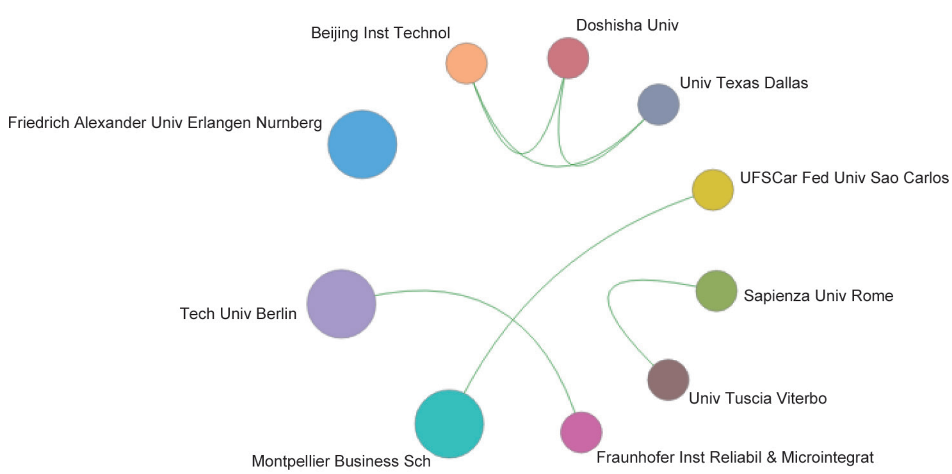

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "research on sustainable development in the Industry 4.0 era"

Table 1.2.3 Countries or regions with the greatest output of citing papers on "research on sustainable development in the Industry 4.0 era"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	USA	42	15.27%	2018.0
2	Germany	39	14.18%	2017.7
3	China	37	13.45%	2017.8
4	Italy	32	11.64%	2017.9
5	UK	27	9.82%	2017.9
6	France	22	8.00%	2017.7
7	Brazil	21	7.64%	2017.8
8	Spain	17	6.18%	2017.5
9	Portugal	14	5.09%	2017.5
10	Russia	12	4.36%	2017.6

Table 1.2.4 Institutions with the greatest output of citing papers on "research on sustainable development in the Industry 4.0 era"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Univ Johannesburg	6	10.34%	2017.8
2	Univ Nova Lisboa	6	10.34%	2017.7
3	Berlin Sch Econ & Law	6	10.34%	2017.3
4	Univ Fed Santa Catarina	6	10.34%	2017.8
5	Norwegian Univ Sci & Technol	6	10.34%	2017.2
6	Worcester Polytech Inst	5	8.62%	2018.0
7	Seoul Natl Univ	5	8.62%	2017.6
8	Friedrich Alexander Univ Erlangen Nurnberg	5	8.62%	2018.2
9	Old Dominion Univ	5	8.62%	2018.0
10	Kyonggi Univ	4	6.90%	2017.5

scene analysis. Machine vision systems are widely used in industries, for applications including detection of the products from automatic production lines, face recognition, and automatic understanding of medical images. The application of machine vision in the construction industry has become a new topic of concern. It can improve the level of automation in the construction field. The mainstream algorithms, hot research issues, and research status of machine vision in the field of architecture are discussed further below.

(1) The main algorithms of machine vision

An important step in machine vision is the detection of a target object, that is, to recognize a specific object from an image. There are many algorithms for target object detection, which can be divided into two kinds: shallow machine learning and deep learning. The main algorithms of the former are histogram of gradient (HOG), histogram of flow (HOF), support vector machine (SVM) and *k*-nearest neighbor. However, these methods need to create features manually, which is time-consuming and cannot satisfy both detection accuracy and computational efficiency. In addition, uncertainties and changing construction scenarios prevailing in a construction site will affect feature extraction in the image, such as viewpoint variance, scale variance, intra-class variance, or background clutter, resulting in reduced accuracy of object detection. As an end-to-end learning method, with a strong ability to represent features and high learning accuracy, deep learning has become the main algorithm in machine learning research of the current construction industry. Examples of deep learning algorithms are Single Shot Multibox Detector (SSD), You Only Look Once (YOLO), and convolutional neural networks (CNN). Of these, CNN is the basic element of deep learning algorithms, including multiple convolution layers, rectification linear unit, pooling layer, and full connection layer. The emergence of CNN greatly improved machine vision in target object detection. Based on CNN, other algorithms have gradually been developed, such as recurrent neural network (RNN), fast region-based convolutional neural network (Fast R-CNN), and mask regions with convolutional neural network (Mask R-CNN).

(2) Construction safety management based on machine vision

The construction sector is one of the high-risk sectors and is prone to safety mishaps and casualties. A major research hotspot is the use of machine vision to realize automated safety supervision in construction processes, and to find out the unsafe behaviors or unsafe states in construction processes in time and feed them back to executives in time.

The research contents include object detection, object tracking, and motion recognition. Of these, object detection is the premise of object tracking and motion recognition and needs to segment an image, extract features, and classify its features using deep learning algorithms. Research in object tracking aims to improve the accuracy of estimation of physical position of an object. Compared with sensing technology, machine vision has a wider coverage, and it can achieve multi-target object tracking without the need to install interventional sensors. Motion recognition aims to extract the movement information of laborers or machines from images, which depends on the extraction and classification of image features.

(3) Productivity analysis based on machine vision

Productivity analysis aims at avoiding inefficiencies arising from waiting, idleness, and excessive transportation during construction. The research mainly focuses on the two aspects: 1) tracking the construction progress of a project and analyzing the deviation of the progress; 2) measuring the efficiency of laborers or equipment during the operation of a project, so as to carry out effective management and maximize operational efficiency. Productivity analysis needs to collect real-time data of construction sites and convert these data into productivity information, such as work sequence and duration. With the popularization and application of camera technology in construction sites, the automatic productivity analysis of recorded images and videos using machine vision technology has attracted wide attention.

(4) Defect detection based on machine vision

Defect detection aims at checking the defects and damages (cracking, peeling, defective joints, corrosion, pits, etc.) and the size of defects (quantity, width, length, etc.) in infrastructure components. This is conducive to assisting investment planning and allocating limited repair and maintenance resources, becoming the main means of ensuring that infrastructure meets its service performance. Defect detection based on machine vision mainly involves image processing technologies such as template matching, histogram transformation, background subtraction, filtering, and feature classification. Most of the research targets are concrete bridges, tunnels, pipelines, asphalt pavements, and other infrastructure. However, data acquisition of bridge images and videos is not fully automated, and the image quality varies with the camera attitude, distance, and environmental conditions. Detecting defects of complex geometric parts is still a challenge; for tunnels and pipelines, the poor illumination condition in the picture, irregular background pattern and contrast, and low-quality data are the main problems at present. For asphalt pavements, detecting and classifying pavement defects in real-time environment is still a challenge.

(5) Current situation and future trend

Currently, machine vision, as a means to realize the automation of construction management, is widely used in all links of construction, such as safety surveillance, productivity analysis, and defect detection. However, in the course of development, it still has some pending problems.

First, deep learning algorithms require a large number of data training models. Moreover, datasets that can be used publicly are still lacking, which greatly hinders the development of machine vision. Second, the current research on machine vision is limited to a specific behavior or scene, such as whether laborers wear safety helmets or not, but practical applications often require the surveillance of a variety of tasks and risks. Third, safety surveillance driven by machine vision is often based on feature extraction but fails to achieve a high level of semantic understanding of a scene. With the increasing complexity of the definition of construction risks, machine vision needs to integrate standard knowledge to improve the ability of scene understanding and risk reasoning. The ontology, as a standardized representation of domain knowledge, can process text standard knowledge and expert experience into a computer-readable mode. Therefore, a research trend in the future is the effective integration of ontology and machine vision to enable ontology to effectively improve background and prior knowledge for image understanding in computer vision.

According to the number of core papers published, the top three countries or regions with the highest number of core papers are China, the USA, and Australia (Table 1.2.5). The top three countries or regions in citations per paper are the USA, Poland, and China (Table 1.2.5). According to the cooperation network chart of major countries or regions outputting core papers (Figure 1.2.3), no closer cooperation network exists yet and cooperation relationships exist between the USA and Germany, and China and Australia. The top three institutions with the highest number of core papers are Huazhong University of Science and Technology, Columbia University, and Hong Kong Polytech University (Table 1.2.6). According to the cooperation network chart of major institutions producing core papers (Figure 1.2.4), no close cooperation network exists yet, but there are preliminary regional characteristics.

China, the USA, and South Korea are the top three countries that have published the largest number of citing papers related to construction management driven by machine vision (Table 1.2.7), while Huazhong University of Science

Table 1.2.5 Countries or regions with the greatest output of core papers on “construction management driven by machine vision”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	7	41.18%	172	40.57%	24.57
2	USA	6	35.29%	169	39.86%	28.17
3	Australia	2	11.76%	49	11.56%	24.50
4	Canada	2	11.76%	38	8.96%	19.00
5	Poland	1	5.88%	26	6.13%	26.00
6	Germany	1	5.88%	19	4.48%	19.00
7	South Korea	1	5.88%	19	4.48%	19.00

Table 1.2.6 Institutions with the greatest output of core papers on “construction management driven by machine vision”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Huazhong Univ Sci & Technol	3	17.65%	75	17.69%	25.00
2	Columbia Univ	2	11.76%	87	20.52%	43.50
3	Hong Kong Polytech Univ	2	11.76%	48	11.32%	24.00
4	Univ Nottingham Ningbo	1	5.88%	30	7.08%	30.00
5	Univ Michigan	1	5.88%	28	6.60%	28.00
6	Curtin Univ	1	5.88%	27	6.37%	27.00
7	Hubei Engn Res Ctr Virtual Safe & Automated Const	1	5.88%	27	6.37%	27.00
8	Tongji Univ	1	5.88%	26	6.13%	26.00
9	AGH Univ Sci & Technol	1	5.88%	26	6.13%	26.00
10	Queensland Univ Technol	1	5.88%	22	5.19%	22.00

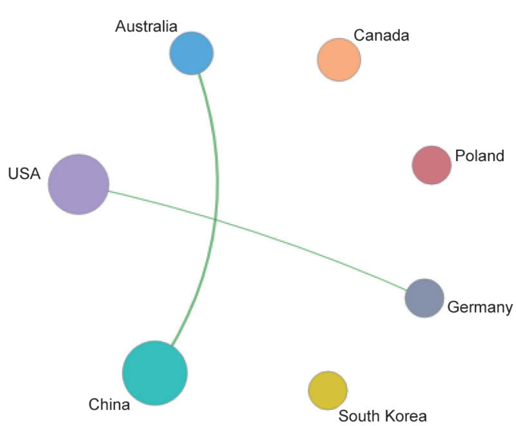

Figure 1.2.3 Collaboration network among major countries or regions in the engineering research front of “construction management driven by machine vision”

& Technology, Hong Kong Polytech University, and Tongji University are the top three institutions that have published the largest number of citing papers (Table 1.2.8).

1.2.3 Resilience of the infrastructure systems

The word “resilience” originated from the Latin word “resilio,” meaning “return to its original state.” Prof. Holling, a Canadian ecologist, first applied the idea of resilience to system ecology to define the steady-state characteristics of ecosystems. Subsequently, the idea of resilience was applied to different disciplines, including engineering resilience, economic resilience, and infrastructure system resilience. Infrastructure system resilience can be understood as the comprehensive ability of a system to maintain certain basic functions during disasters and restore normal functions soon after disasters. As the infrastructure system sustains the social and economic functions of a city and is the main artery of the city, a resilient infrastructure system is the core and key to realize the resilient city.

The assessment and improvement of the infrastructure system resilience are deeply analyzed and the future development trend of the research on infrastructure system resilience are subsequently summed up below.

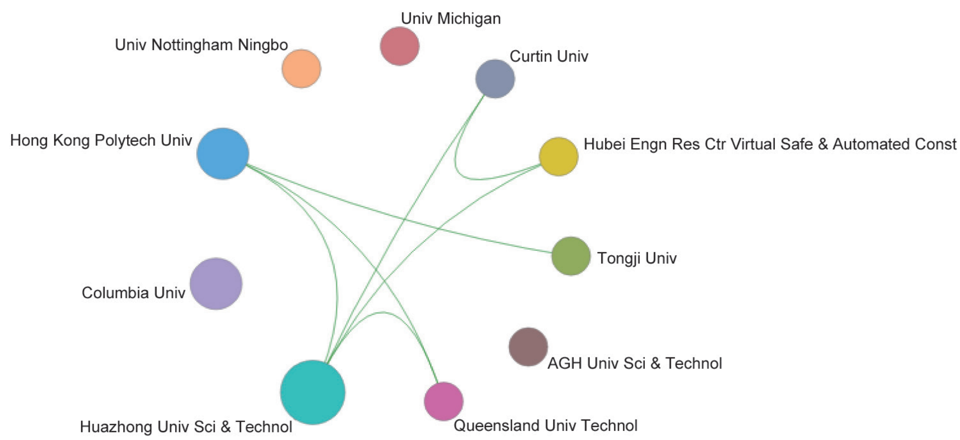

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of “construction management driven by machine vision”

Table 1.2.7 Countries or regions with the greatest output of citing papers on “construction management driven by machine vision”

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	128	36.26%	2018.1
2	USA	80	22.66%	2017.9
3	South Korea	32	9.07%	2017.9
4	UK	29	8.22%	2018.0
5	Australia	26	7.37%	2018.1
6	Canada	16	4.53%	2017.8
7	Spain	15	4.25%	2018.1
8	Germany	10	2.83%	2017.6
9	Italy	7	1.98%	2017.9
10	Turkey	5	1.42%	2017.8

Table 1.2.8 Institutions with the greatest output of citing papers on “construction management driven by machine vision”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Huazhong Univ Sci & Technol	21	16.28%	2018.2
2	Hong Kong Polytech Univ	19	14.73%	2018.2
3	Tongji Univ	17	13.18%	2018.1
4	Curtin Univ	15	11.63%	2018.1
5	Harbin Inst Technol	11	8.53%	2018.4
6	Columbia Univ	9	6.98%	2017.0
7	Dalian Univ Technol	8	6.20%	2017.9
8	Zhejiang Univ	8	6.20%	2017.4
9	Cent S Univ	8	6.20%	2018.3
10	Yonsei Univ	7	5.43%	2017.7

(1) Research on assessment of infrastructure system resilience

Although different definitions of resilience exist, when evaluating infrastructure system resilience, almost all the resilience indicators in available literature are put forward based on the actual function curve of the system in disaster events and the expected function curve in disaster-free situations. Before an event, the system runs normally with a 100% function index; when the event occurs, there may be a process of fault generation and spread until the function indicator reaches the lowest value; after the event, the system damage condition is evaluated and gradually repaired, and the post-recovery system function indicator may be less than, equal to, or greater than the 100% before the event. Based on the actual function change curve and expected function curve, scholars have put forward various resilience indicators and related resilience assessment methods. The research hotspots of assessment of infrastructure system resilience mainly include: assessment of infrastructure system resilience oriented to multiple disasters, assessment of infrastructure system resilience with system relevance taken into account, setting of resilience objectives of the infrastructure system, verification of the resilience assessment model of the infrastructure system, and construction of a testing system.

(2) Research on improvement of resilience of the infrastructure systems

One of the main purposes of defining and assessing the resilience of infrastructure systems is to research how to improve system resilience. With the purpose to improve the resilience of infrastructure systems, many countries have stipulated infrastructure protection plan documents with a series of management or policy tactics such as optimizing the allocation of resources for disaster prevention and recovery, formulating disaster insurance policy incentives and planning programs for post-disaster land use, promoting cooperation and information sharing among different systems, strengthening the awareness and culture of resilience, enhancing leadership, enriching executives' experience in dealing with large-scale disasters, and attaching importance to the relevance of different systems. For improvement tactics for engineering technology resilience, such as strengthening system components, adjusting system structures, and configuring redundant systems, the resilience improvement can be modeled as a multi-stage dynamic optimization with a limited budget. The research hotspots of infrastructure system resilience improvement include: resilience improvement for infrastructure system organizations, resilience improvement for infrastructure systems based on the whole-life cycle, an efficient solution algorithm of multi-stage resilience improvement and optimization model, resilience-driven decision optimization for post-disaster recovery for infrastructure systems, and resilience improvement for infrastructure systems considering the functional relevance of building communities.

(3) Current situation and future development trend

The National Science Foundation of the USA funded a series of research projects on resilience of infrastructure systems, such as resilient and sustainable infrastructure, and resilient associated infrastructure systems and processes. The National Institute of Standards Testing (NIST) issued guidelines for urban resilience planning in 2016 and funded Colorado State University to establish the research center of "risk-based urban resilience planning" (involving ten universities of the USA) which took the resilience of infrastructure systems as the key point of research and planning. The Federal Emergency Management Administration (FEMA) has developed the software HAZUS and FEMA P58 to analyze the risk, economic loss, and recovery time of the infrastructure systems of different cities of the USA in flood, hurricane, and earthquake disasters. The Infrastructure Transitions Research Consortium, which is charged by the University of Oxford, has researched measures to improve the resilience of associated infrastructure systems to flood disasters. The SYNER-G project funded by the EU's FP7 has researched the vulnerability and resilience of infrastructure systems to earthquake disasters; the European Union Joint Research Centre has developed the software for decision making for post-disaster recovery and resilience improvement of infrastructure systems. In 2015, the National Natural Science Foundation of China issued a joint British–Chinese fund to improve the resilience of earthquake-prone areas in China to natural disasters; in 2017, it issued emergency response projects, i.e., research on theoretical methods and tactics for the construction of the safe and resilient Xiong'an New Area; and in 2018, it held the 204th Shuangqing Forum in Harbin to discuss the basic scientific issues of the construction of anti-seismic and resilient cities, wherein, the infrastructure system resilience was the key point of discussion. Based on the current research situation, the future development trends mainly include: resilience assessment and improvement under the coupling of multi-hazards (especially those related to climate change), modeling and validation of the relevance among systems and between a system and its environment, and efficient solution algorithms for large-scale improvement of system resilience.

The top three countries or regions with the highest number of core papers in the engineering research front of "infrastructure system resilience" are, the USA, China, and the UK, respectively (Table 1.2.9) and the top three countries or regions in the citations per paper are Denmark, Israel, and the UK, respectively (Table 1.2.9). According to the cooperation network chart of major countries or regions producing core papers (Figure 1.2.5), the USA, China, the UK, Australia, and Greece have frequent cooperation.

The top three institutions with the highest number of core papers are, the University of Manchester, the University of Melbourne, and City University of Hong Kong (Table 1.2.10). According to the cooperation network chart of major institutions producing core papers (Figure 1.2.6), University of Manchester, University of Melbourne, National Technical University of Athens, and Newcastle University have frequent cooperation.

From Table 1.2.11, we can see that China ranks first in the number of citing papers. From Table 1.2.12, we can see that Shanghai Jiao Tong University and Tsinghua University are the leaders of the front.

Table 1.2.9 Countries or regions with the greatest output of core papers on "infrastructure system resilience"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	11	39.29%	282	40.81%	25.64
2	China	9	32.14%	230	33.29%	25.56
3	UK	8	28.57%	229	33.14%	28.63
4	Australia	6	21.43%	167	24.17%	27.83
5	Greece	3	10.71%	68	9.84%	22.67
6	Switzerland	2	7.14%	52	7.53%	26.00
7	Germany	2	7.14%	42	6.08%	21.00
8	Denmark	1	3.57%	38	5.50%	38.00
9	Israel	1	3.57%	38	5.50%	38.00
10	Norway	1	3.57%	28	4.05%	28.00

Table 1.2.10 Institutions with the greatest output of core papers on "infrastructure system resilience"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Univ Manchester	4	14.29%	121	17.51%	30.25
2	Univ Melbourne	3	10.71%	86	12.45%	28.67
3	City Univ Hong Kong	3	10.71%	59	8.54%	19.67
4	Lehigh Univ	2	7.14%	64	9.26%	32.00
5	Newcastle Univ	2	7.14%	57	8.25%	28.50
6	Natl Tech Univ Athens	2	7.14%	53	7.67%	26.50
7	Huazhong Univ Sci & Technol	2	7.14%	27	3.91%	13.50
8	Univ Michigan	1	3.57%	69	9.99%	69.00
9	Univ Bath	1	3.57%	44	6.37%	44.00
10	Xi An Jiao Tong Univ	1	3.57%	44	6.37%	44.00

Figure 1.2.5 Collaboration network among major countries or regions in the engineering research front of “infrastructure system resilience”

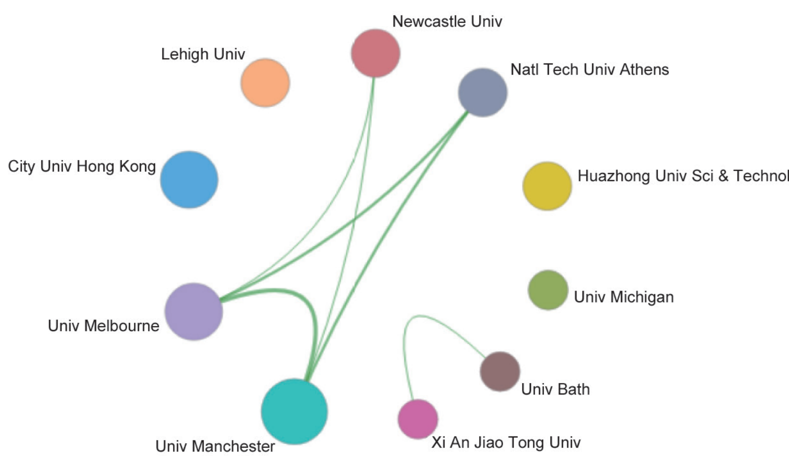

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of “infrastructure system resilience”

Table 1.2.11 Countries or regions with the greatest output of citing papers on “infrastructure system resilience”

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	191	31.41%	2018.4
2	USA	166	27.30%	2018.3
3	UK	49	8.06%	2018.5
4	Australia	43	7.07%	2018.3
5	Italy	41	6.74%	2018.3
6	Germany	26	4.28%	2018.2
7	Iran	23	3.78%	2018.3
8	France	20	3.29%	2018.2
9	Spain	18	2.96%	2018.5
10	South Korea	16	2.63%	2018.3

2 Engineering development fronts

2.1 Trends in top 10 engineering development fronts

In the field of engineering management, the fronts of global engineering development mainly include the following ten parts, i.e., (1) visualization technology oriented to engineering management, (2) warning technologies and methods oriented to engineering safety, (3) IoT technology development oriented to engineering management, (4) smart logistics, (5) risk evaluation and management systems, (6) vehicle information and resource sharing systems, (7) intelligent medical health management, (8) cloud-computing-based integration management methods and technology, (9) wearable-device-based management and techniques, and (10) quality engineering technology oriented to intelligent manufacturing. Their core patents are shown in Table 2.1.1 and Table 2.1.2. These engineering development fronts contain mechanisms, transport, medicine, architecture, electronics, and other disciplines. Of these, the visualization technology oriented to engineering management, warning technology and methods oriented to engineering safety, and IoT technology development oriented to engineering management, are the key fronts and their development situation and future trends are detailed below.

(1) Visualization technology oriented to engineering management

Visualization technology refers to a technical method that is based on computer image technology and generates human visual stimulus graphics through computers so that people

Table 1.2.12 Institutions with the greatest output of citing papers on "infrastructure system resilience"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Shanghai Jiao Tong Univ	22	17.60%	2018.2
2	Tsinghua Univ	14	11.20%	2018.4
3	RMIT Univ	12	9.60%	2018.3
4	Swinburne Univ Technol	12	9.60%	2018.0
5	Hong Kong Polytech Univ	10	8.00%	2018.2
6	Univ Hong Kong	10	8.00%	2018.6
7	Huazhong Univ Sci & Technol	10	8.00%	2018.0
8	City Univ Hong Kong	9	7.20%	2018.1
9	Univ Calif Berkeley	9	7.20%	2018.6
10	Lehigh Univ	9	7.20%	2018.0

Table 2.1.1 Top10 engineering development fronts in engineering management

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Visualization technology oriented to engineering management	14	80	5.71	2014.9
2	Warning technologies and methods oriented to engineering safety	16	59	3.69	2015.3
3	IoT technology development oriented to engineering management	17	55	3.24	2015.5
4	Smart logistics	26	118	4.54	2014.9
5	Risk evaluation and management systems	22	164	7.45	2014.2
6	Vehicle information and resource sharing systems	11	36	3.27	2015.6
7	Intelligent medical health management	23	174	7.57	2014.7
8	Cloud-computing-based integration management methods and technology	31	189	6.10	2014.8
9	Wearable-device-based management and techniques	6	46	7.67	2015.2
10	Quality engineering technology oriented to intelligent manufacturing	26	98	3.77	2014.9

Table 2.1.2 Annual number of core patents published for the top 10 engineering development fronts in engineering management field

No.	Engineering development front	2013	2014	2015	2016	2017	2018
1	Visualization technologies oriented to engineering management	0	6	4	4	0	0
2	Warning technology and methods oriented to engineering safety	5	0	0	8	3	0
3	IoT technology development oriented to engineering management	0	3	5	6	3	0
4	Smart logistics	2	8	8	8	0	0
5	Risk evaluation and management systems	6	10	1	5	0	0
6	Vehicle information and resource sharing systems	1	1	3	3	2	1
7	Intelligent medical health management	2	7	11	1	2	0
8	Cloud-computing-based integration management methods and technology	5	8	9	7	2	0
9	Wearable-device-based management and techniques	0	1	3	2	0	0
10	Quality engineering technology oriented to intelligent manufacturing	2	8	8	8	0	0

can accept and understand the original data and information. Currently, visualization technology shows a promising application, which can be used in engineering safety, progress management, and human–computer interaction. With the rise of AI technologies such as deep learning, the research and application of visualization technology have become new academic research hotspots, and it is considered to be another revolutionary information technology. However, in the practical application of engineering management, the engineering data types are multi-source and heterogeneous, the amount of data is large, and the information is fragmented; therefore, the advantages of visualization technology in engineering management cannot be fully exploited. A key bottleneck restricting the application of visualization technology in engineering management is its expandability. Parallel computing and deep learning, 5G, IoT and other AI technologies can more accurately, efficiently, and intelligently perceive, calculate, and analyze massive engineering data to support real-time visualization and interactive operation. Therefore, two major trends of future research will be combining large-scale parallel computing, supercomputers, and AI technologies to make the visualization system more intelligent, and upgrading and extending the current valuable visualization methods and human–computer interaction technology to the field of engineering management.

(2) Warning technologies and methods oriented to engineering safety

Engineering includes construction engineering, industrial engineering, mining engineering, traffic engineering, and environmental engineering, and engineering safety is the basic premise and guarantee of various engineering activities. Engineering safety, which is still a serious issue, is a high concern by professionals and executives of all engineering sectors. In terms of how to improve engineering safety levels, the traditional safety management is conducted by safety training, standardized process operation, and site patrol and monitoring, which has prevented the incidence of safety accidents and improved safety management levels to some extent but is not striking in its safety effect. The rapid development of emerging information and data analysis technologies has provided new thinking directions for the solution of engineering safety concerns. Engineering control methods, technologies, and devices integrated with IoT, sensors, cloud computing, visualization, machine vision, and big data are constantly being produced. However, with the purpose of effectively controlling engineering safety concerns, on one hand, the instantaneity of site safety surveillance and warning shall be taken into account and, on the other hand, the acquisition of the data supporting safety management decision making shall be taken into account. Therefore, the future engineering safety control must develop and absorb diverse information technologies, improve the instantaneity and effectiveness of safety warning, as well as develop applicable technologies for engineering data acquisition to support the everlasting decision making of executives for safety management so as to form effective engineering safety control programs for the system.

(3) Development of IoT technology oriented to engineering management

The IoT technology is an Internet technology that connects all items related to the Internet through a series of information sensing devices and in accordance with the provided relevant digital agreements for information exchange and communication so as to realize intelligent recognition, positioning, tracking, monitoring, and management. IoT technology has been widely used in medical logistics, intelligent agriculture, vehicle integrated management, and steel warehousing. The IoT technology oriented to engineering management must adapt to the complex and diverse environment of construction sites and the dynamic changes of engineering elements and should handle a large number of sensors and enormous amounts of communication data. From the perspective of the technical architecture of the IoT, three mainstream architectures based on electronic product code (EPC) global standard, ubiquitous sensor network (USN), and machine to machine (M2M) IoT have been matured. The key technologies include intelligent sensing, high-reliability and secure transmission, integrated application, and public technologies. The core modules of system development include radio frequency communication, network transmission, storage, and data analysis modules.

The development of IoT technology oriented to engineering management mainly solves the collection and transmission of engineering information. Through RFID tags, sensing devices, QR codes, video surveillance, and other sensing technologies, the materials and equipment from a construction site as well as personnel information can be collected and transmitted to the backend of the information system to realize the trace of the basic, location, and transformation status information of the targets monitored. Success cases of the application of engineering IoT have been recorded in bridges, super high-rise structure health surveillance, positioning of metro construction personnel, engineering environment monitoring, material planning and tracking, and dynamic monitoring of construction machinery, in China and abroad. The fronts of the development of IoT technology involve massive sensing data compression, three-dimensional video intelligent analysis, IoT and BIM integration, IoT-based large data analysis, and IoT and 5G mobile communication technologies, etc.

(4) Smart logistics

In the field of smart logistics, the managers always face enormous logistics transportation network and complex business processes. All logistical activities are closely connected by the Internet or IoT and certain logistical operations have realized high automation levels. The managers must require mass data and intelligent optimization algorithms for decision making. The logistical enterprises are increasingly more concentrated, the size of top logistical enterprises are increasingly larger, and the business types, as well as transport modes, are increasingly more diverse, thus making the logistical transport networks of enterprises increasingly larger and the business process as well as the information system increasingly more complex. Logistical activities cannot exist without the Internet and tend to use IoT. The upcoming 5G will become integral to the operational activities of logistical enterprises. Along with the popularization of smartphones and the wide application of image and video collectors as well as various sensors, the logistics-related data have boomed in recent years. A current research front is the exploitation of the potential values of these data. Many logistical enterprises have begun to use industrial robots (including UAVs and unmanned vehicles) instead of laborers for sorting, packaging, handling, and distribution. Another current research front is the designing, deploying, and scientific use of such automation equipment. Making decisions based on labor experience has been inapplicable to modern logistical enterprises and the traditional logistical optimization technologies are unsuitable to the new environment of smart logistics, too; therefore, research must be conducted on the data-driven intelligent optimization technologies to armor the decision-making brains of enterprises and work out a series of new theories and new methods in demand prediction, network design, transport planning, stock management, warehouse operation, and staff duty shift.

(5) Risk evaluation and management systems

The risk evaluation and management system is a management information system that stores and analyzes the acquired basic data and identifies and evaluates risks by various risk evaluation methods, thus to realize risk control. Its main functional modules include data acquisition, storage, risk analysis and processing, and risk warning-control modules. From the perspective of system design level structure, it includes an infrastructure service level, data service level, supporting service level, application program service level, and user level. The system operation process generally includes: to acquire data through traditional data input or hardware sensor sampling, conduct structure or semi-structured storage, analyze and process data through risk evaluation algorithms, evaluate risk incidence and determine risk level, and finally put forward countermeasures and push the relevant information to the managers. It has been widely applied in industrial production, water supply, electric power generation, mechanical equipment management, medical resource distribution, and business exchanges.

In the field of engineering management, the risk evaluation and management oriented to the whole life cycle of projects have always been the keys to research. Especially for safety risk evaluation and management of construction sites, the research hotspot has been the real-time automatic acquisition of site surveillance data, intelligent dissection of monitor videos and images, real-time sensing as well as evaluation on safety risks with the help of the backend risk evaluation rules (including incidence threshold value and risk classification rules), and timely risk warning and control. The current main quantitative analysis methods include FMEA, HAZOP, FTA, Improved Interval AHP, and Multivariate Weight Matrix Analysis. Future risk evaluation and management systems will be combined with engineering IoT, cloud service platform, engineering big data, data combination, data exploitation methods, and swarm intelligence algorithms and trends to be more integrated, digitalized, and intelligent.

(6) Vehicle information and resource sharing systems

The vehicle information and resource sharing system is a resource utilization mode for the entities that use vehicle sharing to realize the effective flow of information and resources through various coordination mechanisms, satisfy the scarcity of vehicles for demanding clients, and achieve vehicle sharing. The vehicle information and resource sharing system provides a new trip mode, and it shows a promising application for the present stage where traffic congestion has severe impact on people's living quality, which can alleviate the trouble in urban trips incurred by traffic congestion and reduce the cost of trips. As a new concept of resource sharing, the research and development of vehicle information and resource sharing systems has entered a stage of fast development and all countries are conducting R&D of relevant devices and technical updates. This technology includes at least one sharing unit and one delivery unit which are connected with available communication. The sharing unit includes one sharing tactic generation module and one selection module, and the delivery unit includes one delivery module. They can communicate with each other according to certain rules. The key technology restraining the development and extensive application of vehicle information and resource sharing systems is the vehicle distribution optimization algorithm during receiving the reservation request. This optimization algorithm is always implemented based on a pre-set processor with the purpose of showing users reservation results in a rapid manner and reducing the operation cost of vehicle sharing services. The efficient vehicle information and resource distribution optimization algorithm is the foundation of future vehicle sharing and it can reduce the operation cost of systems, as well as improve user satisfaction; therefore, it is the most convenient and feasible approach to promote the development in this direction.

(7) Intelligent medical health management

As the third health revolution is upcoming, medical health management service has become the leading tactic of the health system—a system oriented by health. The so-called medical health management is a whole-life, whole-process, and all-around intervention management process for the factors influencing the health of individuals and communities, their action process, and the health results, with the purpose of improving the health level and life quality of individuals and communities. Along with the development of Internet technology, the medical health management service has not been limited by face-to-face communication between doctors and patients nor by time, space, and method. The service targets can learn their health status and obtain related health guides as well as interventions through information and intelligence technologies in time. Currently, big data platforms for regional health are being built gradually. Guided by evidence-based medicine, through deep learning and machine learning, AI has achieved initial success in medical imaging, clinical decision support, speech recognition, pathology, and other fields, making the O2O (online-to-offline) intelligent medical health management a new trend of medical health service development. However, the development of intelligent medical health management is currently at a primary stage. It lacks organic combination of online and offline management as well as the ability to regulate health management programs in a timely manner in light of the actual conditions of the service targets, making the health management effect unideal. Supported by 5G technology, with the intelligent medical elements such as wearable health devices, remote diagnosis, and remote imaging, the intelligent medical health will become more mature.

(8) Cloud-computing-based integration management methods and technology

Cloud computing is an information processing mode to realize mass computation through consolidated organization and flexible utilization of various ICT information resources, and the software and hardware resources and information through this mode can be provided to users' computers and other devices as required. So far, storage, medical, financial, and education clouds have been formed, showing extremely promising applications in finance, governmental affairs, industries, and medical treatment. Cloud computing has characteristics such as expandability, high flexibility, high reliability, and high-cost performance. In the future, it will be combined with AI to form ABC (AI + Big Data + Cloud Computing) and enter multi-application scenes of multi sectors.

Carrying out effective combinations of various data and resources is the basic function of the dynamic resource management of cloud computing while cloud data management technology is the key to realizing cloud computing. The data management technologies based on cloud computing mainly include GFS technology (document/data management), MapReduce technology (cluster parallel operation), BigTable technology (data management system), and Dynamo technology (data storage platform). They can provide services of different resources and different levels through data resources sharing at cloud end which involve infrestrncture as a service (IaaS), software as a service (SaaS), and platform as a service (PaaS). Of these, PaaS is the ultimate aim of cloud computing. In terms of cloud data integration management, with strong distributed storage and computing power, the cloud computing can conduct specific retrieval and analysis for mass data, realize effective combination of various isomerous data and service resources through mass data integration management, and can provide services for virtualized computing resources, Internet construction applications, business hosting, and management software applications.

(9) Wearable-device-based management and techniques

Wearable devices are portable devices with local computing and wearable properties, which are capable of sensing the physiological state, motion mode of human bodies, and the environment. Through communicating with diverse smart terminals (smartphones, clouds, etc.), they can provide continuous personal health monitoring and management, and regional residential health and life information management. Currently, wearable devices have taken notable evolutionary leaps in terms of product forms (watches, glasses, clothes, accessories, etc.) and interactive modes (touch, gesture, voice, etc.), which have been accepted by the market. However, new problems and challenges are gradually emerging as wearable devices are bringing great changes to our daily lives. Because wearable devices collect and record a huge body of data on personal physiology, daily activities, and the surrounding environment, it is important to process, integrate, and manage these data. On the one hand, the devices should provide accurate health status information to the wearer in a timely and dynamic manner, containing effective exercise methods, pre-emergency alarms, etc.; on the other hand, they should avoid the disclosure of personal information or infringement of personal privacy such as one's life preferences and behavioral habits. With the emergence of various wearable devices, enhancing the secure communication among the wearable devices, smart terminals, and the central servers; improving the natural interaction between the wearable devices and human beings; developing the intelligent management and techniques based on wearable devices; and providing multi-scenario and multi-level service experience are of great significance for the improvement of people's health status and living standards.

(10) Quality engineering technology oriented to intelligent manufacturing

Along with the extensive application of various robots, intelligent sensors, built-in chips, and edge computing devices, and the fast development of the Internet, IoT, big data, AI, cloud computing, and 3D printing, the manufacturing system is gradually evolving toward intelligence. Intelligent manufacturing, the deep combination based on the new generation of ICT and advanced manufacturing technology, can realize the full sensing of the real-time status of humans, machines, and materials, conduct intelligent analysis and processing for mass isomerous data from industrial sites, and push forward the transformation of manufacturing businesses to product demand, design, manufacturing, sale, and service based on industrial big data analysis and application intelligence. A lot of quality control methods based on traditional mathematical statistics are inapplicable to the intelligent manufacturing system which features real-time data acquisition (high-dimension and high-frequency) and highly-customized requirement (small quantity and even single piece). The quality engineering research oriented to intelligent manufacturing aims to resolve the quality control problems arising from product design, process monitoring, and manufacturing service in the environment of intelligent manufacturing. Its major technical directions include intelligence-sensing-based acquisition of big data of product utilization and consumer preference and user portraits; quality assurance modes and methods for integration design of products and arts oriented to personalized demands; parametric optimization technologies of the processes based on the combination of real-time, high-dimension, and isomerous big data; process quality monitoring technologies oriented to high frequency, high dimension, and small quantity; quality diagnosis technologies based on the big data of production process parameters, product quality, and device status; quality tracing technologies of supply chains based on the new generation of information technology (in particular blockchain); and operation status monitoring, remote fault diagnosis, and device prevention management technologies based on big data during equipment and product services. In the future, the quality engineering technology oriented to intelligent manufacturing shall be combined with modern information technology and big data technology and the statistic learning method will be the main tool for quality engineering technology of intelligent manufacturing.

2.2 Interpretations for three key engineering development fronts

2.2.1 Visualization technology oriented to engineering management

"Visualization" means "turning something invisible, inexpressible, or abstract into a visible image or an image that can be imagined by the brain." In 1986, the concept of Visualization in Scientific Computing was proposed, and visualization technology was considered an independent major computer technology. Visualization technology is an interdisciplinary subject, which covers many research fields, such as computer graphics, computer vision, human–computer interaction, and other technologies. Visualization technology makes the invisible phenomena hidden in data be visible to better analyze, understand, and exploit the rules of data. The rise of AI technologies such as deep learning has promoted the development of visualization technology, making the research and application of visualization technology in engineering management become a new academic research hotspot and be considered as another revolutionary information technology for engineering management.

In practical engineering management applications, engineering data types are multi-source and heterogeneous, and the amount of data is large and the information is fragmented, so the advantages of visualization technology cannot be fully utilized to serve engineering management. A key bottleneck restricting the application of visualization technology in engineering management is its expandability. From the point of view of patent analysis, visualization technology for engineering management mainly includes computer vision, AR and VR, BIM, geographic information systems (GIS), and graph visualization technology.

(1) Computer vision: Computer vision is an interdisciplinary scientific field, which mainly solves the use of computational models to obtain high-level information from images or multi-dimensional data in order to build AI systems. From the point of view of engineering, computer vision mainly aims at automatically completing tasks that human visual systems can accomplish. Machine vision can automatically detect and understand the information in pictures for engineering management, for example, identification of unsafe behaviors of the laborers at a construction site. However, due to low real-time performance and low accuracy, the engineering requirements for complex and large scenarios cannot be satisfied. Parallel computing, deep learning, and other AI technologies can analyze and process data in graphics more accurately, efficiently, and intelligently, making machine vision serve engineering management better.

(2) AR and VR: AR refers to the application of virtual information to the real world through computer technology, superimposing the real environments and visual objects in one frame or space. VR is a computer-generated artificial simulation process or the reproduction of some real-life situations or environments with the aim to immerse users by giving them the feeling of simulating reality. Currently, the application of AR and VR in practical engineering management is still primary, which is mainly due to many challenges in practical applications, such as the inconvenience of using VR and AR, the inability to process large amounts of data in

real time, and the vulnerability to external environmental interference. The combination of deep learning, 5G, and other AI technologies with VR and AR is expected to achieve real-time data acquisition and analysis.

(3) BIM: BIM is a kind of digital three-dimensional modeling which contains the building information in design, construction, operation, and maintenance. BIM functions through calculation, collaboration, sharing, and visualization, which can realize the integration of building information through digital technology. Although BIM can promote the transformation of the construction industry from the extensive management to refined management mode, the current BIM software are weak in application, insufficient in computing power, and unavailable in seamless management of whole-life cycles, which is a concern to be solved in future.

(4) GIS: GIS is an interdisciplinary technology of computer science, geography, surveying, and cartography and has not been uniformly defined yet. However, the information involved in the actual project management has the characteristics of massive heterogeneous data, bringing new challenges to the current GISs.

(5) Graph visualization technology: Graph visualization technology refers to the application of graph theory to store the information of relationships among entities, represented by the visualization of nodes and edges. For massive engineering data, visualizing nodes and edges in limited space will be the key challenge to be solved. In addition to visualizing the static network topology, large engineering data often evolve dynamically as time goes. Therefore, visualizing the features of dynamic networks is also an important research concern.

According to the number of published patents, the top two countries or regions by number are China and the USA (Table 2.2.1). The top three countries or regions in the citation frequency per paper are the USA, South Korea, and China (Table 2.2.1). According to the cooperation network chart of major patent output countries (Figure 2.2.1), no close cooperation network exists yet. The top two institutions in the number of patents are the State Grid Corporation of China and the International Business Machines Corporation (Table 2.2.2). According to the cooperation network chart of patent output institutions (Figure 2.2.2), we can see that no close cooperation network exists yet. Jiangxi Jiujiang Power Supply Co. has cooperation with the State Grid Corporation of China, and China Design Group Co., Ltd. has cooperation with Jiangsu Transportation Planning & Design.

2.2.2 Warning technologies and methods oriented to engineering safety

Engineering, as a basic activity for human beings to learn and transform the world, has been evolving and deepening from ancient times to the present. In this process, safety concerns have been accompanied by engineering. Safety surveillance and warning is an effective means to prevent engineering accidents, that is, it can provide safety warning information to engineering executives in time by identifying safety hazards or accident causes, analyzing status, and distinguishing safety extents so as to effectively reduce the likelihood of the occurrence of an accident or even avoid it. However, along with the growth of engineering size and the improvement of complexity in recent years, the engineering safety concern has been rather striking. For example, in construction engineering, the number of housing accidents in municipal engineering production has been up to 3000 and that of the deceased up to 3600 in the last five years and has trended to grow, which has brought enormous economic loss, as well as enormous social loss. Under the general background of a national safety

Table 2.2.1 Countries or regions with the greatest output of core patents on “visualization technologies oriented to engineering management”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	6	42.86%	34	42.50%	5.67
2	USA	5	35.71%	34	42.50%	6.80
3	South Korea	1	7.14%	6	7.50%	6.00
4	Denmark	1	7.14%	4	5.00%	4.00
5	Japan	1	7.14%	2	2.50%	2.00

Table 2.2.2 Institutions with the greatest output of core patents on “visualization technologies oriented to engineering management”

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	State Grid Corporation of China	3	21.43%	18	22.50%	6
2	International Business Machines Corporation	2	14.29%	11	13.75%	5.5
3	Boeing Co. (THE)	1	7.14%	13	16.25%	13
4	Jiangxi Jiujiang Power Supply Co.	1	7.14%	9	11.25%	9
5	China Design Group Co., Ltd.	1	7.14%	8	10%	8
6	Jiangsu Transportation Planning & Design	1	7.14%	8	10%	8
7	PurePredictive Inc.	1	7.14%	8	10%	8
8	Korea Institute of Civil Engineering and Building Technology	1	7.14%	6	7.50%	6
9	Changzhou Agriculture and Aquatic Products Quality Supervision and Inspection Testing Center	1	7.14%	4	5%	4
10	Changzhou Rongrui Information Automation Co., Ltd.	1	7.14%	4	5%	4

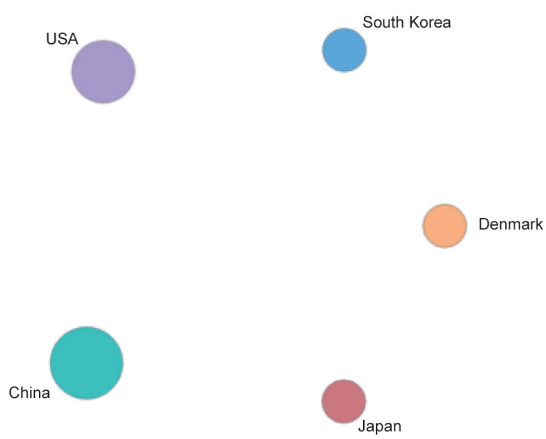

Figure 2.2.1 Collaboration network among major countries or regions in the engineering development front of “visualization technologies oriented to engineering management”

development strategy, further research and development is required in applicable engineering safety warning methods and technologies combined with characteristics of various types of engineering, as well as improving the overall level of engineering safety.

Currently, the warning methods and technologies oriented to engineering safety, supported by emerging information technologies and related safety warning methods, technologies, or devices, are formed in combination with the uniqueness of concrete engineering activities, mainly including: safety warning technology based on IoT or sensors, safety warning technology based on machine vision, and safety warning technology based on mobile terminals.

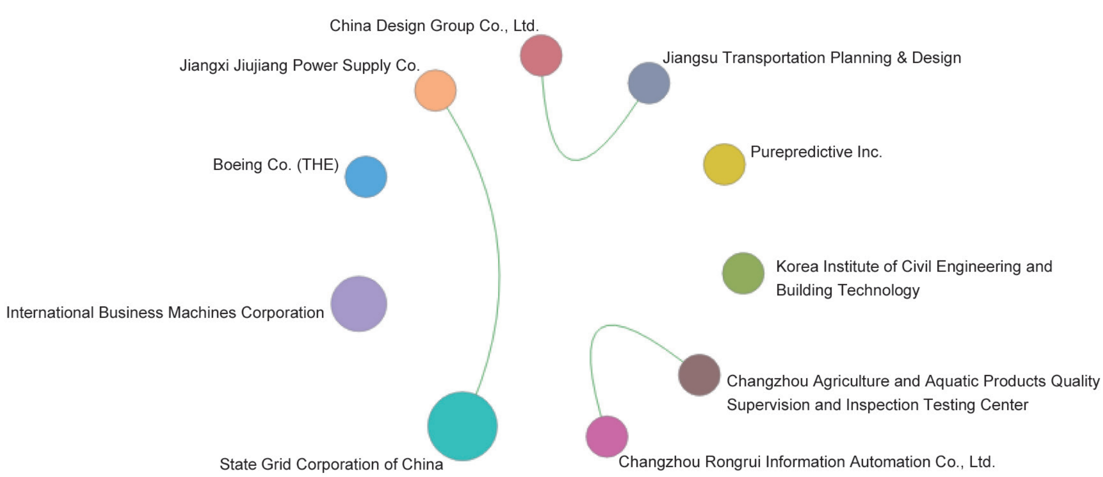

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of “visualization technologies oriented to engineering management”

The safety warning technology based on IoT or sensors is a technology that automatically acquires and transmits engineering safety data in real time through integration and application of various sensors as well as network facilities (wired or wireless) and conducts real-time analysis, distinguishing, and warning of safety risks combined with data analysis methods and warning mechanisms. The safety warning technology based on machine vision is a technology that conducts rapid automatic processing of engineering safety images or videos and extracting of safety elements by the method or technology of image and video analysis, and further distinguishes and warns of safety risks. The safety warning technology based on mobile terminals is a technology that acquires engineering safety data, identifies and reports engineering safety hazards through artificial methods, and further conducts comprehensive distinguishing as well as warning of safety risks. In view of the differences in engineering environments and the advantages and disadvantages of all technologies, these safety warning technologies are always integrated and applied in engineering practices.

(1) Safety warning technology based on IoT or sensors: This technology involves various sensors such as the sensors for temperature, humidity, pressure, gas, light, sound, stress, strain, displacement, location, and ID. Of these, the frequently-used location sensors include UWB, RFID, Beacon, and GPS; and ID sensors include RFID, UWB, Beacon, and NFC QR Code. This technology is mainly used in safety surveillance and warning in environmental engineering (e.g. air quality and geographic environment), construction engineering (e.g. deep pits, major structures, and openings), traffic engineering (e.g. dangerous item transportation vehicle management), and mine engineering (e.g. dangerous geology and dangerous gas). However, due to the complexity of engineering environments, the signal transmission of sensors can be easily influenced by site environment, making its precision fluctuate greatly.

(2) Safety warning technology based on machine vision: This technology relies on video and image acquisition of engineering sites, such as cameras, 3D scanners, radar, UAVs, aircrafts, and aerial photography equipment; and image processing technologies such as background subtraction, sliding detection window, HOG, SVM, *k*-nearest neighbor method, CNN, and long short term memory (LSTM). This technology is mainly used in safety surveillance and warning in construction engineering (e.g. labor practices and dangerous areas), environmental engineering (e.g. landslide and flood), and traffic engineering (e.g. cargo safety detection). However, it is influenced much by site light, sightline, and dynamics, and also limited by algorithms and performance of computing devices.

(3) Safety warning technology based on mobile terminals: This technology has benefited from the rapid development of mobile terminal devices (e.g. smartphones, smart tablet PCs, and smart bracelets) and the development technology of WeChat, WhatsApp and other small programs. It is mainly used for safety surveillance and warning in construction engineering (e.g. site safety hazards or risk factors), environmental engineering (e.g. natural disasters and artificial disasters), and mine engineering safety (e.g. site safety hazards or risk factors). Although it is widely applied, limited by artificial detection and reporting of relevant data, it has narrow or incomplete data coverage.

The R&D of engineering safety warning methods and technologies in China and worldwide has trended as follows: (1) Support technology diversification. Along with the constant consummation and performance improvement of sensor technologies, image processing technologies, and communication technologies, the safety warning support technologies have trended toward diversification and due to the difference of the environments applicable to various technologies, the warning technologies have trended toward integration. (2) Warning method automation. Along with the automatic acquisition of data and improvement of transmission and processing technical capabilities, safety distinguishing and warning have trended toward automation. (3) Application field popularization. Along with the improvement of safety warning technical capabilities, the engineering application field is being constantly deepened. In addition, along with the constant accumulation of safety data and continuous development of big data analysis technologies, the decision making of engineering safety management has trended toward data-supported decision making from subjective decision making.

The top three countries or regions with the highest output of core patents in this engineering development front are, respectively, China, the USA, and South Korea. Of these, the number of core patents output by China is 10, ranking the highest (Table 2.2.3). The institution outputting the largest number of core patents in this field in China is China Yangtze

Table 2.2.3 Countries or regions with the greatest output of core patents on "warning technologies and methods oriented to engineering safety"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	10	16.95%	33	55.93%	3.30
2	USA	2	3.39%	13	22.03%	6.50
3	South Korea	2	3.39%	10	16.95%	5.00
4	France	1	1.69%	1	1.69%	1.00
5	Japan	1	1.69%	2	3.39%	2.00

Table 2.2.4 Institutions with the greatest output of core patents on "warning technologies and methods oriented to engineering safety"

No.	Institution	Published patents	Percentage published patents	Citations	Percentage of citations	Citations per patent
1	China Yangtze Power Co., Ltd.	2	12.50%	16	27.12%	8
2	Jubix	1	6.25%	9	15.25%	9
3	Fluor Corp.	1	6.25%	9	15.25%	9
4	Tsinghua University	1	6.25%	6	10.17%	6
5	Wuhan Shuzhen Information Integration	1	6.25%	5	8.47%	5
6	Verizon Communications Inc.	1	6.25%	4	6.78%	4
7	Chongqing Hehang Internet Things Technol	1	6.25%	3	5.08%	3
8	Nanjing Xuean Network Technology Co., Ltd.	1	6.25%	3	5.08%	3
9	NTT Docomo Inc.	1	6.25%	2	3.39%	2
10	Hangzhou Hikvision Digital Technology Co., Ltd.	1	6.25%	2	3.39%	2

Power Co., Ltd. which has two published patents and eight citations per paper (Table 2.2.4).

According to the cooperation network charts of major patent output countries (Figure 2.2.3) and institutions (Figure 2.2.4), no close cooperation network exists yet, and Tsinghua University has cooperation with China Yangtze Power Co., Ltd.

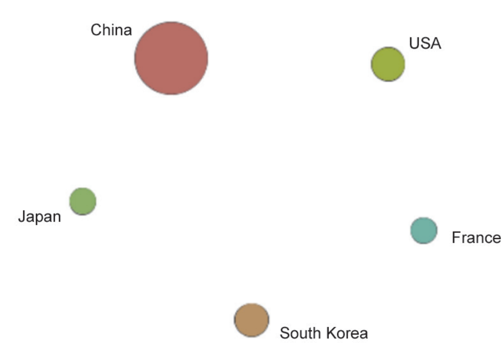

Figure 2.2.3 Collaboration network among major countries or regions in the engineering development front of "warning technologies and methods oriented to engineering safety"

2.2.3 IoT technology development oriented to engineering management

The IoT technology is an Internet technology that connects all related items to the Internet through a series of information sensing devices and in accordance with the provided relevant digital agreements for information exchange and communication so as to realize intelligent recognition, positioning, tracking, monitoring, and management. The IoT oriented to engineering management is defined as engineering IoT to distinguish it from the industrial IoT of manufacturing. The engineering IoT technology must adapt to the complex and diverse environment of the construction site and the dynamic changes of engineering elements and can handle a large number of sensors and enormous communication data. The technology architecture of IoT is relatively mature with the key pending issues—data perception, transmission, and management application.

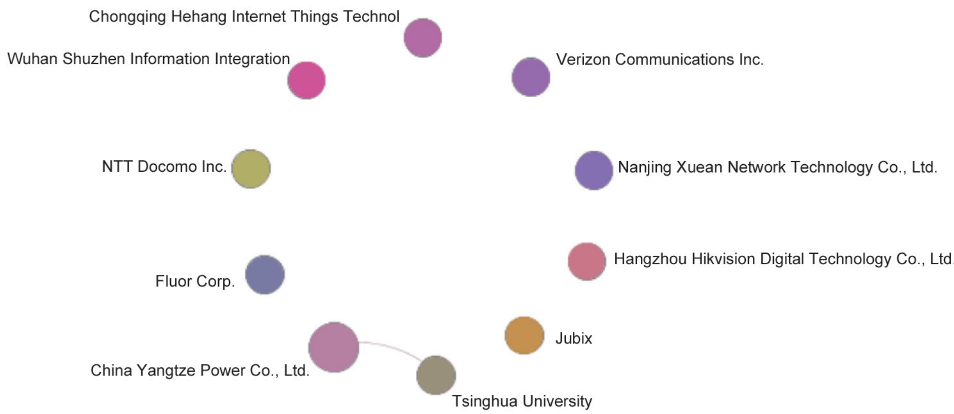

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of "warning technologies and methods oriented to engineering safety"

Success cases in the development of IoT technology oriented to engineering management have been observed in China and abroad, and the future technology is developing towards integration, standardization, and intellectualization.

The development of engineering IoT technology involves many fields such as modern sensor technology, embedded computer technology, distributed information processing technology, modern network, and wireless communication technology. The key technology system can be divided into four levels: perception technology, network technology, application technology, and public technology levels.

(1) Intelligent sensing technology: The engineering IoT mainly uses RFID tag, QR codes, various sensors, video surveillance, and other sensing, acquisition, and measurement technologies to collect and acquire real-time information of targets being monitored. Communication between an RFID tag and RFID reader is usually encapsulated as middleware for system development. There are many kinds of sensors in complex engineering environment (including stress, strain, temperature, water level, etc.). As there are a large number of RFID tags for personnel, materials, and equipment identification, the intelligent sensing technology must solve sensor power supply, electromagnetic shielding, enormous communication data, etc.

(2) Highly reliable and secure transmission technology: This technology can achieve short-distance transmission, and self-organized local area network (LAN) and wide area network (WAN) transmission of perceived information without obstacles and with high reliability and security. The engineering IoT integrates sensor networks with mobile communication technology and Internet technology. With the purpose to improve data transmission efficiency in complex engineering environments, different sampling frequencies and transmission time intervals shall be set according to the type and management requirements of sensors. For the trajectory monitoring of personnel and equipment, it is also necessary to meet the technical requirements of data acquisition, data transmission, and monitoring instructions feedback.

(3) Integrated application technology: The engineering IoT applications can be divided into monitoring (bridge health monitoring), inquiry (personnel identification), and control (equipment movement trajectory control). Integrated application technology includes general technology for supporting information collaboration, sharing, and interoperability across industries, applications, and systems. An application support platform sub-level is established by deploying ONS servers, PML servers, and EPS/IS servers to isolate the technology level; and then an application service sub-level is constructed for intelligent transportation, construction, and logistics to provide industry applications.

(4) Public technology: Public technology includes data analysis, data security, network management, and quality of service (QoS), which are of universal significance. These technologies are applied to all technical levels of the engineering IoT.

The concept of IoT originated from the proposal by Auto-ID Research Center of Massachusetts Institute of Technology (MIT) in 1999 that an RFID technology of the Internet shall be applied in daily articles so as to realize intelligent recognition and management. In 2005, the International Telecommunication Union (ITU) formally put forward the concept of "Internet of Things," describing IoT features and future opportunities as well as challenges in the report *ITU Internet reports 2005——the Internet of Things* and expressed that the future IoT can connect to any item at any time and place and the sensor technology and intelligent terminal technology would have deep space of research and development. In 2008, IBM put forward the concept of "smart earth" and proposed to mount sensors in items to form a network through universal connection. In 2009, the EU Commission issued its IoT strategy, describing the development trend of IoT in the coming two decades, and Chinese Premier Wen Jiabao visited the Research and Development Center of Micro/Nano Sensor Engineering Technology and delivered an important speech, opening the prelude of the IoT technology in China. IoT technology has been widely used in medical logistics, intelligent agriculture, vehicle integrated management, steel warehousing, and other fields.

The engineering IoT is a key technology of data perception, transmission, analysis, and decision control. The engineering IoT can realize ubiquitous perception, interconnection, and monitoring of various engineering elements (including human, machine, material, method, loop, and product) in the process of engineering construction. Foreign countries have more mature experience in the application of engineering IoT in the field of construction. For example, the Akashi Kaikyō Bridge in Japan, the Miyo Bridge in France, and the Asker Bridge in Norway have been provided with IoT systems for surveillance of bridge structure health; the Gotthard-Basistunnel in Switzerland has been provided with an automatic monitoring IoT platform composed of 2600 km cables, 200 000 sensors, and 70 000 data nodes.

The engineering IoT has been successfully applied in bridges, super high-rise structure, health surveillance, and personnel positioning as well as engineering environment monitoring in Metro Construction in China. It is especially widely used in the field of construction engineering. For example, it can measure and transmit the changes of stress, vibrating frequency, temperature, deformation, and other parameters inside the machines and equipment such as crane towers, elevators, and scaffolds to realize the dynamic monitoring of the operation of construction machinery and equipment; acquire the values of displacement, deformation, and cracks of components through the reading of their RFID tag information and seek the components in danger by RFID positioning technology promptly for timely reinforcement and restoration; make statistics using BIM technology and engineering IoT technology; and according to time, position, and work procedure, prepare detailed material procedure plan and provide RFID tags to material lot to control the entrance or exit time as well as quality status of materials.

From the perspective of the technical architecture of the IoT, three main architectures based on EPC global standard, USN, and M2M IoT have been matured. In the future, the IoT will develop toward several key areas: massive-sensing data compression technology, three-dimensional video intelligent analysis technology, IoT and BIM integration technology, IoT-based large data analysis technology, and IoT and 5G mobile communication technology. From the perspective of the development of engineering IoT technology in China, life-cycle engineering IoT integration technology, engineering IoT architecture design theory supporting edge computing and cloud computing collaboration, and the networking technology with wide coverage, hyperlink, low power consumption, and low cost, will become the research directions in future.

From Tables 2.2.5 and 2.2.6, China is still in a leading position. According to the cooperation networks of major patent output countries or regions (Figure 2.2.5) and institutions (Figure 2.2.6), no close cooperation network exists yet.

Table 2.2.5 Countries or regions with the greatest output of core patents on "IoT technology oriented to engineering management"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	17	100%	55	100%	3.24

Table 2.2.6 Institutions with the greatest output of core patents on “IoT technology oriented to engineering management”

No.	Institution	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Beijing Qingda Tianyan View Control	1	5.88%	9	16.36%	9
2	Chongqing Shengxin Technology Co., Ltd.	1	5.88%	6	10.91%	6
3	Hefei Caixiang Information Technology Co.	1	5.88%	6	10.91%	6
4	Shanghai Renywell Technology Co., Ltd.	1	5.88%	5	9.09%	5
5	Guangzhou Baosteel Southern Trade Co., Ltd.	1	5.88%	4	7.27%	4
6	Qingdao Lianggu Wireless Technology Co.	1	5.88%	4	7.27%	4
7	Guizhou Normal University	1	5.88%	4	7.27%	4
8	Chengdu Gips Energy Technology Co., Ltd.	1	5.88%	3	5.45%	3
9	Chengdu Chuangshi Technology Co., Ltd.	1	5.88%	2	3.64%	2
10	Zhejiang China Tobacco Industrial Co., Ltd.	1	5.88%	2	3.64%	2

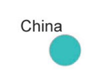

Figure 2.2.5 Collaboration network among major countries or regions in the engineering development front of “IoT technology oriented to engineering management”

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of “IoT technology oriented to engineering management”

Participants of the Field Group

Leaders

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