V. Civil, Hydraulic & Architecture Engineering

1 Engineering research fronts

1.1 Development trends in the top 10 engineering research fronts

The top 10 engineering research fronts related to the field of civil, hydraulic & architecture engineering are summarized in Table 1.1.1. These fronts cover a variety of disciplines, including structural engineering; construction materials; roads and railway engineering; architecture; heating, ventilation, air conditioning, and gas supplying; municipal engineering; surveying and mapping engineering; and hydraulic engineering. Among these research fronts, "intelligent control systems for building environment," "migration and transformation mechanisms of microplastics in wastewater treatment," and "dynamic fusion of geographical spatiotemporal big data for smart cities" are the emerging fronts, while the others are extended from conventional disciplines. Table 1.1.2 presents the annual statistical data of the core papers published between 2012 and 2017 relevant to the top 10 research fronts. The increasing rate of core papers on intelligent control systems for building environment is the highest among the top 10 research fronts.

(1) Lifecycle reliability of civil engineering structures and systems

This research front refers to the time-dependent reliability of civil-engineering structures and resulting systems considering the random distribution of loads and the degrading performances of materials, components, and structures during their service life. Under long-term environmental and mechanical loads, structural properties experience stochastic and time-dependent degradation. Based on the theory of stochastic processes, time-dependent structural reliability can be determined through use of probabilistic models of load effects and structural properties. Major issues concerning

Table 1.1.1 Top 10 engineering research fronts in civil, hydraulic & architecture engineering

No.	Engineering research fronts	Core papers	Citations	Citations per paper	Mean year	Percentage of consistently-cited papers	Patent-cited papers
1	Lifecycle reliability of civil engineering structures and systems	215	4 440	20.65	2014.57	–	–
2	Ultrahigh-performance and smart cement-based composite materials	64	2 594	40.53	2013.59	–	–
3	Highway pavement renewable materials and pavement materials rejuvenation	27	601	22.26	2013.74	–	–
4	Green vernacular architecture	317	9 213	29.06	2013.89	–	–
5	AI-based architectural design methodology	107	3 704	34.62	2013.92	–	–
6	Intelligent control systems for building environment	31	1 244	40.13	2015.32	38.7%	0.00
7	Migration and transformation mechanisms of microplastics in wastewater treatment	7	243	34.71	2016.14	28.6%	0.00
8	Fusion and processing of multilevel space-air-ground remote-sensing data	141	7 023	49.81	2014.39	–	–
9	Dynamic fusion of geographical spatiotemporal big data for smart cities	52	1 244	23.92	2015.50	–	–
10	Lifecycle safety of water-related engineering	49	913	18.63	2013.78	–	–

Table 1.1.2 Annual number of core papers published for the top 10 engineering research fronts in civil, hydraulic & architecture engineering

No.	Engineering research fronts	2012	2013	2014	2015	2016	2017
1	Lifecycle reliability of civil engineering structures and systems	30	39	31	39	45	31
2	Ultrahigh-performance and smart cement-based composite materials	14	17	17	13	3	0
3	Highway pavement renewable materials and pavement materials rejuvenation	7	3	9	6	2	0
4	Green vernacular architecture	56	76	76	70	34	5
5	AI-based architectural design methodology	17	26	27	25	10	2
6	Intelligent control systems for building environment	1	0	4	11	13	2
7	Migration and transformation mechanisms of microplastics in wastewater treatment	0	0	0	2	2	3
8	Fusion and processing of multilevel space-air-ground remote-sensing data	25	21	21	32	32	10
9	Dynamic fusion of geographical spatiotemporal big data for smart cities	1	1	6	18	15	11
10	Lifecycle safety of water-related engineering	10	9	18	6	6	0

this research front include the evolution of structural performance under environmental actions, quantification of the time-dependent reliability index, and reliability of structural systems. Evolution of structural performance has a direct impact on quantification of the reliability index, and introduction of related random variables into the deterministic models of resistance degradation has been widely accepted. The time-dependent reliability index at a component level can be calculated through use of such approaches as the first-passage method, time-independent reliability index for an equivalent series system, Monte Carlo simulation method, and probability-density-evolution method. That said, reliability analysis of systems remains a challenging task. Between 2012 and 2017, 215 core papers have been published relevant to this research front, and these papers have received 4440 citations with an average of 20.65 citations per paper published.

(2) Ultrahigh-performance and smart cement-based composite materials

Ultrahigh-performance materials refer to composites with superior mechanical properties and durability. Accordingly, smart cement-based composite materials refer to composites with smart functions, such as self-sensing, self-thermal insulation, self-cleaning, and self-damping. With the development of civil engineering structures, the complexity of upgrading structures raises an increasing demand for novel construction materials. Compared with conventional concrete, the ultrahigh-performance concrete (UHPC) demonstrates high compressive strength, excellent toughness, super-high abrasive resistance, antiknock property, and significantly increased durability. The workability and mechanical properties of UHPC have attracted increased research attention in recent years. Owing to the development of carbon-based materials and phase change materials, it is possible to produce smart cement-based composite materials capable of performing intelligent functions, such as self-sensing, self-thermal insulation, and self-cleaning. The use of carbon-based materials, such as carbon nanotubes, graphene, and nano-carbon fiber, improves the mechanical as well as electrical performance of such materials. Upgraded materials can, therefore, ensure safety and reliability of structures and functionalize resulting structures with smart monitoring properties. Between 2012 and 2017, 64 core papers have been published relevant to this research front, and these papers have received 2594 citations in total with an average of 40.53 citations per paper published.

(3) Highway pavement renewable materials and pavement materials rejuvenation

Concepts of circular economy and sustainable development have drawn increased attention in the field of highway paving, and the use of renewable materials in highway-paving applications and their rejuvenation have become hot topics of research in recent years. Renewable materials are those that follow the principle of bionics and perform dual functions of perception and excitation. Active self-sensing, automatic healing, and self-healing are basic features of such materials. Developing innovative renewable materials, revealing appropriate regeneration mechanisms, and establishing design theories for renewable composite materials are important issues concerning the realization of sustainable development of highway-pavement materials. Material rejuvenation refers to the recycling of industrial and civil wastes, such as steel slags, plastic granules, construction wastes, reclaimed pavement materials, and other materials. Relevant research topics include development of new material recycling technologies, physical and chemical properties of rejuvenated materials, and mechanisms for blending of new and old materials. Between 2012 and 2017, 27 core papers have been published relevant to this research front and have received 601 citations in total with an average of 22.26 citations per paper.

(4) Green vernacular architecture

Contemporary green vernacular architecture is based on modern building technologies and materials whilst still featuring regional environmental adaptability and cultural continuity. Over the course of its long-term development, vernacular architecture has developed a clear adaptive relationship with its environment. On one hand, such architecture needs to critically absorb the characteristics of climatic adaptation within conventional construction systems while on the other hand, it must respond to requirements of contemporary life and form a sustainable development system that is benign to circumstances and the social environment. Green vernacular architecture not only focuses on the application of technologies concerning modern environmental control, structural safety, culinary and sanitary facilities, and intelligent communication systems to the existing conventional architectural heritage but also devotes itself to discovering the wisdom and experience of vernacular architecture with respect to environmental coordination, climatic adaptation, cultural heritage, and functional organization. Research endeavors in this field pay special attention to the contribution of local architectural forms, construction of national cultural landscapes within environmental adaption, self-adjustment, and self-improvement. Between 2012 and 2017, 317 core papers have been published relevant to this research front and have received 9213 citations with an average of 29.06 citations per paper published.

(5) AI-based architectural design methodology

The AI-based architectural design methodology considers the architectural design process as its object, artificial intelligence (AI) as its engine, and various virtual reality (VR) technologies as its interface. It brings into full play a combination of the human ability of creating and dealing with uncertainty issues, accurate perception of machines, and high-speed computing ability via intelligent machine systems via real-time interaction. This new concept is superior to conventional ones in three aspects. First, conventional architectural design methodologies are based on monism that sees the architect as the sole subject, whereas the modern approach emphasizes on interaction between human beings and intelligent machines to complete a design, thereby breaking through the monistic mindset of the theoretical framework. Second, the field of AI—with breakthroughs based on the deep neural network technology as its highlight—can recognize and analyze images with accuracies that far exceed human perception and has already outplayed human beings in various game problems through application of enhanced learning algorithms. All these factors enable machines to possess a certain degree of intelligence. Lastly, the light weight and popularization of VR technology in hardware greatly broadens its applications. Compared with the conventional two-dimensional graphical user interface of the screen, its immersive real-time three-dimensional environment greatly enhances the efficiency of information interaction. Simultaneously, with the development of various real-time scanning and projection technologies, the tangible user interface has become popular, got rid of the perception agent mode of both the screen and virtual environment, directly enabled architects to implement various operations with computable information in real objects, and realized direct interactions between humans and machines. Between 2012 and 2017, 107 core papers have been published relevant to this research front and have received 3704 citations with an average of 34.62 citations per paper published.

(6) Intelligent control systems for building environment

By monitoring the indoor thermal, acoustic, lighting, and air-quality parameters, building intelligent systems (BISs) are primarily used to automatically control and manage mechanical and electrical systems, such as cooling and heating, ventilation, lighting, shading, and façade within residential and corporate buildings, thereby providing, adjusting, and maintaining the desired indoor environment. Presently, major research trends relevant to this front include ① monitoring and transmission of environmental parameters; ② intelligent analysis, identification, and diagnosis of control systems; and ③ intelligent control and optimization of mechanical and electrical systems. BISs are essentially derived and upgraded from building automation systems, which initially play a supplementary role in monitoring and managing the cooling and heating, elevator, water-supply, security, fire-extinguishing, and power-supply and distribution systems within buildings. Following the rapid development of computers and sensors as well as increasing popularization of intelligent terminals (e.g., smartphones, smart wearable devices, and display screens), BIS offers more possibilities and opportunities for providing an appropriate, customizable, and comfortable indoor environment. For example, the subjective perception of an indoor environment by occupants can be first collected via intelligent terminals and subsequently used as input to BIS to integrate personalized preferences with regard to indoor temperature, humidity, airflow, lighting, etc. Between 2012 and 2017, 31 core papers have been published relevant to this research front and have received 1244 citations with an average of 40.13 citations per paper published.

(7) Migration and transformation mechanisms of microplastics in wastewater treatment

Microplastics correspond to plastic particles and textile fibers with tiny particle sizes. These are generally considered plastic particles measuring less than 5 mm in dimension. The primary source of these particles is plastics, which are widely used in daily life, and after being exposed to the natural environment, gradually reduce in size owing to the effect of the wind and sun. Additionally, there exists a large quantity of frosted particles in cosmetics or cleansing products in addition to the large number of fibers contained in the wastewater discharged from household washing machines. These microplastics possess small volumes, large specific surface areas, and a strong ability to adsorb pollutants. They are, therefore, likely to form organically contaminated spheres with persistent organic pollutants, such as hydrophobic polychlorinated biphenyls and bisphenol A. Microplastics cannot be effectively removed in conventional urban wastewater treatment plants because they tend to float on the water surface during treatment. Wandering microplastics can easily be swallowed by such organisms belonging to the lower end of the food chain as mussels and zooplanktons. These plastics, however, cannot be digested, thereby causing disease and mortality in such organisms. If microplastics containing organic contaminants are eaten, the contaminants tend to be released—under the action of enzymes—within the organisms' bodies, thereby exacerbating their damaging impacts. If the said microplastics and organic pollutants enter bodies of organisms belonging to the upper part of the food chain, the "enrichment" effect of the food chain can cause widespread mortality of a larger organism community. Researches concerning mechanisms of migration and transformation of microplastics relevant to sewage treatment focus on determination of ① the composition of microplastics present within sewage via use of various approaches—observations, experiments, theoretical models, and numerical simulations; and ② migration pathways, conversion products, transformation, and distribution of microplastics and other pollutants within sewage-treatment systems using various techniques. The said researches target elimination of microplastics, persistent organic pollutants, heavy metals, endocrine disruptors, emerging pollutants, etc. Between 2012 and 2017, 7 core papers have been published relevant to this research front and have received 243 citations with an average of 34.71 citations per paper published.

(8) Fusion and processing of multilevel space-air-ground remote-sensing data

Fusion and processing of multilevel space-air-ground remote-sensing data refers to a deep fusion of remote-sensing big data, including multisource and multilevel aerospace and ground remote-sensing data, to analyze image features and discover inherent regularities between multisource data based on physical characteristics of ground objects. Using the hybrid multi-level fusion technology, desired information can be extracted by combining the pixel, feature, and decision-making layers and integrating professionally constructed models. Major issues encountered in this research front include ① high-precision preprocessing of multisource remote-sensing data, including radiometric calibration, geometric correction, atmospheric correction, and co-accurate correction of multisource heterogeneous data; ② spatial fusion of multisource remote-sensing data, major methods of which include combined block adjustment and image registration; the former method converts a spatial fusion problem into a joint block-adjustment problem involving multisource remote-sensing data from the perspective of photogrammetry, whereas the latter converts a spatial fusion problem into an image registration problem from the perspective of image processing and computer vision; and ③ the informational fusion of spatially fused multisource remote-sensing data to extract new and meaningful information. The process of informational fusion can, in general, be divided into three levels—pixel level, feature level, and decision level. Development trends in this research front include ① support of combined block adjustment of multisource data to enable automatic search and joint adjustment of corresponding points among various sources, phases, and resolutions; ② in-depth informational fusion based on multilayer blending; and ③ information extraction based on deep learning and neural networks. Between 2012 and 2017, 141 core papers have been published relevant to this research front and have received 7023 citations with an average of 49.81 citations per paper.

(9) Dynamic fusion of geographical spatiotemporal big data for smart cities

With the construction of smart cities, numerous widespread sensors generate PB, EB, or even ZB levels of urban geographical spatiotemporal datasets. Dynamic fusion of geographical spatiotemporal big data of a smart city aims at automatically discovering and extracting implicit and non-obvious patterns, rules, and knowledge from real-time, multiplatform, multitemporal, multisensor, multitype, high-resolution, hyper-spectral, and massive multisource geographical spatiotemporal big data followed by a quick transformation of geographical spatiotemporal big data to valuable information via efficient, intelligent, and dynamic processing. The proposed fusion process, is believed, would greatly improve the spatial cognition ability of smart cities. Major issues concerning this research front include basic theories and methods for representation, measurement, and understanding of geographical spatiotemporal big data of smart cities along with revelation of relationships between spatiotemporal big data and real objects, behaviors, and events. Worldwide research endeavors being undertaken relevant to this topic have resulted in multidisciplinary studies being performed for collecting geospatial and temporal data of physical objects and human activities within smart cities via various methods and integrated approaches, information extraction, network management, knowledge mining, spatial knowledge perception, and provision of intelligent location services. Between 2012 and 2017, 52 core papers have been published relevant to this research front and have received 1244 citations with an average of 23.92 citations per paper.

(10) Lifecycle safety of water-related engineering

Water-related engineering is a key component of infrastructure systems and plays an irreplaceable role in ensuring water safety as well as social and economic development. In recent years, water-related construction activities have expanded from inland regions into the deep sea, and higher safety requirements are being specified to be met during deep-sea construction and operation with the working environment becoming more complex and diverse within deep water. Lifecycle safety of water-related engineering is a concept raised in view of security threats and changes in surrounding environments encountered during all stages of a structure's service life. Major research endeavors in this regard are concerned with ① development of anti-vibration, anti-corrosion, and anti-seismic technologies for water-related engineering structures; ② nondestructive detection, damage identification, and rapid repair technologies for underwater structures; ③ diagnostic evaluation of safety of water-related structures; and ④ optimization of lifecycle safety design of water projects. Compared to hydraulic structures, port structures, and offshore engineering, deep-sea engineering operations are confronted with more complex environmental factors, including both normal (e.g., wind, wave, current, and salinity) and extreme factors (e.g., typhoons and earthquakes). In order to ensure the safety of deep-sea engineering operations, the combined action of various environmental factors must be taken into consideration. Response and failure mechanisms of deep-sea engineering structures under complex environments could be analyzed via experiments as well as numerical simulations, on the basis of which lifecycle performance monitoring and damage repair systems could be established. This would ultimately lead to satisfaction of lifecycle safety assessment and design criteria concerning deep-sea operations. Consequently, researches concerning catastrophic mechanisms, intelligent monitoring, and automatic repair technologies under complex conditions, lifecycle safety evaluations, and optimization design of the structural system will remain the major focus in this research front. Between 2012 and 2017, 49 core papers have been published relevant to this research front and have received 913 citations with an average of 18.63 citations per paper.

1.2 Interpretations for three key engineering research fronts

1.2.1 Lifecycle reliability of civil engineering structures and systems

Owing to rapid industrialization, large-scale infrastructure constructions have been undertaken in many countries since the middle of the twentieth century. Meanwhile, the durability and service life of civil-engineering structures have become topics of concern for the entire society. Certain structures tend to degrade prematurely owing to insufficient knowledge concerning the evolution of structural performance. Structural engineers have, over the years, realized the significance of the service life of structures and proposed a series of design methods, including the allowable stress, ultimate strength, and limit state design methods, all relating to the service life of structures. Presently, the limit-state design method, based on the probability theory, has been examined and adopted in several engineering practices. This approach, however, considers a structure to demonstrate a state of construction completion with loads varying over the target service life whilst ignoring performance degradation of the structure itself over a period of time.

In an attempt to determine more appropriate approaches, researchers proposed stochastic-process-based reliability-analysis methods by introducing time-dependent probabilistic models for degradation resistance of structures. However, there continues to exist the lack of an in-depth understanding of performance evolution of various structures subjected to environmental and mechanical loads. This is because the available models often provide results largely deviating from observations in actual scenarios. Based on the different resistance degradation models, time-dependent reliability-analysis techniques have been proposed, such as the first-passage method, time-dependent reliability of an equivalent series system, and Monte Carlo simulation. The first two methods are either inapplicable to time-dependent reliability-index calculation or limited to specific stochastic physical systems. The Monte Carlo simulation method is relatively time-consuming, although it has been widely employed with high accuracy without being limited to stochastic physical systems and limit state equations.

Currently, major topics of research concerning the lifecycle reliability of civil engineering structures and systems include

(1) Improved methods for time-dependent reliability analysis. Examples under this topic include the Poisson-process-based analytical and Monte-Carlo-simulation-based stochastic methods, both of which have been proposed to reduce the high computational cost associated with the direct simulation method and resolve the difficulty in sampling events with a small probability. Additionally, the probability density evolution method—based on the principle of probability conservation—has been extended to applications involving time-dependent reliability analysis.

(2) Improved time-dependent state functions of structures and systems. Related studies include a) assessment of the reliability of reinforced concrete (RC) structures considering time-dependent corrosion rate of steel bars and spatially varying distribution of corrosion current density and corrosion morphology; and b) establishment of equivalent extreme events and performing associated reliability analysis considering complex structural failure modes.

(3) Design and maintenance of structures and systems based on time-dependent reliability.

As listed in Table 1.1.1, 215 core papers have been published between 2012 and 2017 concerning "lifecycle reliability of civil engineering structures and systems," and each paper has been cited an average of 20.65 times. The top 3 nations in terms of core-paper output in this regard are China, USA, and Italy (Table 1.2.1). China is one of the most active players in this topic, publishing 33.49% of core papers and ranking first in terms of quantity. In terms of core-paper citation, papers published by the Chinese have each been cited 21.15 times on average, slightly exceeding the corresponding global average number. This indicates that researchers from China are gradually gaining more attention. As illustrated by the international collaborative network depicted in Figure 1.2.1, close cooperation has been observed among the most productive top 10 countries/regions except Czech Republic.

As listed in Table 1.2.2, the top 3 institutions publishing the most number of core papers are Hunan University (China), Dalian University of Technology (China), and Tongji University (China). As illustrated in Figure 1.2.2, collaborative studies are rare among the top 10 most productive institutions in this regard.

As listed in Table 1.2.3, the top 3 most productive countries/regions (i.e., China, USA, and Italy) are also the most active ones in terms of the most number of citing papers between 2012 and 2017. Note that approximately 40% citations of core papers are contributed by China, thereby indicating that Chinese researchers pay increased attention to researches performed concerning this front. As presented in Table 1.2.4, the top 3 institutions citing the most number of core papers are Hunan University (China), Tongji University (China), and Lehigh University (USA).

Summarizing the above statistical data, it can be stated that China is, at present, the leading player in terms of research trends concerning "lifecycle reliability of civil engineering structures and systems." As such, continuous support at the national and provincial levels is important for sustaining dedicated studies to maintain China's leading position concerning this topic.

Table 1.2.1 Countries or regions with the greatest output of core papers on the "lifecycle reliability of civil engineering structures and systems"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	72	33.49%	1 523	34.30%	21.15
2	USA	40	18.60%	911	20.52%	22.78
3	Italy	24	11.16%	528	11.89%	22.00
4	Australia	19	8.84%	396	8.92%	20.84
5	UK	18	8.37%	421	9.48%	23.39
6	Iran	18	8.37%	303	6.82%	16.83
7	Czech Republic	12	5.58%	124	2.79%	10.33
8	Singapore	11	5.12%	254	5.72%	23.09
9	France	9	4.19%	279	6.28%	31.00
10	Germany	9	4.19%	151	3.40%	16.78

Table 1.2.2 Institutions with the greatest output of core papers on the "lifecycle reliability of civil engineering structures and systems"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Hunan Univ	13	6.05%	342	7.70%	26.31
2	Dalian Univ Technol	12	5.58%	207	4.66%	17.25
3	Tongji Univ	10	4.65%	240	5.41%	24.00
4	Lehigh Univ	9	4.19%	256	5.77%	28.44
5	Univ Sydney	8	3.72%	199	4.48%	24.88
6	Univ Zabol	8	3.72%	118	2.66%	14.75
7	Natl Univ Singapore	6	2.79%	183	4.12%	30.50
8	Tech Univ Munich	6	2.79%	103	2.32%	17.17
9	VSB Tech Univ Ostrava	6	2.79%	48	1.08%	8.00
10	Politecn Milan	5	2.33%	149	3.36%	29.80

Figure 1.2.1 Collaborative network among major countries or regions in the engineering research front of "lifecycle reliability of civil engineering structures and systems"

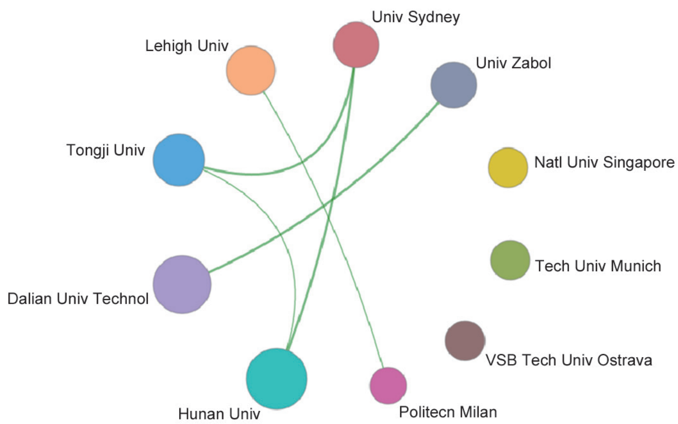

Figure 1.2.2 Collaborative network among institutions in the engineering research front of "lifecycle reliability of civil engineering structures and systems"

Table 1.2.3 Countries or regions with the greatest output of citing papers on the "lifecycle reliability of civil engineering structures and systems"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	1 191	38.72%	2016.48
2	USA	645	20.97%	2016.00
3	Italy	241	7.83%	2015.86
4	UK	216	7.02%	2016.23
5	Australia	182	5.92%	2016.42
6	Iran	167	5.43%	2016.54
7	Germany	132	4.29%	2016.47
8	India	112	3.64%	2016.23
9	Singapore	96	3.12%	2016.07
10	France	94	3.06%	2016.30

Table 1.2.4 Institutions with the greatest output of citing papers on the "lifecycle reliability of civil engineering structures and systems"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Hunan Univ	150	18.82%	2016.40
2	Tongji Univ	131	16.44%	2016.37
3	Lehigh Univ	90	11.29%	2015.42
4	Dalian Univ Technol	76	9.54%	2016.50
5	Politecn Milan	66	8.28%	2016.02
6	Beihang Univ	65	8.16%	2016.74
7	Huazhong Univ Sci & Technol	57	7.15%	2016.60
8	Univ Sydney	55	6.90%	2016.33
9	Wuhan Univ	54	6.78%	2015.70
10	Northwestern Polytech Univ	53	6.65%	2016.43

1.2.2 Ultrahigh-performance and smart cement-based composite materials

With the advancement in social economy, structural design theory, and construction technology, engineering structures have grown higher, longer, and deeper in recent years. To enable construction of complicated engineering structures, there exists an increasing demand for development of non-conventional construction materials, such as ultrahigh-performance composite (UHPC) materials with superior mechanical properties, toughness, abrasive resistance, antiknock property, and durability. Meanwhile, there also exists a need for structures capable of performing delicate and intelligent functions to meet the objective of realizing reliable and safe living and traffic conditions. The smart cement-based composite material is one such material capable of demonstrating the said intelligent functions. It has great potential for use in the monitoring stress, strain, and temperature within important structural components. It could serve as a useful nondestructive tool to estimate structural damage as well as to achieve timely recovery of such damages. Moreover, this smart material can also be specially functionalized to relieve impacts from typhoons and earthquakes as well as manipulate temperature, humidity, and energy consumption within indoor environments. As a highly technical material, the use of smart cement-based composite has opened new avenues with regard to future development of conventional construction materials as well as new research opportunities. Further studies concerning basic theories and applications are required to realize breakthrough development concerning novel structural materials, which in turn, would help researchers create a huge market with great social and economic benefits.

Major research topics concerning ultrahigh-performance and smart cement-based composite materials include the following.

(1) Preparation technology and performance control of UHPC. This topic mainly covers two aspects, the first of which concerns determination of UHPC characteristics whilst focusing on the rheology and pumping ability of UHPC and aims at its successful applications in complex high, long, and deep structures. The second aspect relates to investigations concerning macroscopic mechanical properties and durability of UHPC as well as the relationship between UHPC microstructures and said macroscopic properties.

(2) Engineering applications of UHPC. In addition to ensuring its own performance requirements, UHPC applications in engineering structures require a comprehensive study concerning mechanical properties of various structural members made of this material. Such studies are potentially useful in the establishment of mature reliability design calculation methodologies. There, however, exist many challenges with regard to extensive applications of this material to engineering structures, such as buildings, bridges, roadbeds, and dams.

(3) Intelligent monitoring characteristics of smart cement-based composite materials. An important area of research concerning smart cement-based composite materials is to functionalize conventional cement-based materials with self-monitoring and self-diagnosis abilities. More attention is paid to the self-monitoring ability of structures with regard to stress, deformation, and temperature monitoring. Against a background of rapid development of carbon-based materials, such as carbon fiber, carbon nanotubes, and graphene, improving the sensitivity, stability, application range, and durability of smart cement-based materials holds great potential.

(4) Intelligent adjustment characteristics of smart cement-based composite materials. Another intelligent direction of smart cement-based composites is self-regulation and self-healing abilities. These materials adapt to changes in the service environment as well as their own structures, such as self-adjustment to temperature and humidity, self-control of shape and damping, and self-healing of microcracks. Researches performed in this direction have a broad future market.

As listed in Table 1.1.1, 64 core papers have been published between 2012 and 2017 concerning "ultrahigh-performance and smart cement-based composite materials," and each paper has been cited 40.53 times on average. The top 3 countries in terms of core paper output are the USA, South Korea, and China (Table 1.2.5). China is one of the most active players in this context, producing 17.19% of the core papers. In terms of core-paper citations, papers published by China have each been cited 42.45 times on average, slightly exceeding the global average number. This indicates that researchers from China are gradually gaining increased attention. As illustrated by the international collaborative network depicted in

Figure 1.2.3, a relatively close cooperation is noted among China, USA, and UK.

As listed in Table 1.2.6, the top 3 institutions publishing the most number of core papers are Korea University (South Korea), the University of Michigan (USA), and the University of Connecticut (USA). As illustrated in Figure 1.2.4, domestic cross-organization collaborations are frequent in USA and South Korea, whereas crossover collaborations between different countries are rare.

As listed in Table 1.2.7, the top 5 countries/regions citing the most core papers are China, USA, South Korea, Australia, and Italy. Note that 31.45% citations of core papers have been contributed by China, indicating that Chinese researchers pay close attention to researches performed in this regard. As presented in Table 1.2.8, the top 3 institutions citing the most core papers are Korea University (South Korea), Harbin Institute of Technology (China), and Hanyang University (South Korea).

Summarizing the above statistical data, China is currently among leading players with regard to research endeavors concerning "ultrahigh-performance and smart cement-based composite materials." Enhanced support at national and provincial levels is, therefore, significant in promoting China's contribution towards creating greater awareness concerning the topic.

Table 1.2.5 Countries or regions with the greatest output of core papers on the "ultrahigh-performance and smart cement-based composite materials"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	USA	18	28.13%	721	27.79%	40.06
2	South Korea	13	20.31%	552	21.28%	42.46
3	China	11	17.19%	467	18.00%	42.45
4	UK	6	9.83%	225	8.67%	37.50
5	Netherlands	4	6.25%	215	8.29%	53.75
6	Italy	4	6.25%	174	6.71%	43.50
7	France	4	6.25%	119	4.59%	29.75
8	Canada	4	6.25%	106	4.09%	26.50
9	Malaysia	3	4.69%	89	3.43%	29.67
10	India	1	1.56%	102	3.93%	102.00

Table 1.2.6 Institutions with the greatest output of core papers on the "ultrahigh-performance and smart cement-based composite materials"

No.	Institution	Core papers	Percentage of core papers	Citations	Proportion of citations	Citations per paper
1	Korea Univ	8	12.50%	299	11.53%	37.38
2	Univ Michigan	7	10.94%	297	11.45%	42.43
3	Univ Connecticut	6	9.38%	271	10.45%	45.17
4	Korea Inst Construct Technol	4	6.25%	233	8.98%	58.25
5	Eindhoven Univ Technol	4	6.25%	215	8.29%	53.75
6	Univ Liverpool	4	6.25%	150	5.78%	37.50
7	Daegu Univ	4	6.25%	126	4.86%	31.50
8	Sejong Univ	3	4.69%	185	7.13%	61.67
9	Univ Perugia	3	4.69%	140	5.40%	46.67
10	Univ Suwon	3	4.69%	108	4.16%	36.00

Figure 1.2.3 Collaborative network among major countries or regions in the engineering research front of "ultrahigh-performance and smart cement-based composite materials"

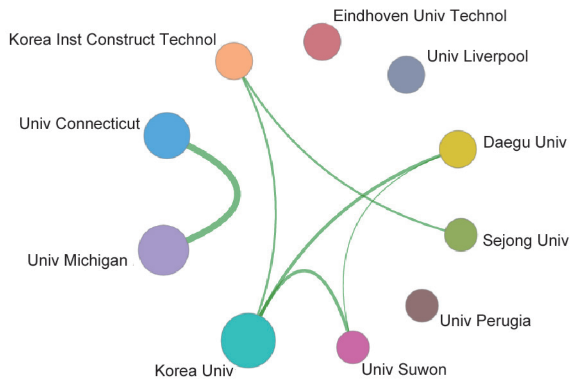

Figure 1.2.4 Collaborative network among major institutions in the engineering research front of "ultrahigh-performance and smart cement-based composite materials"

Table 1.2.7 Countries or regions with the greatest output of citing papers on the "ultrahigh-performance and smart cement-based composite materials"

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	452	31.45%	2016.52
2	USA	310	21.57%	2016.34
3	South Korea	142	9.88%	2016.15
4	Australia	107	7.45%	2016.64
5	Italy	96	6.68%	2016.51
6	Canada	73	5.08%	2016.49
7	India	72	5.01%	2016.28
8	UK	66	4.59%	2016.23
9	Iran	60	4.18%	2016.45
10	Malaysia	59	4.11%	2016.41

Table 1.2.8 Institutions with the greatest output of citing papers on the "ultrahigh-performance and smart cement-based composite materials"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Korea Univ	51	13.67%	2015.59
2	Harbin Inst Technol	41	10.99%	2016.61
3	Hanyang Univ	40	10.72%	2016.85
4	Southeast Univ	39	10.46%	2016.33
5	Dalian Univ Technol	37	9.92%	2016.57
6	Hunan Univ	35	9.38%	2016.51
7	Univ British Columbia	33	8.85%	2016.27
8	Northwestern Univ	33	8.85%	2015.88
9	Iowa State Univ	32	8.58%	2016.31
10	Missouri Univ Sci & Technol	32	8.58%	2016.91

1.2.3 Highway pavement renewable materials and pavement materials rejuvenation

Concepts of circular economy and sustainable development have drawn increased attention in the field of highway paving. Renewable materials in highway-paving applications and pavement materials rejuvenation have become hot topics of research in recent years. Renewable materials are those that follow the principle of bionics and perform dual functions of perception and excitation. Active self-sensing, automatic healing, and self-healing are basic features of such materials. Developing innovative renewable materials, revealing appropriate regeneration mechanisms, and establishing design theories for renewable composite materials are important issues concerning the realization of sustainable development of highway-pavement materials. Material rejuvenation refers to the recycling of industrial and civil wastes, such as steel slags, plastic granules, construction wastes, reclaimed pavement materials, and other materials. Relevant research topics include development of new material recycling technologies, physical and chemical properties of rejuvenated materials, and mechanisms for blending of new and old materials.

Researches concerning use of recycled materials for pavements mainly focus on the application of self-healing materials. Currently available self-healing materials can repair millimeter-scale cracks, but self-repair of wide and deep cracks requires theoretical innovations and development of related technologies. Some smart materials, such as self-aware materials and shape memory polymers, have been successfully employed in aerospace and other niche applications. Although these materials have found applications in the highway-pavement industry within Europe and USA, the overall technology is still in its infancy. Researches concerning material regeneration primarily focus on sustainable utilization of solid wastes in highway pavement engineering, but the blending mechanism of the regeneration process is unclear, thereby resulting in degrading road performance. It is, therefore, necessary to further investigate scientific issues concerning renewable materials and materials rejuvenation.

Sustainable development of global transportation infrastructure promotes research endeavors concerning highway pavement whilst focusing on both renewable materials and materials rejuvenation. Owing to the self-repairing and shape-memory functions of new recycled materials, realization of effective improvement in pavement performance, prolonged pavement life, reduction in pavement maintenance costs can now be made possible. Material regeneration can effectively alleviate problems concerning global resource shortage and environmental pollution. Researches concerning highway pavement through use of renewable materials and their regeneration are, therefore, conducive to the improvement of technology and the economy as well as environmental protection, which is in accordance with the objective of sustainable development.

Major areas of the research concerning “highway pavement renewable materials and pavement materials rejuvenation” include the following.

(1) Revelation of physicochemical properties, intelligent perception, and self-repair mechanism of renewable materials; development of new renewable highway pavement materials; establishment of synergistic models of composite renewable materials; analysis of the synergistic mechanism between regenerated and original materials; development of intelligent and adaptive renewable materials; and performance optimization of renewable materials under multi-physics coupling conditions.

(2) Revelation of long-term cooperative working mechanism of various components of material regeneration, such as the synergy between new and old asphalt mixtures, synergy between external components and original materials, and synergistic effect of various components of new cement-based materials; establishment of industrial and civil waste materials gene database; exploration of advantages and defects of waste materials; and application of material calculation design theory to facilitate realization of green, refined, and efficient material regeneration processes.

As listed in Table 1.1.1, 27 core papers were published between 2012 and 2017 concerning "highway pavement renewable materials and pavement materials rejuvenation", and each paper was cited 22.26 times on average. The top 5 countries in terms of core-paper publishing are Spain, Australia, USA, Italy, and Portugal (Table 1.2.9). The top 5 countries/regions receiving the highest citations are Sweden, USA, Canada, Spain, and Switzerland. International collaboration is not very common among the most productive countries/regions with regard to this research front, as illustrated in Figure 1.2.5.

As listed in Table 1.2.10, the University of Córdoba (Spain) has published the most number of core papers. As illustrated in Figure 1.2.6, collaborative studies are rare among the top 10 most productive institutions.

As indicated in Table 1.2.11, the top 5 countries/regions citing the most number of core papers include China, USA, Spain, Australia, and UK. It can, therefore, be inferred that Chinese researchers pay keen attention to researches performed in this field. As presented in Table 1.2.12, the top 3 institutions citing the most number of core papers are the Swinburne University of Technology (Australia), University of Córdoba (Spain), and University of Nottingham (UK).

Summarizing the above statistical data, it can be said that China is catching up and paying keen attention to researches concerning "highway pavement renewable materials and pavement material rejuvenation," and that enhanced support at the national and provincial levels is important for promoting China's contribution to this topic.

2 Engineering development fronts

2.1 Development trends in the top 10 engineering development fronts

Top 10 engineering development fronts in the field of civil,

Table 1.2.9 Countries or regions with the greatest output of core papers on the "highway pavement renewable materials and pavement materials rejuvenation"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Spain	9	33.33%	222	36.94%	24.67
2	Australia	5	18.52%	82	13.64%	16.40
3	USA	3	11.11%	88	14.64%	29.33
4	Italy	3	11.11%	64	10.65%	21.33
5	Portugal	3	11.11%	51	8.49%	17.00
6	Canada	2	7.41%	52	8.65%	26.00
7	Switzerland	2	7.41%	47	7.82%	23.50
8	UK	2	7.41%	45	7.49%	22.50
9	France	2	7.41%	34	5.66%	17.00
10	Sweden	1	3.70%	31	5.16%	31.00

Table 1.2.10 Institutions with the greatest output of core papers on the "highway pavement renewable materials and pavement materials rejuvenation"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Univ Córdoba	6	22.22%	156	25.96%	26.00
2	Univ Granada	3	11.11%	57	9.48%	19.00
3	Univ Palermo	2	7.41%	46	7.65%	23.00
4	Univ Beira Interior	2	7.41%	35	5.82%	17.50
5	Swinburne Univ Technol	2	7.41%	34	5.66%	17.00
6	Paradox Access Solut Inc	1	3.70%	35	5.82%	35.00
7	Univ Kansas	1	3.70%	35	5.82%	35.00
8	Empa	1	3.70%	33	5.49%	33.00
9	KTH Royal Inst Technol	1	3.70%	31	5.16%	31.00
10	Univ Nottingham	1	3.70%	30	4.99%	30.00

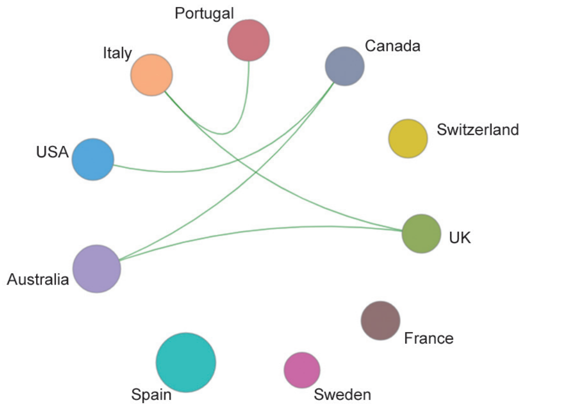

Figure 1.2.5 Collaborative network among major countries or regions in the engineering research front of “highway pavement renewable materials and pavement materials rejuvenation”

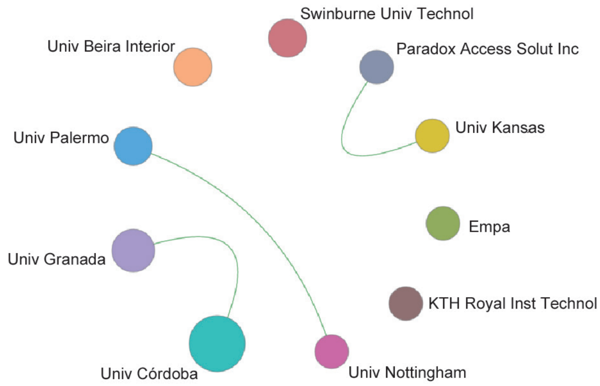

Figure 1.2.6 Collaborative network among major institutions in the engineering research front of “highway pavement renewable materials and pavement materials rejuvenation”

Table 1.2.11 Countries or regions with the greatest output of citing papers on the “highway pavement renewable materials and pavement materials rejuvenation”

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	151	18.48%	2016.83
2	USA	146	17.87%	2016.44
3	Spain	123	15.06%	2016.22
4	Australia	88	10.77%	2016.47
5	UK	74	9.06%	2016.24
6	Italy	64	7.83%	2016.52
7	India	49	6.00%	2016.80
8	Portugal	47	5.75%	2016.15
9	France	39	4.77%	2016.08
10	Thailand	36	4.41%	2016.36

Table 1.2.12 Institutions with the greatest output of citing papers on the “highway pavement renewable materials and pavement materials rejuvenation”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Swinburne Univ Technol	37	16.30%	2015.86
2	Univ Córdoba	34	14.98%	2015.18
3	Univ Nottingham	30	13.22%	2015.93
4	Suranaree Univ Technol	29	12.78%	2016.00
5	Tongji Univ	20	8.81%	2016.65
6	Southeast Univ	19	8.37%	2016.89
7	KN Toosi Univ Technol	16	7.05%	2015.56
8	Univ Politecn Valencia	16	7.05%	2016.81
9	Univ Melbourne	13	5.73%	2016.77
10	Chang’an Univ	13	5.73%	2016.62

hydraulic & architecture engineering are summarized in Table 2.1.1. These fronts cover a variety of disciplines, including structural engineering, urban and rural planning and landscape, roads and railway engineering, geotechnical and underground engineering, bridge engineering, construction materials, municipal engineering, hydraulic engineering, and surveying and mapping engineering. Among these development fronts, "intelligent construction and 3D printing technology," "green planning and building technology" and "collaborative development and utilization of urban underground space" are emerging fronts, whereas other fronts have been extended from conventional subjects. Table 2.1.2 presents annual statistical data of core patents published between 2012 and 2017 concerning the top 10 development fronts.

(1) Intelligent construction and 3D printing technology

Intelligent construction refers to use of a cyber-physical system (CPS) with advanced construction technologies deeply integrated with information technology. Developed from industrial construction and digital construction systems, intelligent construction comprises a combination

Table 2.1.1 Top 10 engineering development fronts in civil, hydraulic & architecture engineering

No.	Engineering development fronts	Published patents	Citations	Citations per patent	Mean year
1	Intelligent construction and 3D printing technology	65	951	14.63	2014.45
2	Green planning and building technology	49	245	5.00	2015.41
3	Key technological systems in intelligent transportation	85	1 022	12.02	2013.44
4	Construction technology and intelligent equipment for ultra-long and ultra-deep tunnels	14	34	2.43	2014.50
5	Collaborative development and utilization of urban underground space	135	49	0.36	2016.61
6	Novel deepwater foundation and wind resistance of cable-supported bridges	179	240	1.34	2015.09
7	Eco-friendly building materials	254	380	1.50	2015.28
8	Advanced treatment of urban water	153	1 757	11.48	2013.67
9	Regulation technology for urban storm-water	67	542	8.09	2014.28
10	High-precision positioning navigation and spatiotemporal big data	570	20 781	36.46	2013.42

Table 2.1.2 Annual number of core patents published for the top 10 engineering development fonts in civil, hydraulic & architecture engineering

No.	Engineering development fronts	2012	2013	2014	2016	2016	2017
1	Intelligent construction and 3D printing technology	9	7	15	17	14	3
2	Green planning and building technology	4	3	3	11	15	13
3	Key technological systems in intelligent transportation	22	31	16	8	5	3
4	Construction technology and intelligent equipment for ultra-long and ultra-deep tunnels	4	1	2	1	3	3
5	Collaborative development and utilization of urban underground space	0	3	0	3	34	95
6	Novel deepwater foundation and wind resistance of cable-supported bridge	21	10	32	36	28	52
7	Eco-friendly building materials	22	20	39	43	44	86
8	Advanced treatment of urban water	39	29	43	30	9	3
9	Regulation technology for urban storm-water	9	12	10	25	9	2
10	High-precision positioning navigation and spatiotemporal big data	205	127	112	57	57	12

of physical and cyber systems. The physical system includes members, components, and systems of buildings and infrastructure, whereas a twin model is established within the cyber system. During the entire lifecycle of the physical system (including project approval, design, manufacture, transportation, assembling, maintenance, and service), intelligent construction performs information perception and analysis, data mining and modeling, state assessment and prediction, and intelligent optimization as well as decision making of the physical system using the twin model embedded within the cyber system. Via that process, knowledge reasoning, intelligent sensing and precision control, and execution of the construction target and corresponding construction process, construction facilities and construction systems can be realized. An intelligent construction system can be composed of three subsystems—design and planning, equipment and construction, and maintenance and service—and involves advanced technologies, such as AI, 3D printing, digital construction, robotics, big data, Internet of things, and cloud computing. With increased industrialization of the construction activity, productivity of the construction industry has become increasingly dependent on inter-disciplinary research, and new disciplines, such as intelligent construction, have been further established. An intelligent construction system can only be realized by performing in-depth interdisciplinary investigations concerning architecture, civil engineering, computer science, machinery, telecommunications, materials, management, and other disciplines. Meanwhile, corresponding research endeavors result in greater requirements of joint ventures in terms of innovation mechanism and capability between universities and enterprises. Between 2012 and 2017, 65 patents on this topic have been published with 951 patent citations and an average of 14.63 citations per patent.

(2) Green planning and building technology

Green planning and building technology has received great attention in recent years owing to increasing recognition of the significance of protecting the Earth's limited resources in the process of urban and rural development. A common consensus has been arrived at in the sense that "we only have one Earth," and the planning and building strategy for realizing sustainable development of the human society and community is a demanding need. Major research directions concerning green planning and building technology include not only green ecology and open-space planning but also lifecycle urban planning, management, development, and building construction. Under the premise of ensuring functional requirements, the following points have been advocated: ① conservation of resources and energy; ② improvement in efficiency of energy resource utilization; ③ effective extraction and use of renewable energy; and ④ utilization of methods integrating data analysis, parametric design, and AI. Specific applications include sponge city construction (low-impact development, water-sensitive cities), adaptive climate planning, and construction involving sunshine, daylighting, ventilation, and thermal-comfort regulation. Current research scales considered in researches concerning this front include individual buildings, local parts of cities, or entire urban or rural areas. Between 2012 and 2017, 49 patents concerning this topic have been published with 245 citations and an average of 5 citations per patent.

(3) Key technological systems in intelligent transportation

Based on advanced technologies and new theories, such as information technology, communication technology, control technology, intelligent technology, and system technology, intelligent transportation systems (ITSs) discover and solve traffic problems with regard to different factors, including humans, vehicles, roads, and the environment, thereby aiming at an efficient, safe, ecological, and intelligent yet comprehensive transportation system. The development of ITSs in different countries differs in terms of emphasis; the main contents, however, remain roughly the same, including such intelligent systems as traffic information, traffic management, public transportation, traffic control, commercial vehicle management, electronic toll collection, security assurance, and emergency management and rescue. With the advent of new technologies, ITS development has been rejuvenated; cross-border integration and innovation have led to creation of new development patterns and service contents, which in turn, has promoted the update of technology as well as development patterns of ITS. At present, ITS technical innovations mainly concentrate on aspects, such as accurate perception and interaction of traffic status, intelligent and cooperative management and service of comprehensive transportation systems, scheduling and service of sharing transportation, transportation vehicle intellectualization and intelligent eco-driving, and cooperative vehicle–infrastructure systems and active traffic-safety assurance. Between 2012 and 2017, 85 patents concerning this topic have been published with 1022 citations and an average of 12.02 citations per patent.

(4) Construction technology and intelligent equipment for ultra-long and ultra-deep tunnels

Ultra-long and ultra-deep tunnels generally refer to those with lengths exceeding 10 km, depths exceeding 500 m (mountain tunnels), or water pressures exceeding 0.5 MPa (underwater tunnels). With the development of tunnel construction technology and equipment, tunnels with lengths exceeding 50 km and water pressures of more than 1 MPa have appeared when crossing mountains, rivers, and lakes. Because of the considerable length and buried depth, great technical challenges are encountered during construction of ultra-long and ultra-deep tunnels. Major technical issues faced relate to ① geological and hydrogeological refinement and detection technologies and equipment used in construction of ultra-deep buried tunnels; ② load- and structural-design methods of ultra-deep buried tunnels; ③ use of intelligent materials and structural forms for ultra-long, ultra-deep buried tunnels; ④ use of modern construction technologies and equipment for tunnels with high stresses, ground temperatures, and water pressures; ⑤ use of construction technologies and equipment for constructing tunnels with super-high operating pressures in water and soil as well as those spanning ultra-long distances; ⑥ use of intelligent and high-performance construction equipment with small disturbances adapted to complex environments; ⑦ use of modern waterproofing and water-controlled technologies and equipment during operation and maintenance of ultra-deep tunnels; ⑧ use of intelligent sensing and maintenance technologies to ensure safety and efficient service performance of ultra-long tunnels; ⑨ operational security of ultra-long, ultra-deep buried tunnels along with development of intelligent disaster prevention and rescue technologies; and ⑩ dynamic risk management and monitoring of the entire process of ultra-deep-tunnel construction. Between 2012 and 2017, 14 patents on this topic have been published with 34 citations and an average of 2.43 citations per patent.

(5) Collaborative development and utilization of urban underground space

Collaborative development and utilization of urban underground space is based on overall urban planning along with relevant laws and regulations. This concept aims at conducting planning, layout, development, and utilization of the urban underground space in an integrated manner to meet the requirements of different functions, scales, and properties; establish a resource-sharing development and utilization model for underground spaces; develop a collaborative technology for urban underground spaces with different functions; and ultimately achieve sustainable development of the underground space. Technical directions in this regard include suitability evaluation of urban underground spaces; mutual adaptation of underground spaces with different functions, scales, and properties via collaborative development and utilization; creation of development and utilization models for different functions and forms of underground spaces, rational structures, and co-construction technologies concerning collaborative development of the urban underground space; collaboratively developing models and methods for operation and maintenance management of underground spaces; and multifunctional collaborative development and utilization, safety management, and disaster control of underground spaces. Rapid expansion of cities and strict regulations to protect cultivable lands would lead to insufficient land availability for construction of cities in the near future. Collaborative development and utilization of urban underground spaces can switch the development pattern of underground spaces from the single-function isolated type to multifunctional, diversified, and shared development. Under conditions of urban land shortage, collaborative development and utilization techniques could be employed to achieve an overall orderly development and utilization of the urban underground space, thereby enhancing its sustainable development. Between 2012 and 2017, 135 patents have been published on this topic with 49 citations and an average of 0.36 citations per patent.

(6) Novel deepwater foundation and wind resistance of cable-supported bridges

Deepwater foundations and long-span cable-supported bridges are usually adopted in construction of bridges across deep bays. The structural form of deepwater foundations and the wind-resistance measures of cable-supported bridges are key factors in controlling the long-term performance evolution of structures. Major technical challenges concerning this research front include time-varying mechanical behavior analysis and control of deepwater foundations, deterioration analysis and control of the long-term bearing capacity of deepwater foundations under wave and current actions, analysis and control of scouring characteristics of deepwater foundations, wind characteristics and simulation of the near-surface boundary layer, identification of aerodynamic admittance of bridge structure components, refined analysis and control of flutter and buffeting of bridges, and turbulent vortex analysis and structural effects. Correspondingly, key technical issues relevant to this field of study include the scouring mechanism and method of protection of gravel cushion caisson foundations, analysis and optimization of nonlinear vibration characteristics of composite foundations with piles and caissons, observation and optimization of long-term bearing and settlement behavior of suction foundations, spatial distribution of wind fields and non-stationary buffeting analysis under typhoon-prone climatic conditions, theoretical method for active flutter control and its verification under different inflows, process simulation of wind-induced vibration, and aerodynamic limit of long-span bridges. Between 2012 and 2017, 179 patents have been published on this topic with 240 citations and an average of 1.34 citations per patent.

(7) Eco-friendly building materials

Eco-friendly building materials refer to green civil engineering materials produced considering energy saving and environmental protection via material performance optimization and comprehensive utilization of wastes. Urban construction and industrial processes produce a large quantity of wastes, and consequently, the contradiction between environmental protection and urban development has become increasingly severe. Recycling of wastes is an effective material circulation solution. Large amounts of construction wastes, such as waste concrete and abandoned blocks, generated during urban construction practices can be utilized to produce renewable aggregates, which in turn, could be used as substitutes for ordinary or high-performance or even ultrahigh-performance concrete through use of certain preparation processes. Industrial wastes, such as steel slag, nickel slag, fly ash, and waste gypsum, can be used to prepare concrete with desired mechanical properties and high durability through use of reasonable active excitation and component compatibility techniques. Additionally, by optimizing material properties, ultrahigh-performance concrete can be produced to achieve excellent mechanical properties, high durability, high wear resistance, and excellent explosion resistance. The abovementioned eco-friendly building materials can be used in various types of structures and possess a broad market. Between 2012 and 2017, 254 patents on this topic have been published with 380 citations and an average of 1.5 citations per patent.

(8) Advanced treatment of urban water

Rapid urbanization has caused an increasing demand for water and intensified the problem of water shortage. Discharged industrial and domestic wastewater leads to pollution of water supply sources. Pollutants in water sources mainly include trace organic pollutants, tiny particulate pollutants, and water eutrophication elements, such as nitrogen and phosphorus. Conventional water purification processes (e.g., coagulation, sedimentation, and filtration) are no longer adequate to meet quality requirements of drinking water. Thus, there exists an urgent need to develop advanced technologies and equipment for treatment of tap water. Examples of the third generation of advanced drinking-water treatment technologies include the advanced oxidation, raw water pretreatment, and purification processes based on membrane filtration.

As one of the unconventional water resources, urban wastewater can be reused as non-direct drinking water after appropriate advanced treatment. Recycling wastewater is effective not only for alleviating water shortage and disruption in ecological environment but also with regard to improving the quality and economic value of recycled water. Sewage water can be treated by physical, chemical, biological, and combined processes to attain a usable standard. Representative technologies for these processes include bio-enhancement treatment, catalytic oxidation, and membrane filtration. Between 2012 and 2017, 153 patents on this topic have been published with 1757 citations and an average of 11.48 citations per patent.

(9) Regulation technology for urban storm-water

With rapid growth in urbanization and social economy, urban rainwater control becomes a significant concern owing to the associated risk of flooding, loss of enormous rainwater resources, intensified pollution in urban rivers, and increasingly degraded urban ecological environment. The concept of urban storm-water control and utilization has been proposed to deal with urban rainwater and flood-related issues. Measures pertaining to infiltration, storage, stagnation, purification, utilization, and drainage have been taken for managing urban rainwater and runoff to effectively control rainwater floods and non-point pollution at the source, halfway, and end. Source-control technologies involve construction of roof greening, low-elevation greenbelts, permeable pavements, rainwater gardens, grassed swales, and rain barrels. Halfway-control technologies, on the other hand, include sewage wells, infiltration pipes and channels, and rainwater filters. End-control technologies include use of rain pools, rainwater wetlands, buffer zones, ecological embankments, and biological floating islands. These technologies have been used in many aspects, such as water resource utilization, flood control and disaster mitigation, and ecological environment protection. The present need of the hour is to speed up the construction of large-capacity drainage systems, develop multiscale water quantity and quality coupled simulation software and digital rainwater resource-management platforms, and study the classification and regulation of storm-water resources. Between 2012 and 2017, 67 patents have been published on this topic 542 citations and an average of 8.09 citations per patent.

(10) High-precision positioning navigation and spatiotemporal big data

High-precision navigation positioning and spatiotemporal big data plays an important role in the fields of Internet of things, smart earth, energy savings and emission reduction, and disaster mitigation. High-precision positioning navigation can be used to realize the location, navigation, and supervision of various targets based on data concerning position, speed, and time provided by navigation and positioning systems. It requires wide-area coverage, and the positioning and navigation accuracy must be of the decimeter-level or even higher. Spatiotemporal big data technology improves spatial positioning, perception, and cognition via data processing, analysis, fusion, and mining. Major techniques include ① global continuous coverage real-time precise satellite navigation and positioning technology, such as the third-generation GNSS technology; ② indoor and outdoor high-precision seamless positioning and navigation technologies, such as Wi-Fi/WSN/RFID/UWB indoor positioning technology; ③ spatiotemporal big data technologies—such as statistical analysis of time series and spatial trend, data mining, and knowledge discovery—for providing knowledge services to spatial decision support systems. Between 2012 and 2017, 570 patents have been published on this topic with 20 781 citations and average of 36.46 citations per patent.

2.2 Interpretations for three key engineering development fronts

2.2.1 Intelligent construction and 3D printing technology

Conventional construction industries around the world still exist in the labor-intensive stage and consume a large quantity of social resources. This is especially true with regard to energy utilized in the construction of buildings and treatment of construction materials, which accounts for 46% of the total energy consumption of the society, and has become a huge burden on national economy. The development of a green, low-carbon, and environmentally protected construction industry has, therefore, become imperative. Intelligent construction systems based on advanced construction and information technologies through use of CPS can effectively solve aforementioned problems by transforming and upgrading the construction industry. Construction of an efficient and intelligent building system requires effective integration of advanced technologies (e.g., AI, 3D printing, digital manufacturing, robots, big data, Internet of things, and cloud computing) to ensure correct coordination between individual stages, disciplines, and players during the lifecycle of a building and enhance individual functions in physical as well as virtual spaces. The ultimate goal here is to upgrade the overall production mode and productivity of the construction industry.

Presently, major topics of research concerning intelligent construction and 3D printing technology include

(1) Structural systems and intelligent design

Architectural and structural designs in conventional construction industries are mostly created for individual projects, thereby leading to repetitive works and low efficiency of coordination between different aspects of work. To ensure material saving, parts and components are project-specified and varied in dimensions, thereby causing difficulties related to industrialization, intellectualization, and managing of construction processes whilst maintaining high operational efficiency. The basic characteristics of intelligent construction include intelligent planning and design, automation of processing and manufacturing, intelligent assembly of field construction, information-based operational and maintenance management, and recycling of dismantled waste. The ultimate objective of intelligent construction is to ensure construction quality and efficiency, reduce labor demand, and facilitate lifecycle maintenance of buildings and infrastructure. Systematization of structural design, and modularization/standardization of structural parts and components form the basis of intelligent architectural designs. In addition, efficient structural systems and joint connection technologies form key issues concerning the fulfillment of intelligent designs; the level of associated technologies available within a country is an important index of its level of intelligence with regard to the construction industry.

(2) Intelligent equipment and construction

Modern construction technologies encompass standardized product manufacturing, prefabricated construction, intelligent construction technologies, and information process management. The construction mode significantly changes to meet the requirements for evolution in the conventional construction industry. Modern construction equipment finds wide applications in the construction of underground spaces, installation of large-scale earthworks and structures, emergency rescue, modern transportation networks, and deep-space and deep-ocean explorations. Efficient construction technologies and equipment rely on extensive collaborations between experts from different fields. They, therefore, possess great potential for promoting simultaneous developments in multiple fields. Modernization of construction equipment and technology is an important indicator of the overall strength of a nation. Therefore, researches performed concerning this topic has received increased attention worldwide, and these have been included under high-tech development plans or key national technologies in many countries.

Presently, conventional methods of building construction are being taken over by advanced modern technologies. The construction industry is rapidly upgraded from the labor-intensive mode to the technology-, knowledge-, and management-intensive mode. The *Information Development Report of the Chinese Construction Industry (2016): Internet Application and Development* thoroughly addresses the current situation and future development trends concerning the application of the Internet in the construction industry. It is believed that transformation of the construction industry strongly relies on the support and extensive application of the Internet. Intelligent construction and intelligent enterprises will be the future trend of transforming the construction industry.

(3) Intelligent maintenance and services

Integrated intelligent construction can achieve the desired safety, durability, fast construction, and low-carbon and friendly environment through factory production and then field assembling. It can minimize construction waste and sewage production, reduce construction noise, and enhance construction quality and efficiency. Meanwhile, a variety of sensors, smart homes, and related management software can be employed to realize lifecycle health monitoring and effective maintenance of building systems. Via efficient construction system management, one can reduce the cost, shorten the time limit, and ensure quality and safety exclusively through management of information and intelligence and standardization of production processes, thereby fully realizing the advantages of construction technology. Meanwhile, production efficiency of the entire construction industry can be further improved, and intelligent construction realized. Over lifecycles of buildings and infrastructure, information channels, such as communication networks and electronic equipment, can be employed to optimize the management process; realize standardization of production processes; and perform real-time, refined, and intelligent management of the design, construction, acceptance, maintenance, and management, dismantling, and recycling of buildings. These will play an important role in promoting rapid development of intelligent construction technologies.

As listed in Table 2.1.1, 65 core patents have been published on this topic between 2012 and 2017, and each patent has been cited an average of 14.63 times. The top 3 countries/regions publishing the most core patents are USA, China (excluding Taiwan of China), and South Korea (Table 2.2.1), among which, USA has contributed 41.54% of the core patents and received, on average, 22.41 citations per patent, thereby ranking first in terms of the total number of core patents. China, being one of the key players with regard to this development front, has contributed 40% of core patents published and received, on average, 8.69 citations per patent. As depicted in Figure 2.2.1, international cooperation is rare among the top 10 core patenting countries/regions.

As listed in Table 2.2.2, the top 3 organizations publishing the most number of core patents are MakerBot Industries LLC (USA), China Construction Group Co. (China), and Samsung Electronics Co., Ltd. (South Korea). Cooperation among the most productive organizations in this regard is also rare (Figure 2.2.2).

2.2.2 Green planning and building technology

Green planning and building technology is an inevitable development trend and a key strategy for sustainable development. The core principle here is to save resources and energy, improve the efficiency of energy-resource utilization, actively develop and utilize renewable energy, and achieve harmony with nature along with environmentally sustainable development under the premise of ensuring a healthy and comfortable living environment over the entire lifecycle of urban development and construction practices. Research endeavors concerning green construction begin from development of energy-saving ecological technologies for

Table 2.2.1 Countries or regions with the greatest output of core patents on the “intelligent construction and 3D printing technology”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	27	41.54%	605	63.62%	22.41
2	China	26	40.00%	226	23.76%	8.69
3	South Korea	5	7.69%	27	2.84%	5.40
4	Netherlands	1	1.54%	22	2.31%	22.00
5	India	1	1.54%	21	2.21%	21.00
6	Finland	1	1.54%	20	2.10%	20.00
7	Japan	1	1.54%	13	1.37%	13.00
8	Denmark	1	1.54%	12	1.26%	12.00
9	Russia	1	1.54%	3	0.32%	3.00
10	Germany	1	1.54%	2	0.21%	2.00

Table 2.2.2 Institutions with the greatest output of core patents on the “intelligent construction and 3D printing technology”

No.	Institutions	Country/Region	Published patents	Percentage of published patents	Citations	Proportion of citations	Citations per patent
1	STTS	USA	8	12.31%	243	25.55%	30.38
2	CSCE	China	3	4.62%	19	2.00%	6.33
3	SMSU	South Korea	3	4.62%	17	1.79%	5.67
4	IROB	USA	2	3.08%	92	9.67%	46.00
5	Aprecia Pharm Co	USA	2	3.08%	77	8.10%	38.50
6	GENE	USA	2	3.08%	32	3.36%	16.00
7	CISC	USA	2	3.08%	17	1.79%	8.50
8	GLDS	South Korea	2	3.08%	10	1.05%	5.00
9	UYTJ	China	1	1.54%	41	4.31%	41.00
10	View Inc	USA	1	1.54%	37	3.89%	37.00

STTS: MakerBot Ind. LLC; CSCE: China State Construction Engrg. Corp. Ltd; SMSU: Samsung Electronics Co., Ltd.; IROB: Irobot Corp.; GENE: General Electric Co.; CISC: Cisco Technology Inc.; GLDS: LG Display Co., Ltd.; UYTJ: Tongji University.

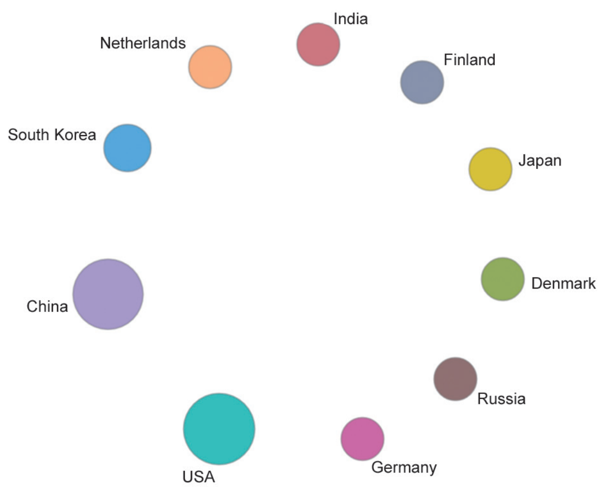

Figure 2.2.1 Collaborative network among countries or regions in the engineering development front of “intelligent construction and 3D printing technology”

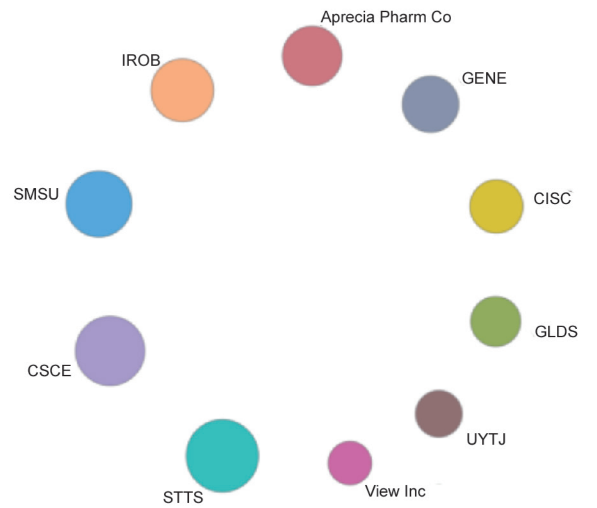

Figure 2.2.2 Collaborative network among institutions in the engineering development front of “intelligent construction and 3D printing technology”

the built environment, and actively develops the utilization of green energy and the comprehensive technological innovation of green buildings on the basis of making full use of passive technologies to achieve building consumption reduction. From the perspective of global green-building development, research and development activities must closely concentrate on green cities and green buildings; and through focusing on ecological cities, climate environment, natural resources, passive technologies, energy efficiency technologies, human comfort and health, comprehensive evaluation technologies, etc., a complete set of consulting frontier technology will be formed. Technical developments in this regard include research on high-density urban climate and energy-consumption assessment methods and information mapping, green building performance optimization based on climatic response, the technology of Internet of energies in urban buildings, application and innovation of passive technologies in green buildings, resident comfort and behavioral pattern assessment and evaluation, and active and passive technology complementary and coordinated green building synergy technology systems.

Development and application of green planning and building technologies are in full swing in China. Eighty percent of its cities with new national districts are developing demonstration projects concerning low-carbon planning. Green energy systems, blue–green ecological patterns, green transportation systems, green buildings, and green infrastructure have been developed in the new district pilots, and the *Assessment Standard for Green Eco-District* has been issued.

As listed in Table 2.1.1, 49 core patents have been published on this topic between 2012 and 2017, and each patent has been cited an average of 5 times. The top 3 countries/regions publishing the most number of core patents are China (excluding Taiwan of China), USA, and Japan (Table 2.2.3), among which, China has contributed over 95% of the core patents published and received, on average, 4.96 citations per patent, thereby ranking first in terms of the total quantity of core patents. As depicted in Figure 2.2.3, international cooperation is rare among the top 10 core patent output countries/regions in this regard.

As listed in Table 2.2.4, the top 3 organizations producing the most number of core patents are the Beijing Taikong Panel Ind. Corp. (China), Changzhou Lvjian Plate Ind. Co., Ltd. (China), and Hengyuan Building Board Ind. Co., Ltd. (China). Cooperation among these organizations is also rare (Figure 2.2.4).

2.2.3 Key technological systems in intelligent transportation

ITSs are based on new theories and such advanced technologies as information, communication, systems and controls, and intelligence. Research endeavors concerning this topic involve discovering and solving traffic problems from different perspectives, including those of humans, vehicles, roads, and the environment, whilst aiming at establishing an efficient, safe, ecological, and intelligent yet comprehensive transportation system. The development of ITSs in different countries differs in terms of emphasis; the main contents, however, remain roughly the same, including such intelligent systems as traffic information, traffic management, public transportation, traffic control, commercial vehicle management, electronic toll collection, security assurance, and emergency management and rescue.

With the advent of new technologies, ITS development has been rejuvenated; cross-border integration and innovation have led to creation of new development patterns and service contents, which in turn, has promoted the update of technology as well as development patterns of ITS. Currently, technical innovations concerning the ITS technology mainly concentrate on the following aspects.

(1) Accurate perception and interaction of traffic status. This involves realizing the intellectualization of and connection between terminal devices; accurate, simultaneous, and comprehensive attainment of the overall operational status of traffic networks; and providing traffic-related clues to both travelers and traffic management departments.

(2) Intelligent and cooperative management and service

Table 2.2.3 Countries or regions with the greatest output of core patents on the “green planning and building technology”

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	47	95.92%	233	95.10%	4.96
2	USA	1	2.04%	8	3.27%	8.00
3	Japan	1	2.04%	4	1.63%	4.00

Table 2.2.4 Institutions with the greatest output of core patents on the “green planning and building technology”

No.	Institution	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Beijing Taikong Panel Ind Corp	China	3	6.12%	9	3.67%	3.00
2	Changzhou Lvjian Plate Ind Co Ltd	China	3	6.12%	9	3.67%	3.00
3	Hengyuan Building Board Ind Co Ltd	China	3	6.12%	9	3.67%	3.00
4	Shandong New Century Municipal Eng Co	China	2	4.08%	10	4.08%	5.00
5	Univ Northeast Petroleum	China	2	4.08%	6	2.45%	3.00
6	CNPW	China	2	4.08%	4	1.63%	2.00
7	Shenzhen Inst Building Res Co Ltd	China	2	4.08%	3	1.22%	1.50
8	Lifengwang Shishi Environmental Protection Building Material	China	1	2.04%	13	5.31%	13.00
9	CRTC	China	1	2.04%	10	4.08%	10.00
10	Dongguan Yueyuan Packaging Co Ltd	China	1	2.04%	9	3.67%	9.00
11	Guangdong Yuansheng Eco-Environment Prot	China	1	2.04%	9	3.67%	9.00
12	UYZH	China	1	2.04%	9	3.67%	9.00

CNPW: Power Construction Corporation of China; CRTC: Railway Eng Res Inst China Academy Railway Sciences; UYZH: Zhejiang University.

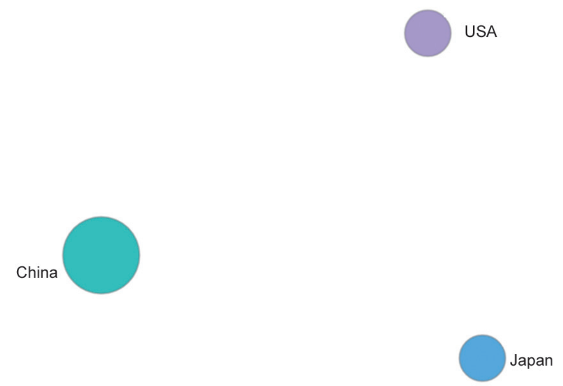

Figure 2.2.3 Collaborative network among countries or regions in the engineering development front of “green planning and building technology”

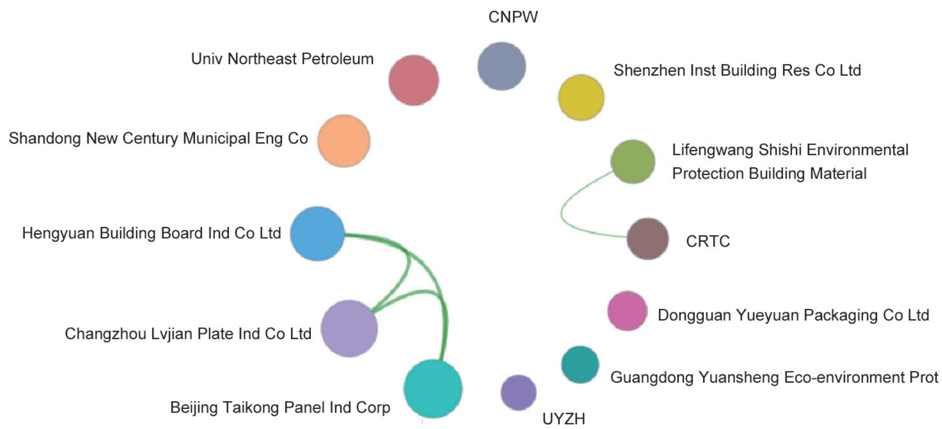

Figure 2.2.4 Collaborative network among institutions in the engineering development front of “green planning and building technology”

of comprehensive transportation systems. This field of study concerns new technologies, including big data, cloud computing, autonomous driving, connected vehicles, and AI, thereby generating new levels of intelligent management of ITSs, realizing accurate guidance and control of each individual, and improving the efficiency and capacity of traffic facilities.

(3) Scheduling and service of sharing transportation. This field of study involves transportation sharing and considers "travel is service" as its orientation, thereby designing multimodal transportation sharing systems and realizing an effective integration of management, organization, scheduling, and service principles.

(4) Transportation vehicle intellectualization and intelligent eco-driving. Intelligent vehicles represent the developing trend of future technologies and high strategic level of industrial upgradation. Related technologies are already in the testing phase with due consideration of revolutions as well as challenges concerning traffic systems.

(5) Cooperative vehicle infrastructure systems (CVISs) and active traffic safety assurance. Based on wireless and sensor technologies, road and vehicle information can be acquired. In addition, vehicles and infrastructure can be intellectually coordinated via vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, thereby realizing the goal of optimizing system resources, improving road safety, and alleviating congestion. Cooperative vehicle–infrastructure system (CVIS) represents cutting-edge research in the field of transportation engineering, thereby attracting extraordinary investments in many countries, such as the IntelliDriveSM program in USA, Smartway in Japan, and eSafety in Europe.

As listed in Table 2.1.1, 85 core patents have been published on this topic between 2012 and 2017, and each patent has, on average, been cited 12.02 times. The top 4 countries/regions publishing the most number of core patents are China (excluding Taiwan of China), USA, Japan, and Australia (Table 2.2.5), among which, China—being one of the key players with regard to this development front—has contributed over 70% of the core patents published and has, on average, received 10.31 citations per patent. As depicted in Figure 2.2.5, international cooperation is rare among the top 10 core patent output countries/regions.

As listed in Table 2.2.6, Qualcomm Incorporated (USA) has published the most number of core patents on this topic. Cooperation among the most productive organizations is also rare (Figure 2.2.6).

Table 2.2.5 Countries or regions with the greatest output of core patents on the "key technological systems in intelligent transportation"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	62	72.94%	639	62.52%	10.31
2	USA	17	20.00%	301	29.45%	17.71
3	Japan	2	2.35%	24	2.35%	12.00
4	Australia	2	2.35%	23	2.25%	11.50
5	Netherlands	1	1.18%	39	3.82%	39.00
6	Finland	1	1.18%	23	2.25%	23.00
7	India	1	1.18%	16	1.57%	16.00
8	Saudi Arabia	1	1.18%	16	1.57%	16.00
9	Sweden	1	1.18%	10	0.98%	10.00

Table 2.2.6 Institutions with the greatest output of core patents on the "key technological systems in intelligent transportation"

No.	Institution	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	QCOM	USA	5	5.88%	61	5.97%	12.20
2	UYQI	China	2	2.35%	35	3.42%	17.50
3	UYXN	China	2	2.35%	25	2.45%	12.50
4	ZGTH	China	2	2.35%	25	2.45%	12.50
5	HAIT	China	2	2.35%	24	2.35%	12.00
6	IBMC	USA	2	2.35%	23	2.25%	11.50
7	Xi'an Feisida Automation Eng Co Ltd	China	2	2.35%	21	2.05%	10.50
8	Wuhan Fenghuo Zhongzhi Digital Technology	China	2	2.35%	17	1.66%	8.50
9	Bravioz OY	Finland	1	1.18%	40	3.91%	40.00
10	TTTA	India	1	1.18%	39	3.82%	39.00

QCOM: Qualcomm Incorporated; UYQI: Tsinghua University; UYXN: Xidian University; ZGTH: China Railway Signal & Communication Corporation Limited; HAIT: Harbin Institute of Technology; IBMC: International Business Machines Corporation; TTTA: TATA Consultancy Service Co., Ltd.

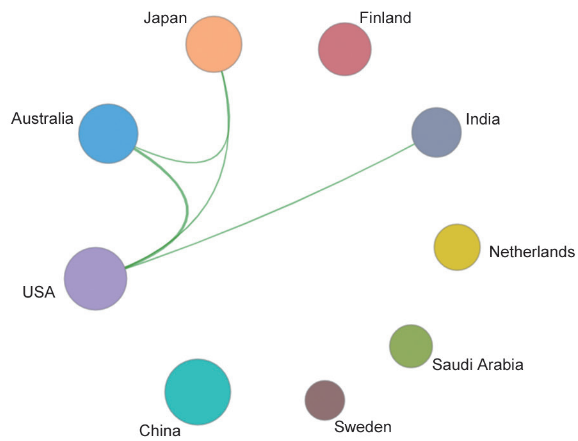

Figure 2.2.5 Collaborative network among countries or regions with the greatest output of core patents in the engineering development front of "key technological systems in intelligent transportation"

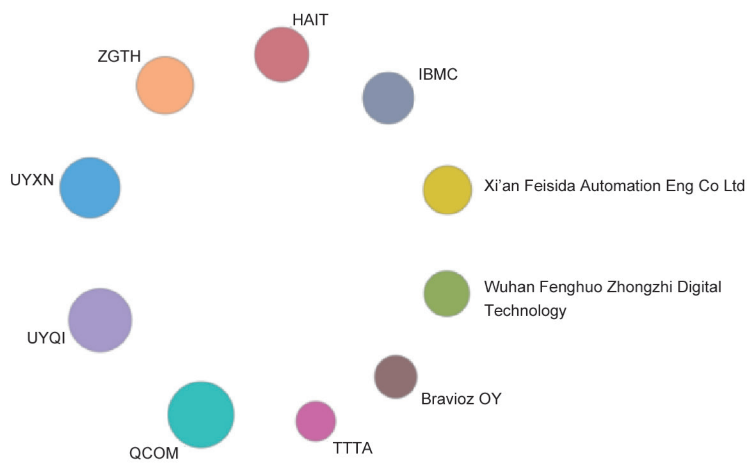

Figure 2.2.6 Collaborative network among institutions in the development front of "key technological systems in intelligent transportation"

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