

Chapter 6 Civil, Hydraulic, and Architectural Engineering Fronts



6.1 Engineering research fronts

6.1.1 Trends in the Top 10 engineering research fronts

The Top 10 engineering research fronts in the fields of civil, hydraulic, and architectural engineering are summarized in Table 6.1. These fronts cover various disciplines, including geotechnical engineering, transportation engineering, architectural design and theory, surveying and mapping engineering, urban planning and landscaping, hydraulic engineering, structural engineering, municipal engineering, and engineering mechanics. Five of them were from expert nomination: "intelligent operation and safety assurance of new energy transportation systems", "hybrid computational paradigm for intelligent mapping", "mechanisms and control of dynamic disaster of long tunnel in extreme environments", "intelligent design theory for green and low-carbon engineering structures", and "mechanisms and optimization of built environment health impacts in urban communities". The other five fronts were identified using the co-citation clustering method applied to the top 10% of the highly cited papers, and they were confirmed in expert panel meetings. Table 6.2 presents the annual statistics of the core papers published between 2018 and 2023 that are relevant to the top ten research fronts.

(1) Mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment

Extreme flood and drought disasters in river basins in changing environments refer to abnormal floods or droughts caused by the combined effects of climate change, human activities, and ecosystem changes that result in severe social, economic, and ecological losses. The occurrence and evolution of such disasters are influenced by multiple factors such as precipitation patterns,

Table 6.1 Top 10 engineering research fronts in civil, hydraulic, and architectural engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment	151	7 236	47.92	2020.8
2	Urban planning and architectural design methods empowered by large models	169	8 670	51.30	2021.4
3	Intelligent operation and safety assurance of new energy transportation systems	335	21 779	65.01	2020.6
4	Physics-informed neural networks for solving engineering mechanics problems and applications	204	13 055	64.00	2022.0
5	Hybrid computational paradigm for intelligent mapping	111	4 819	43.41	2021.2
6	Low carbonization and properties optimization of ultra-high performance concrete	24	986	41.08	2022.2
7	Mechanisms and control of dynamic disaster of long tunnel in extreme environments	48	1 812	37.75	2021.5
8	Advanced oxidation/reduction technology for removing organic pollutants from water	473	43 325	91.60	2021.2
9	Intelligent design theory for green and low-carbon engineering structures	200	7 300	36.50	2021.3
10	Mechanisms and optimization of built environment health impacts in urban communities	195	9 517	48.81	2020.4

Table 6.2 Annual number of core papers published for the Top 10 engineering research fronts in civil, hydraulic, and architectural engineering

No.	Engineering research front	2018	2019	2020	2021	2022	2023
1	Mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment	19	14	30	34	21	33
2	Urban planning and architectural design methods empowered by large models	9	13	24	27	47	49
3	Intelligent operation and safety assurance of new energy transportation systems	50	51	50	66	55	63
4	Physics-informed neural networks for solving engineering mechanics problems and applications	0	1	19	40	56	88
5	Hybrid computational paradigm for intelligent mapping	8	7	19	19	34	24
6	Low carbonization and properties optimization of ultra-high performance concrete	0	1	0	5	4	14
7	Mechanisms and control of dynamic disaster of long tunnel in extreme environments	2	6	6	3	15	16
8	Advanced oxidation/reduction technology for removing organic pollutants from water	0	68	81	115	103	106
9	Intelligent design theory for green and low-carbon engineering structures	12	24	25	31	47	61
10	Mechanisms and optimization of built environment health impacts in urban communities	32	39	32	29	35	28

land use, and urbanization, which exhibit significant uncertainty and complexity. In recent years, extreme flood and drought disasters, represented by major events, such as the "7 · 20" heavy rainfall and flooding in Zhengzhou, China, and the 2022 drought across the entire Yangtze River Basin, have posed significant threats to regional public safety. Therefore, studying the mechanisms underlying extreme flood and drought disasters and risk regulation in river basins is of great significance. The main research directions include: ① multi-source flood and drought disaster monitoring and data assimilation based on the integration of "space-sky-ground"; ② identification and evolution mechanisms of extreme flood and drought events in river basins under changing environment; ③ threshold values and tipping (explosion) point predictions for extreme flood and drought disasters in river basins; ④ risk assessment and regulation technologies for sudden disasters such as flash floods, flash droughts, and rapid transitions between drought and flood in river basins; ⑤ risk assessment and regulation systems for flood disasters in large and medium/large-sized cities. The future development trend lies in clarifying the nonlinear driving-response mechanisms of environmental changes and flood and drought disasters in river basins, and developing large disaster risk models driven by coupled mechanisms and data. On this basis, multi-source information can be integrated to predict and prevent various types of flood and drought disasters in river basins while accelerating the construction of a comprehensive river basin regulation system based on the "point-line-area-system" integration of cities, rivers, lakes, and water networks. A total of 151 core papers relevant to this research front were published between 2018 and 2023. These papers received 7 236 citations, with an average of 47.92 citations per paper.

(2) Urban planning and architectural design methods empowered by large models

The intersection of artificial intelligence (AI), urban planning, and architectural design has become an emerging hot spot in the industry in recent years, making targeted breakthroughs in effectiveness evaluation and design generation; however, the existing progress is mostly limited to a specific scenario. The inherent characteristics of multi-modal information enhancement, knowledge traction, and data driving the large model can effectively integrate the unique graphic and text-mixed knowledge of architectural disciplines to construct a holographic knowledge landscape. Simultaneously, large model optimization technology can provide full-link and full-intelligence transformation support in many key links of planning and architectural design, such as

current situation research and judgment, design generation, and efficiency evaluation. The frontier research directions are mainly reflected in the following aspects: ① construction of holographic knowledge map of disciplines; ② intelligent present status judgment; ③ generative planning and design; ④ efficiency evaluation of digital intelligent design. Therefore, strengthening the development and application of large model-enabled urban planning and architectural design methods in China is of positive and far-reaching significance for promoting the planning and architectural discipline based on experience, leading to a new paradigm of design science. Between 2018 and 2023, 169 core papers relevant to this research front were identified. These papers received 8 670 citations, with an average of 51.30 citations per paper.

(3) Intelligent operation and safety assurance of new energy transportation systems

The new energy transportation system refers to the application of renewable energy and advanced technologies in the field of transportation to reduce reliance on traditional fossil fuels and achieve low-carbon, environmentally friendly, and sustainable development goals. Currently, a new energy transportation system characterized by the high integration of "vehicle-energy-road-cloud" is emerging, aiming to build an intelligent, low-carbon, safe, and efficient operational and assurance system for the transportation system. This has significant implications for enhancing the autonomous controllability and green development level of the entire industry chain, as well as promoting the deep integration of transportation infrastructure with service, energy, and information networks. The main research directions include: ① heterogeneous transportation demand and multi-type clean energy supply forecasting; ② multi-objective scheduling of green smart mobility systems; ③ energy "source-grid-storage" coupling technologies responsive to transportation demand; ④ operation and maintenance of new energy infrastructure and emergency safety assurance for transportation systems. Future development trends should focus on empowering people, vehicles, roads, grids, networks, loads, storage, charging piles, and carbon emissions through intelligent and digital means; achieving efficient regulation and precise matching between transportation supply and demand, energy generation and consumption, and road construction and maintenance; and significantly enhancing the intelligent operation and safety assurance capabilities of new energy-enabled transportation systems. Between 2018 and 2023, 335 core papers relevant to this research front were identified. These papers received 21 779 citations, with an average of 65.01 citations per paper.

(4) Physics-informed neural networks for solving engineering mechanics problems and applications

Physics-informed neural network (PINN) is a type of neural network that can solve supervised learning tasks by embedding physics equations into the loss functions. This enables the neural networks to comply with any physical information described by nonlinear partial differential equations. Therefore, PINN can exhibit better generalization capabilities and stronger applicability under conditions of limited data or high noise, showing potential in solving high-dimensional differential equations for analyzing engineering structural and fluid mechanics problems, as well as in solving multi-physics coupling equations. PINNs mainly consist of two approaches: ① based on partial differential equations; ② based on energy principles. They have been widely applied to solve fluid mechanics problems, and they are primarily used in solid mechanics to address issues such as elastoplastic mechanics, fatigue and fracture problems, thermodynamic analysis, and structural dynamic response analysis. However, PINN is still disadvantageous in terms of accuracy and speed in high-order automatic differentiation numerical solutions. Dealing with complex boundary conditions is challenging. In the future, it will be necessary to further enhance the generalization capabilities of PINNs and improve their performance when facing more complex physical phenomena, which will aid in developing efficient computational tools for analyzing complex engineering mechanics problems. Between 2018 and 2023, 204 core papers related to this research topic were published. These papers received 13 055 citations, with an average of 64.00 citations per paper.

(5) Hybrid computational paradigm for intelligent mapping

Intelligent mapping is the deep fusion of new-generation AI technology with mapping technology to form new theories and methodology systems to enhance the intelligence level of key mapping technologies, such as spatial and temporal sensing, cognition, representation, and service, to aid us in solving unsolved problems, improving accuracy and efficiency, reducing costs, and/or achieving high-level services. To realize an organic integration of machine intelligence and natural intelligence in mapping, it is necessary to grasp the key factors—spatiotemporal characteristics, examine complementary advantages and

coupling mechanisms of natural intelligence in mapping and machine intelligence, reveal the roles and interrelationships of four factors, namely knowledge (K), data (D), algorithm (A), and service (S), and develop a spatiotemporal hybrid computing theory and methodology, which are guided by knowledge, driven by data, based on algorithms, and supported by services, to form an intelligent computing model KDAS that considers spatiotemporal characteristics. The main content includes ① the construction of a spatiotemporal hybrid computational paradigm, ② spatiotemporal perception computation, ③ spatiotemporal cognition computation, ④ situationalized map representation computation, and ⑤ autonomous service computation. Through research on hybrid intelligent computing for intelligent mapping, the basic paradigm of spatiotemporal hybrid intelligent computing will be developed, and a complete set of methods will be developed for real-time spatiotemporal perception, dynamic spatiotemporal cognition, situationalized spatiotemporal representation, autonomous spatiotemporal services, and other hybrid intelligent computing. This will aid in creating a theoretical and methodological system of hybrid intelligent computing for mapping and providing new methods and means for research in scientific fields, including earth science and engineering science, to drive the development of international research in this field. A total of 111 core papers relevant to this research front were published between 2018 and 2023. These papers received 4 819 citations, with an average of 43.41 citations per paper.

(6) Low carbonization and properties optimization of ultra-high performance concrete

Ultra-high performance concrete (UHPC) is an advanced civil engineering material characterized by ultra-high strength, superior ductility, and excellent durability, showing great potential for applications in fields such as bridges and railway infrastructure, marine engineering, and structural reinforcement. Nevertheless, the preparation process of conventional UHPC involves the extensive use of energy-intensive materials, such as cement and silica fume, resulting in low environmental and economic efficiency. Additionally, as the strength of UHPC continues to improve through optimization, its ductility tends to decrease, making it challenging to satisfy the demands of engineering structures in various severe environments. Therefore, research on achieving low-carbon UHPC across its entire life cycle and the design of UHPC materials that balance strength and ductility is of significant importance. Specific research directions include: ① mix design methods for UHPC based on construction and industrial waste resources; ② low-energy UHPC preparation technologies; ③ synergistic enhancement mechanisms for improving the strength and ductility of UHPC; ④ properties optimization technologies for UHPC in complex and harsh environments. Future development trends in this area will focus on addressing the challenges of high carbon emissions over the UHPC life cycle and the difficulty in balancing strength and ductility. Further research will be conducted to reduce the carbon footprint of UHPC by considering its key life cycle stages, including raw material production, mix design, and structural maintenance. On this basis, multiscale research methods will be employed to achieve simultaneous improvements in strength, ductility, and durability of UHPC in severe environments, promoting the application of low-carbon high-performance concrete materials and supporting the green transformation of the construction industry. Twenty-four core papers relevant to this research front were published between 2018 and 2023. These studies received 986 citations, with an average of 41.08 citations per paper.

(7) Mechanisms and control of dynamic disaster of long tunnel in extreme environments

Extreme environments in long tunnels refer to the challenging conditions encountered during their construction and operation of long tunnels, such as intense tectonic zones, high *in situ* stress, high geotemperature, and high seismic intensity. These extreme environments give rise to dynamic hazards, such as strong earthquakes, active fault displacements, and rockbursts, all of which pose significant threats to the safety of tunnel construction and operation. Moreover, the occurrence of such dynamic hazards is characterized by uncertainty and multi-hazard coupling, leading to complex disaster-forming mechanisms. In recent years, the construction of long tunnels in high-stress and intense tectonic areas, especially the transport infrastructure in Sichuan–Yunnan region, has faced serious safety risks. Therefore, it is important to examine the mechanisms and control the dynamic catastrophe evolution in long tunnels under extreme conditions. The key research areas include: ① multi-field coupling mechanism of tectonic stress fields, strong dynamic fields, and surrounding rock seepage fields, and the evolution and characterization of engineering loads; ② disaster evolution mechanisms of tunnel structures under the coupling of complex tectonic stress and strong seismic-fault dislocation effects; ③ triggering mechanism and control strategy of deep rock bursts under complex geological conditions; ④ risk assessment and resilience enhancement system for long tunnels in extreme environments. The development trend in

the future involves clarifying the disaster-bearing mechanism of engineering sites in extreme environments and project load characteristics, and on this basis, revealing the disaster process and failure mode of engineering structures, developing disaster prevention and mitigation control technology for long tunnel structures in extreme environments, and building a multi-disaster risk assessment and safety regulation and decision-making system for long tunnel structures in extreme environments. A total of 48 core papers relevant to this research front were published between 2018 and 2023. These papers received 1 812 citations, with an average of 37.75 citations per paper.

(8) Advanced oxidation/reduction technology for removing organic pollutants from water

High-risk pollutants, such as pesticides, endocrine disruptors (EDs), and disinfection byproducts in aquatic environments are diverse, harmful, and difficult to remove, posing major challenges to human health and ecosystems. Advanced oxidation/reduction processes (AOPs/ARPs) can produce highly concentrated, highly active intermediate states (such as free radicals, high-valence metals, and hydrated electrons) and achieve detoxification and mineralization of high-risk pollutants through electron transfer or hydrogen extraction and oxygen addition mechanisms. AOPs and AOPs/ARPs have developed into the core units of advanced treatment processes, which have far-reaching strategic significance for ensuring water quality safety and improving human health and welfare. Current research focuses on: ① formation and regulation mechanism of active components in advanced oxidation/reduction systems; ② design and development of efficient, green, and stable new catalysts; ③ investigation and application of selective advanced oxidation/reduction processes under complex water quality; ④ research and optimization of novel advanced oxidation/reduction processes for emerging highly toxic organic pollutants; ⑤ development and application of advanced oxidation/reduction processes under the coupling of new energy structures (light, heat, and electricity). The main development trend in the future involves clarifying the degradation behavior of high-risk pollutants in advanced oxidation/reduction processes under extreme water quality conditions and the mechanism of detoxification transformation, developing innovative technologies for advanced oxidation/reduction coupled with biochemistry, adsorption, membrane filtration, pervaporation, and other multi-process units for the enhanced removal of stable organic pollutants, desalination, and enhancing removal of volatile organics. Meanwhile, attention has also been placed on the construction of a dynamic prevention and control technology system for new pollutants with unknown risks under the assistance of AI, the realization of intelligent recommendations for applicable advanced oxidation/reduction technology, and intelligent optimization of multi-functional catalysts to promote the systematic establishment and promotion of sustainable water treatment technologies. Overall, future research should aim to promote the systematic establishment and application of sustainable water treatment technologies. A total of 473 core papers relevant to this research front were published between 2018 and 2023. These papers received 43 325 citations, with an average of 91.60 citations per paper.

(9) Intelligent design theory for green and low-carbon engineering structures

The intelligent design of green low-carbon engineering structures integrates the concepts of sustainable development, innovations in green building materials, and cutting-edge intelligent design technologies, creating a new paradigm in design theory. This paradigm focuses on selecting sustainable, eco-friendly materials, creating a sustainability evaluation system that covers multi-dimensional indicators, such as carbon emissions and economic benefits, and leveraging AI, especially generative AI, to explore innovative, efficient, and rapid structural designs. The aim is to achieve energy conservation, emission reduction, and cost savings. In response to the national “dual carbon” goals and call for promoting green building materials and low-carbon construction technologies, such as prefabricated steel and timber structures in the “Implementation Plan for Carbon Peaking in Urban and Rural Construction”, as well as seizing the opportunity of the “new infrastructure” initiative to drive the intelligent transformation of civil engineering, it is of great significance to deeply explore the collaborative innovation between green materials and AI technologies in structural design. The main research areas include: ① structural layout design of prefabricated (steel/ timber) structures based on generative AI; ② structural form optimization design using generative AI, graph neural networks, and topology algorithms; ③ detailed structural design guided by physical rules or dual-driven by physics and data; ④ component optimization design based on multi-agent reinforcement learning; ⑤ comprehensive structural design considering carbon emission control and multi-objective resilience; ⑥ sustainable structural design and evaluation considering the multi-dimensional factors, including carbon emissions, economy, and society, throughout the entire life cycle. Future development trends will focus on clarifying

the generative mechanisms of AI in green low-carbon structures, enhancing the physical explainability of AI algorithms, and establishing a scientific quantitative design evaluation system. By integrating reinforcement learning and optimization algorithms, the refinement of local structural design can be further enhanced, thereby minimizing carbon footprint. Ultimately, this will lead to the construction of an autonomous intelligent design system for green, low-carbon engineering structures, thereby providing technical support and theoretical guidance for the green and intelligent transformation of the construction industry. Between 2018 and 2023, 200 core papers related to this research topic were published. These papers received 7 300 citations, with an average of 36.50 citations per paper.

(10) Mechanisms and optimization of built environment health impacts in urban communities

The health impacts of built environments in urban communities refer to the short-term and cumulative health effects that various spatial elements at the community level exert on individuals throughout their lives. Both the United Nations and World Health Organization emphasize the role of urban planning in disease prevention. The “Healthy China” national strategy identifies healthy cities as a key initiative. The promotion of physical and mental health through urban planning is a cutting-edge scientific issue in the international academic community. Given that urban communities serve as the primary spatial context for residents’ daily activities, investigating the mechanisms and optimizing the health impacts of the built environment in these areas is crucial. It can contribute to the development of innovative approaches that enhance population well-being through upstream planning and design processes, as well as downstream environmental interventions. The primary research focuses on: ① theoretical models for spatial health interventions in urban communities, identifying easily modifiable indicators with significant impacts and their thresholds; ② key technologies for the precise diagnosis of health performance of urban community spaces, establishing an evaluation indicator system, and developing assessment tools; ③ efficient optimization methods to enhance the health performance of urban community spaces, and predicting and simulating the effects of interventions to support the selection of planning schemes. Future trends should emphasize the clarification of the full-path mediation mechanisms. Therefore, there is a need to develop cross-scale health diagnosis and evaluation technologies that span the macro to micro levels, along with multi-scene and multi-factor synergistic optimization methods. This will enable a full understanding of the upstream health intervention effects of urban planning and provide scientific evidence for evidence-based practices in promoting healthy urban community planning. A total of 195 core papers relevant to this research front were published between 2018 and 2023. These papers received 9 517 citations, with an average of 48.81 citations per paper.

6.1.2 Interpretations for three key engineering research fronts

6.1.2.1 Mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment

Under the combined influence of climate change and human activities, flood and drought disasters in river basins have shown new trends of increased intensity and frequency. Global warming and large-scale rain belt migration have affected human societal development. Increasingly frequent extreme events that result in flood and drought disasters in river basins carry high levels of uncertainty and unpredictability, posing significant challenges to global water, food, and ecological security. Meanwhile, the accelerated pace of socioeconomic development has further exacerbated the risk of flood and drought disasters. Examining the mechanisms of extreme flood and drought disasters and risk regulation in river basins in changing environments is of great importance for ensuring the stable development of human society. The main research directions are as follows:

1) Multi-source monitoring of flood and drought disasters and data assimilation based on the integration of space, sky, and ground single-observation technologies and models have significant uncertainties in the monitoring, simulation, and prediction of flood and drought disasters. By integrating multi-source data from space, sky, and ground, it is possible to build a three-dimensional observation system for hydrometeorological elements and obtain multi-scale hydrometeorological fusion data. Developing data assimilation methods suited to multi-modal hydrometeorological data will enable high-precision simulations and predictions of flood and drought disasters through the assimilation of hydrological or land surface models.

2) Identification and evolution mechanisms of extreme flood and drought events in river basins in changing environments. In response to the new circumstances of changing rainfall characteristics and land surface factors, intelligent recognition algorithms based on coupled mechanistic and machine learning models will be developed to identify extreme flood and drought events in river basins. These algorithms provide quantitative, refined, and multi-dimensional insights into the mechanisms of occurrence, developmental processes, and distribution characteristics of these events.

3) Threshold and tipping (explosion) point predictions for extreme flood and drought disasters in river basins. By integrating the complex feedback mechanisms of hydrometeorological and ecological processes and human development, this research will focus on the disaster-triggering mechanisms of flood and drought events in river basins and identify their disaster-causing thresholds. Furthermore, it will estimate the trends and potential abrupt changes in flood and drought disasters at different spatial and temporal scales under changing environments, predicting future frequencies, intensities, and tipping (explosion) points.

4) Risk assessment and regulation technologies for sudden disasters, such as flash floods, abrupt droughts, and rapid drought-to-flood transitions. To address the challenges of defining, characterizing, and quantifying sudden flood and drought disasters, research will focus on revealing their clustering mechanisms and disaster-causing effects and developing high-frequency dynamic risk identification and assessment technologies. These studies will examine planning and emergency regulation methods for short-duration extreme flood and drought disasters, focusing on disaster-prone areas and processes.

5) Risk assessment and regulation systems for flood disasters in large and medium-sized cities. Focusing on highly urbanized areas, in this study, risk assessments of rainstorm-induced flood disasters, triggered by typhoons, strong convective weather, and other extreme events, were conducted. This includes the development of multiple platforms, multi-model ensemble forecasting, and early warning methods. A collaborative defense strategy for urban floods based on “retention, storage, diversion, and drainage” will be proposed, establishing a comprehensive flood regulation system from early warning to post-disaster recovery.

Based on the above statistical data, in the research frontier of “mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment”, Chinese scholars have a certain advantage when compared to their international counterparts and are gradually advancing to a leading position.

As shown in Table 6.1, a total of 151 core papers regarding “mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment” were published, with each paper being cited 47.92 times on average. The top five countries in terms of core papers were China, the USA, the UK, Australia, and Germany (Table 6.3). China is one of the most active countries, accounting for 52.32% of core papers. The five countries with the highest citations per paper were Brazil, Australia, the UK, the USA, and Pakistan. Papers published by Chinese authors were cited 45.75 times on average, which is slightly below the overall average. As illustrated by the international collaborative network depicted in Figure 6.1, close cooperation was observed among the ten most productive countries.

The five institutions that published the most core papers were Chinese Academy of Sciences, Wuhan University, Tsinghua University, Hohai University, and Nanjing University (Table 6.4). The Chinese Academy of Sciences mainly studies changes in glaciers and their hydrological impacts in the Himalaya and Karakoram regions; groundwater, precipitation, floods, and drought assessment and prediction in the river basins of China and Pakistan; the impact of climate change on water resources and agricultural water resource management; and the role of reservoirs in regulating flood and drought risks. Wuhan University has mainly examined the impacts of climate change on the hydrological cycle, water resources, drought and flood disasters, and hydropower generation in the Yangtze River Basin, as well as how to use remote sensing data and hydrological models to assess and predict these impacts. Tsinghua University mainly examines real-time reservoir operation using recurrent neural networks and distributed hydrological models; the impact of climate change on the yield and water footprint of major crops in Thailand; the spatiotemporal characteristics and causes of wet and dry conditions in the Weihe River Basin, a typical monsoon transition zone in East Asia; and changes in future river annual runoff and hydroclimatic extremes. As illustrated in Figure 6.2, the ten most productive institutions have conducted collaborative studies in this regard.

As listed in Table 6.5, the five most active countries in terms of citing papers were China, the USA, India, the UK, and Brazil. The top

five institutions in terms of citing papers were Chinese Academy of Sciences, Wuhan University, Hohai University, Beijing Normal University, and Nanjing University of Information Science and Technology (Table 6.6).

Based on the statistical data above, research on "mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment" is still in its infancy. Compared with their foreign counterparts, Chinese scholars are in a leading position.

In the next decade, the key development directions of this frontier will be to clarify the nonlinear driving response mechanisms between changing environments and flood and drought disasters in river basins, develop forecasting and prediction technologies based on the coupling of AI and mechanistic models, and enhance risk identification and systematic regulation of extreme flood and drought disasters in river basins. Simultaneously, this frontier will trend towards multi-dimensional, refined, systematic, and intelligent development. As extreme flood and drought disasters in river basins become more frequent in changing environments, human society's exposure and vulnerability to such risks will also increase. The research outcomes from this frontier can be widely applied to ensure water security and public safety, demonstrating great potential for growth (Figure 6.3).

Table 6.3 Countries with the greatest output of core papers on "mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	79	52.32	3 614	45.75	2021.1
2	USA	28	18.54	1 785	63.75	2020.4
3	UK	16	10.60	1 030	64.38	2020.5
4	Australia	11	7.28	743	67.55	2020.0
5	Germany	11	7.28	512	46.55	2021.4
6	India	11	7.28	361	32.82	2020.7
7	Brazil	8	5.30	579	72.38	2020.1
8	Pakistan	8	5.30	456	57.00	2020.9
9	Netherlands	8	5.30	426	53.25	2020.5
10	Republic of Korea	8	5.30	302	37.75	2021.6

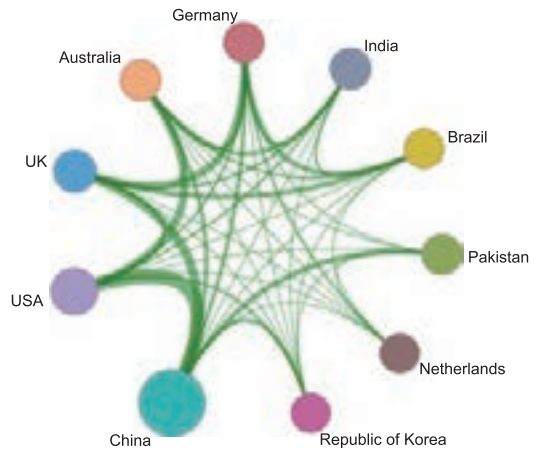


Figure 6.1 Collaboration network among major countries in the engineering research front of "mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment"

Table 6.4 Institutions with the greatest output of core papers on "mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	23	15.23	1 051	45.70	2021.1
2	Wuhan University	11	7.28	419	38.09	2020.5
3	Tsinghua University	8	5.30	368	46.00	2021.8
4	Hohai University	8	5.30	241	30.12	2021.4
5	Nanjing University	6	3.97	352	58.67	2020.5
6	Beijing Normal University	6	3.97	242	40.33	2020.8
7	Xi'an University of Technology	4	2.65	356	89.00	2020.0
8	China Meteorological Administration	4	2.65	169	42.25	2021.2
9	China Institute of Water Resources and Hydropower Research	4	2.65	155	38.75	2021.5
10	ETH Zurich	4	2.65	150	37.50	2021.2

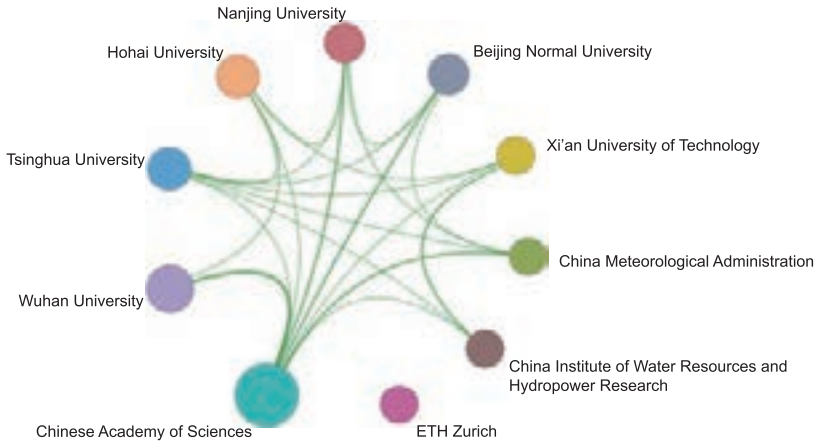


Figure 6.2 Collaboration network among major institutions in the engineering research front of "mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment"

Table 6.5 Countries with the greatest output of citing papers on "mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	2 919	40.35	2022.1
2	USA	1 101	15.22	2022.0
3	India	672	9.29	2022.3
4	UK	393	5.43	2021.8
5	Brazil	372	5.14	2021.9
6	Australia	367	5.07	2021.9
7	Germany	354	4.89	2022.1
8	Iran	337	4.66	2022.0
9	Pakistan	257	3.55	2022.3
10	Canada	243	3.36	2022.0

Table 6.6 Institutions with the greatest output of citing papers on "mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	741	34.35	2022.1
2	Wuhan University	242	11.22	2022.1
3	Hohai University	236	10.94	2022.1
4	Beijing Normal University	187	8.67	2022.1
5	Nanjing University of Information Science and Technology	150	6.95	2022.2
6	China Institute of Water Resources and Hydropower Research	133	6.17	2021.7
7	China University of Geosciences	109	5.05	2022.3
8	Tsinghua University	105	4.87	2022.2
9	Sun Yat-sen University	90	4.17	2022.2
10	Xi'an University of Technology	84	3.89	2021.2

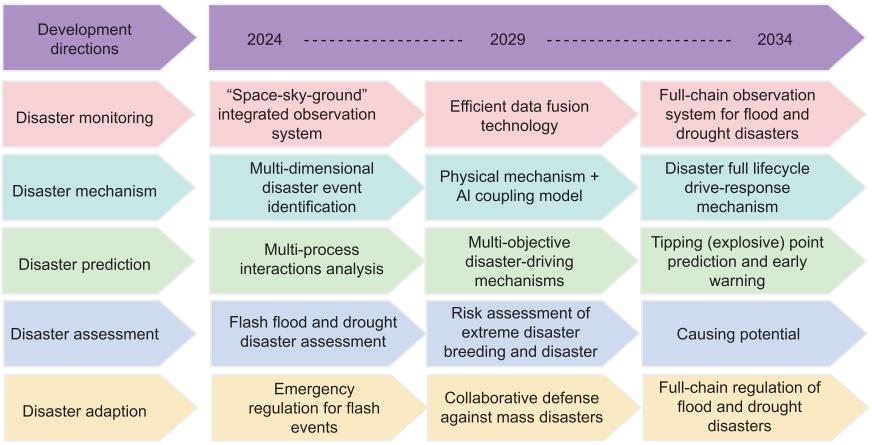


Figure 6.3 Roadmap of the engineering research front of "mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment"

6.1.2.2 Urban planning and architectural design methods empowered by large models

The core of the large model-enabled urban planning and architectural design method lies in: ① realizing the digital construction of planning and architectural design methods through multi-modal knowledge enhancement, forming a disciplinary holographic knowledge map, and realizing the analysis and identification of complex theoretical mechanisms; ② provide full-process support for the three key design steps of research, generation, and evaluation through large models. Through the exploration of the aforementioned two dimensions, we can train the design model of "analytic, computable, inferential, and evolvable", change the design paradigm dominated by personal subjective experience, and realize the intelligentization of the entire process of planning and architectural design. Frontier research directions are mainly reflected in the following aspects.

1) Construction of holographic knowledge map of disciplines: The traditional discipline of cognitive systems, based on personal experience and text knowledge map construction, is fragmented and one-sided, and the theoretical mechanism construction of planning and architecture is still lacking. Simultaneously, as an important part of the theoretical knowledge of urban planning and architectural design, it is difficult to analyze and identify complex multi-modal information and

theoretical mechanisms using traditional methods. This research uses the multi-modal data fusion technology of graphs and texts in a large model to integrate data from different sources and formats, construct a subject holographic knowledge map with full-aperture knowledge, and form a comprehensive analysis and understanding of the previous "divergent" urban planning and architectural design theories. This can effectively promote the digital description and knowledge fusion of the current fragmented multi-modal knowledge of the subject.

2) Intelligent present status judgment: The traditional study of the status quo of cities and buildings has the problems of "unclear characteristics" and "difficult to judge". Based on knowledge traction and data-driven large-scale model training, it can not only efficiently integrate various material physical elements, such as spatial form, functional composition, architectural texture, and non-material economic and social effects, but also realize the analysis of the status quo feature recognition, refine the evaluation dimensions that meet the needs of the site, establish an evaluation and judgment system that spans large- (urban planning), medium- (urban design), and small-scale (architectural design), and quantitatively evaluate the multi-scale status quo elements, including urban morphological characteristics, block vitality, and architectural style. With the support of massive data, intelligent research, judgment of experts, and multiple dimensions can be realized. Finally, it promotes the transformation of the status quo from a discussion of qualitative experiences to quantitative intelligent judgments.

3) Generative planning and design: The problem of a large model generating image architectural design and urban planning schemes often lies in its insufficient grasp of the spatial scale. To address this problem, based on the image generated by a large model, in this study, a strategy recommendation model is developed according to different scales, clusters, and functions, and explores its generative design method. Based on the external chain of knowledge graphs and research results on intelligent status, generative design is promoted for application in demonstration projects. However, owing to its high text-generation efficiency, a large model can efficiently generate professional text after fine-tuning and manual instructions, thus opening the full link between text generation and image generation to serve generative planning and design.

4) Efficiency evaluation of digital intelligent design: Based on the professional backgrounds of architectural disciplines, the big model can be used to construct multi-scale efficiency measurement models and accurate diagnostic methods for cities, blocks, and buildings in view of the difficulties in planning and design. Under the guidance of a multi-modal knowledge graph, knowledge embedding is performed, and pre-training large-scale model tuning is realized with the support of proprietary datasets. Through the dual-drive training of knowledge and data, the specialized design efficiency of large-scale models is examined and judged. This solves the problem of long time consumption and low reliability of traditional scheme evaluation and realizes the rapid processing of complex information. Simultaneously, the evaluation paradigm dominated by experience is changed to improve the scientificity of the scheme's evaluation results.

As shown in Table 6.1, a total of 169 core papers on "urban planning and architectural design methods empowered by large models" were published, with each paper being cited 51.30 times on average. The top five countries in terms of core papers were China, the USA, the UK, Australia, and the Republic of Korea (Table 6.7). China is one of the most active countries, accounting for 34.91% of core papers. The five countries with the highest citations per paper were Canada, Singapore, Australia, the UK, and France. Papers published by Chinese authors were cited 47.85 times on average, which is slightly below the overall average. As illustrated by the international collaborative network depicted in Figure 6.4, close cooperation was observed among the ten most productive countries.

The five institutions that published the most core papers were the National University of Singapore, Wuhan University, Harbin Institute of Technology, the University of Hong Kong, and Chinese Academy of Sciences (Table 6.8). The National University of Singapore primarily examines the use of machine learning and AI technology to analyze urban spatial data to optimize urban planning, environmental monitoring, and architectural design. Wuhan University is also focusing on new technologies and methods for urban land change simulation, PM2.5, architectural heritage recognition, shear wall structure design, assessment of nonstationary extreme precipitation, medical image segmentation, urban vitality analysis, rice phenology detection, and driver fatigue detection. Harbin Institute of Technology primarily researches the use of AI and machine learning technology to improve data analysis, design optimization, environmental assessment, and health

monitoring in the fields of urban and civil engineering. As illustrated in Figure 6.5, the ten most productive institutions have conducted collaborative studies in this regard.

As shown in Table 6.9, the five most active countries in terms of citing papers were China, the USA, India, the UK, and Germany. The top five institutions in terms of citing papers were Chinese Academy of Sciences, Tsinghua University, Tongji University, Wuhan University, and National University of Singapore (Table 6.10).

Summarizing the above statistics, Chinese scholars have performed well and have become leaders in research on "urban planning and architectural design methods empowered by large models".

The key development directions of urban planning and architectural design methods enabled by large models over the next ten years are as follows (Figure 6.6):

Table 6.7 Countries with the greatest output of core papers on "urban planning and architectural design methods empowered by large models"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	59	34.91	2 823	47.85	2021.7
2	USA	42	24.85	2 124	50.57	2021.3
3	UK	14	8.28	858	61.29	2021.3
4	Australia	13	7.69	802	61.69	2021.5
5	Republic of Korea	10	5.92	317	31.70	2022.2
6	Singapore	9	5.33	691	76.78	2021.2
7	Germany	9	5.33	319	35.44	2021.6
8	France	8	4.73	428	53.50	2020.0
9	India	7	4.14	313	44.71	2022.0
10	Canada	6	3.55	646	107.67	2021.0

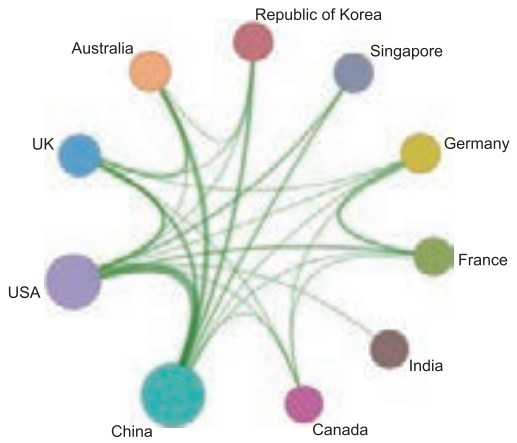


Figure 6.4 Collaboration network among major countries in the engineering research front of "urban planning and architectural design methods empowered by large models"

Table 6.8 Institutions with the greatest output of core papers on "urban planning and architectural design methods empowered by large models"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	National University of Singapore	7	4.14	509	72.71	2021.6
2	Wuhan University	5	2.96	265	53.00	2021.2
3	Harbin Institute of Technology	5	2.96	175	35.00	2021.4
4	The University of Hong Kong	5	2.96	111	22.20	2022.0
5	Chinese Academy of Sciences	4	2.37	239	59.75	2021.2
6	Guangzhou University	4	2.37	176	44.00	2020.2
7	Massachusetts Institute of Technology	4	2.37	126	31.50	2021.0
8	Tsinghua University	4	2.37	104	26.00	2022.5
9	University of Oxford	3	1.78	514	171.33	2020.3
10	ETH Zurich	3	1.78	498	166.00	2021.3

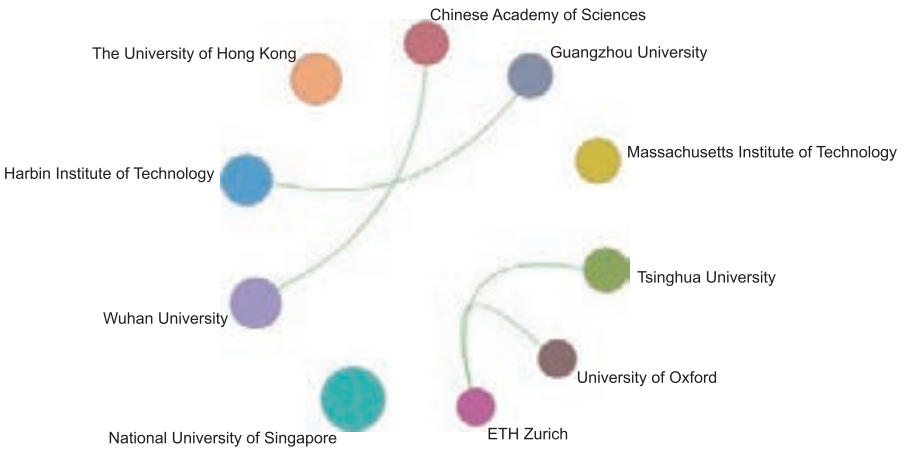


Figure 6.5 Collaboration network among major institutions in the engineering research front of "urban planning and architectural design methods empowered by large models"

Table 6.9 Countries with the greatest output of citing papers on "urban planning and architectural design methods empowered by large models"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	3 322	39.84	2022.4
2	USA	1 424	17.08	2017.2
3	India	644	7.72	2022.4
4	UK	613	7.35	2010.4
5	Germany	425	5.10	2022.2
6	Australia	373	4.47	2022.3
7	Canada	329	3.95	2022.2
8	Italy	327	3.92	2022.3
9	Republic of Korea	324	3.89	2022.4
10	Saudi Arabia	312	3.74	2022.4

Table 6.10 Institutions with the greatest output of citing papers on "urban planning and architectural design methods empowered by large models"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	250	19.81	2022.4
2	Tsinghua University	169	13.39	2022.4
3	Tongji University	128	10.14	2022.4
4	Wuhan University	125	9.90	2022.3
5	National University of Singapore	115	9.11	2022.3
6	Southeast University	86	6.81	2022.4
7	Zhejiang University	82	6.50	2022.6
8	Massachusetts Institute of Technology	77	6.10	2022.4
9	Stanford University	77	6.10	2022.2
10	The Hong Kong Polytechnic University	77	6.10	2022.7

1) Construction of a discipline holographic knowledge map: A large amount of interdisciplinary knowledge in the fields of architectural design and urban planning should be integrated, and the emergence of large models makes the construction of knowledge maps more efficient and qualitative. Collect multi-modal resources, such as discipline-related policies, papers, books, data, and videos, use the method of large models to enable multi-modal knowledge graph fusion and perform tuning through expert dialogue to construct an addictive, interdisciplinary, and multi-modal holographic knowledge graph in the field.

2) Intelligent present status judgment: In the current research and judgment stage, with the aid of large models, intelligent data capture is conducted to quickly read the characteristics of the population, space, culture, and other aspects; generate refined multi-dimensional portraits; and realize intelligent research and judgment from a single dimension to multi dimensions. The large model is used to further refine and summarize the phased conclusions and research results and professionally empower intelligent platform development and project demonstration.

3) Generative planning and design: The problem of a large model generating image architectural design and urban planning schemes often lies in its insufficient grasp of the spatial scale. To address this problem, based on the image generated by a large model, this study constructs a strategy recommendation model according to different scales, clusters, and functions and explores its generative design method. Based on the external chain of knowledge graphs and research results on intelligent status, generative design is promoted for application in demonstration projects. However, owing to its high text-generation efficiency, a large model can generate professional text efficiently after fine-tuning and manual instructions, thus opening up the full link between text generation and image generation to serve generative planning and design.

4) Efficiency evaluation of digital intelligent design: Intelligent planning and design scheme evaluation can overcome the problem of the difficult handling of huge amounts of data owing to time and manpower in the past, and expert experience is easily limited by subjective preferences or inherent thinking. Based on a comprehensive perception of multi-modal knowledge graphs, we can make more accurate and appropriate judgments and responses to current urban planning and design schemes, form an evaluation paradigm from single to comprehensive efficiency, and guide the refined and scientific development of urban design.

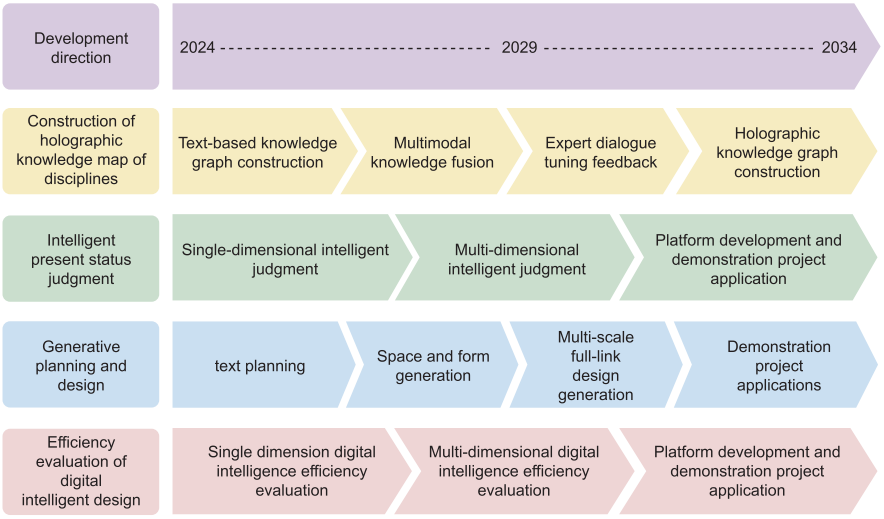


Figure 6.6 Roadmap of the engineering research front of "urban planning and architectural design methods empowered by large models"

6.1.2.3 Intelligent operation and safety assurance of new energy transportation systems

Efficient operating technologies and safety assurance systems for new energy transportation systems are crucial for the integrated development of transportation and energy. Existing research lacks systematic demand modeling and forecasting for multiple energy sources and transportation modes, making it difficult to accurately respond to dynamic changes. Current operational services primarily focus on efficiency optimization, neglecting multi-objective issues, such as energy consumption, efficiency, and carbon emissions across various transportation modes. This leads to low levels of intelligent emergency assurance for infrastructure, resulting in insufficient flexibility and efficiency in responding to complex transportation-energy coupling scenarios. It is essential to explore the multiple attributes of new transportation infrastructure sources, grids, loads, and storage, and develop digital and intelligent methods to transition the new energy transportation system from inefficient to efficient and from high-carbon to low-carbon systems. The main research topics were as follows:

1) Forecasting heterogeneous transportation demand and multi-type clean energy supply: Develop a multi-dimensional parameter perception system focused on the characteristics of new energy transportation activities and energy use, and propose a high-precision model structure that integrates transportation activity trajectories, energy consumption behaviors, and spatiotemporal environments to achieve accurate spatiotemporal parameter extraction for transportation activities and energy use. Furthermore, we established a forecasting methodology for short- and long-term energy demands applicable to heterogeneous transportation energy scenarios, predicting the energy demand characteristics of transportation activities in conjunction with different transportation modes, energy types, geographic features, and consumption behaviors. Furthermore, we established forecasting models for clean energy supply from various sources, including solar, wind, and geothermal, responsive to geographic conditions and energy network operations, to comprehensively enhance the supply-demand matching efficiency and flexibility of the new energy transportation system.

2) Multi-objective scheduling for green smart mobility systems: Construct a dynamic scheduling and control model for vehicles in multi-modal mobility systems, including new energy buses, shared electric vehicles, and electric ride-hailing services. Given the volatility of new energy outputs, such as grid load, wind, and solar power, as well as the heterogeneity and randomness of travel demand, the objective is to optimize travel efficiency, operational costs, energy consumption, carbon emissions, and fluctuations in grid load. Develop large-scale network human-vehicle-road-pile matching and planning algorithms based on AI to optimize fleet size, vehicle types, speeds, scheduling, routes, charging/discharging combinations, and real-time vehicle dispatching.

3) Energy "source-grid-storage" coupling technology responsive to transportation demand: Rationally layout and optimize the

energy infrastructure network of the new energy transportation system and establish a comprehensive management control architecture covering energy collection, distribution, storage, and usage. Construct interactive mechanisms and models for transportation and energy systems considering the spatiotemporal variation characteristics of both environments. Based on this, an efficient dynamic collaboration of the energy source–grid load storage system can be realized through adaptive regulation. This in turn can enhance the energy utilization efficiency of new energy transportation systems under changing conditions and realize real-time coupling configurations between the energy supply and transportation demand.

4) Operation and maintenance of new energy infrastructure and emergency safety assurance technologies: New energy infrastructure (charging facilities, hydrogen refueling stations, storage devices, new energy vehicles, etc.) is characterized by high stock, large increments, high risks, and difficult maintenance. Key technologies for the evolution and early warning of new energy transportation infrastructure conditions and maintaining and enhancing facility performance and addressing rapid responses to failures in transportation operations. This overcomes technical bottlenecks in resource scheduling for repairs and intelligent rescue equipment; forms a repair and rescue technology system for incident prevention, response, and recovery; enhances the safety assurance and resilience recovery capabilities of the new energy transportation system; and achieves integrated operational requirements for autonomous monitoring, analysis, early warning, and response.

As shown in Table 6.1, a total of 335 core papers regarding “intelligent operation and safety assurance of new energy transportation systems” were published, with each paper being cited 65.01 times on average. The top five countries in terms of core papers were China, the USA, the UK, Canada, and India (Table 6.11). China is one of the most active countries, accounting for 44.48% of core papers. The five countries with the highest citations per paper were Germany, the UK, China, Italy, and the USA. Papers published by Chinese authors were cited 74.13 times on average, which is above the overall average. As illustrated by the international collaborative network depicted in Figure 6.7, close cooperation is observed among the ten most productive countries.

The five institutions that published the most core papers were Tsinghua University, Chinese Academy of Sciences, Zhejiang University, Harbin Institute of Technology, and Beijing Jiaotong University (Table 6.12). Tsinghua University mainly examines the traffic flow of autonomous vehicles, service pricing, and charging scheduling for electric vehicle-sharing systems and plug-in hybrid electric city buses. Chinese Academy of Sciences mainly studies new developments and applications of intelligent transportation systems, low-temperature lithium-ion battery electrolytes, ammonia energy storage, and triboelectric nanogenerators. Zhejiang University mainly researches technological innovation and environmental benefit analysis in multiple fields, such as intelligent transportation systems, energy efficiency, electric vehicles, environmental monitoring, new materials, and urban carbon cycles. As illustrated in Figure 6.8, the ten most productive institutions have conducted collaborative studies in this regard.

As listed in Table 6.13, the five most active countries in terms of citing papers were China, the USA, India, the UK, and Australia. The top five institutions in terms of citing papers were Chinese Academy of Sciences, Tsinghua University, Zhejiang University, Wuhan University, and Shanghai Jiao Tong University (Table 6.14).

Summarizing the above statistics, Chinese scholars have performed well and have become leaders in the research on “intelligent operation and safety assurance of new energy transportation systems”.

In the next 10 years, key development directions in this frontier will include intelligent demand forecasting and scheduling optimization algorithms for new energy transportation systems, optimization and decision-making systems for energy management, and the development of safety assurance equipment for energy infrastructure. Specifically, in terms of intelligent algorithms, this includes multi-modal transportation demand forecasting, cross-energy-type transportation energy consumption forecasting, and real-time scheduling for large-scale network vehicles and energy. In system development, the goal is adaptive regulation of transportation-energy systems, optimizing energy supply in multiple transportation scenarios, and equipment R&D, focusing on the needs for autonomous monitoring, analysis, early warning, and response of new energy transportation infrastructure, and developing emergency assurance equipment for rapid repair and recovery (Figure 6.9).

Table 6.11 Countries with the greatest output of core papers on “intelligent operation and safety assurance of new energy transportation systems”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	149	44.48	11 046	74.13	2020.8
2	USA	66	19.70	4 732	71.70	2020.3
3	UK	27	8.06	2 010	74.44	2020.5
4	Canada	19	5.67	1 017	53.53	2020.7
5	India	16	4.78	1 012	63.25	2021.4
6	Germany	15	4.48	1 297	86.47	2020.0
7	Italy	15	4.48	1 104	73.60	2020.3
8	Australia	15	4.48	872	58.13	2020.5
9	France	13	3.88	543	41.77	2019.9
10	Iran	12	3.58	642	53.50	2020.3

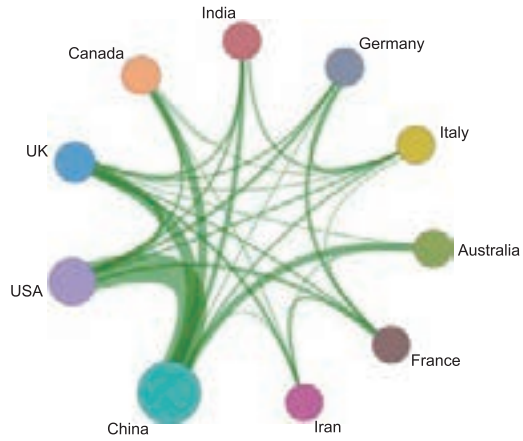


Figure 6.7 Collaboration network among major countries in the engineering research front of “intelligent operation and safety assurance of new energy transportation systems”

Table 6.12 Institutions with the greatest output of core papers on “intelligent operation and safety assurance of new energy transportation systems”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Tsinghua University	9	2.69	946	105.11	2020.4
2	Chinese Academy of Sciences	9	2.69	789	87.67	2020.9
3	Zhejiang University	7	2.09	356	50.86	2021.1
4	Harbin Institute of Technology	6	1.79	541	90.17	2020.3
5	Beijing Jiaotong University	6	1.79	343	57.17	2021.5
6	Shandong University	6	1.79	244	40.67	2021.5
7	South China University of Technology	5	1.49	380	76.00	2019.2
8	Chongqing University	5	1.49	375	75.00	2021.0
9	Southwest Jiaotong University	5	1.49	339	67.80	2020.2
10	The University of New South Wales	5	1.49	215	43.00	2020.8

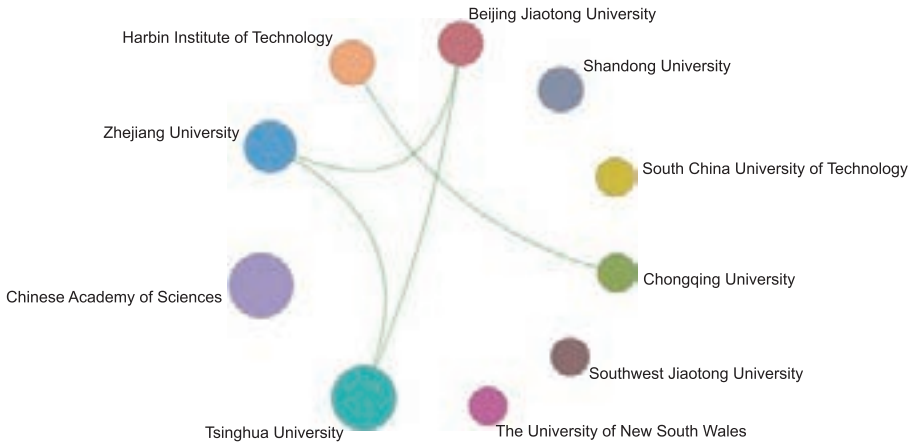


Figure 6.8 Collaboration network among major institutions in the engineering research front of "intelligent operation and safety assurance of new energy transportation systems"

Table 6.13 Countries with the greatest output of citing papers on "intelligent operation and safety assurance of new energy transportation systems"

no.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	10 313	48.43	2022.1
2	USA	2 660	12.49	2021.9
3	India	1 531	7.19	2022.2
4	UK	1 347	6.33	2021.9
5	Australia	880	4.13	2021.9
6	Germany	876	4.11	2021.8
7	Republic of Korea	834	3.92	2022.1
8	Canada	774	3.63	2021.9
9	Saudi Arabia	757	3.55	2022.3
10	Italy	697	3.27	2022.0

Table 6.14 Institutions with the greatest output of citing papers on "intelligent operation and safety assurance of new energy transportation systems"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	785	24.61	2022.1
2	Tsinghua University	470	14.73	2022.0
3	Zhejiang University	260	8.15	2022.1
4	Wuhan University	245	7.68	2022.2
5	Shanghai Jiao Tong University	238	7.46	2022.2
6	Chongqing University	210	6.58	2021.9
7	Xi'an Jiaotong University	206	6.46	2021.9
8	Harbin Institute of Technology	199	6.24	2021.7
9	The Hong Kong Polytechnic University	197	6.18	2022.2
10	South China University of Technology	195	6.11	2021.8

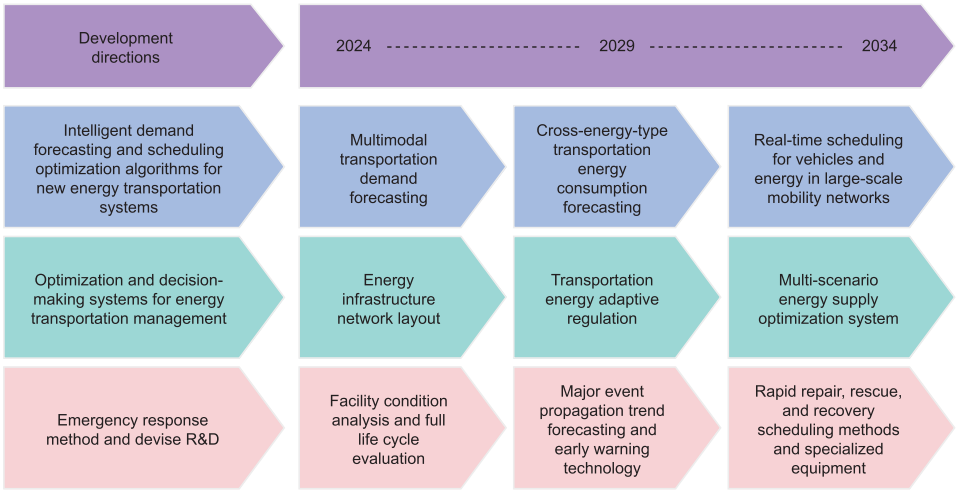


Figure 6.9 Roadmap of the engineering research front of "intelligent operation and safety assurance of new energy transportation systems"

6.2 Engineering development fronts

6.2.1 Trends in the Top 10 engineering development fronts

The Top 10 engineering development fronts in the fields of civil, hydraulic, and architectural engineering are summarized in Table 6.15. These fronts cover various disciplines, including geotechnical and underground engineering, hydraulic engineering, architectural design and theory, surveying and mapping engineering, construction materials, transportation planning, urban planning and landscaping, municipal engineering, and bridge engineering. The following development fronts were from expert nomination: "intelligent simulation and resilience enhancement technology for urban drainage systems", "large scale 3D real scene modeling and dynamic updating", "intelligent coordination and safety assurance of low-altitude and ground transportation systems", "carbon reduction techniques for planning infrastructure renewal in urban areas", and "intelligent construction and maintenance of infrastructure under extreme climatic conditions". The remaining fronts were identified from patent maps and confirmed in expert panel meetings. Table 6.16 presents the annual statistics on patents registered between 2018 and 2023 related to the top ten development fronts.

(1) Intelligent scheduling technology and equipment for hydro-wind-photovoltaic-storage hybrid system

Basin-scale hydro-wind-photovoltaic (PV)-storage complementary systems rely on large hydropower bases. It fully utilizes the flexible regulation capabilities of cascade hydropower and energy storage facilities and develops wind and PV power generation projects, achieving integrated resource allocation, coordinated operation, and centralized consumption of renewable energy. Intelligent scheduling technology and equipment for hydro-wind-PV-storage complementarity aim to comprehensively utilize new-generation information technologies such as AI, big data, and the Internet of Things to perform intelligent analysis and decision-making for resource forecasting, complementary scheduling, real-time operation, and market transactions in multi-energy complementary systems. Through intelligent equipment, the scheduling process of clean energy bases is precisely controlled and efficiently managed to improve the comprehensive power generation efficiency, control safety operation risks, and enhance the level of intelligent management of the system. However, in the context of the explosive development of new energy, the hydro-wind–PV–storage complementary system faces a series of new challenges, such as difficulties in balancing power supply and demand, severe curtailment of new energy, and increased risks of safe operation. Traditional scheduling, operation technologies, and equipment can no longer satisfy the new requirements of multi-energy complementary systems. The main technical directions

Table 6.15 Top 10 engineering development fronts in civil, hydraulic, and architectural engineering

No.	Engineering development front	Core papers	Citations	Citations per paper	Mean year
1	Intelligent scheduling technology and equipment for hydro-wind-photovoltaic-storage hybrid system	64	1 778	27.78	2021.3
2	Intelligent simulation and resilience enhancement technology for urban drainage systems	229	1 176	5.14	2021.3
3	Large scale 3D real scene modeling and dynamic updating	87	468	5.38	2021.8
4	Intelligent coordination and safety assurance of low-altitude and ground transportation systems	204	4 611	22.60	2021.3
5	Carbon reduction techniques for planning infrastructure renewal in urban areas	108	2 360	21.85	2021.5
6	Structure-function integrated technology of organic composite materials in complex environments	116	319	2.75	2020.8
7	Intelligent construction and maintenance of infrastructure under extreme climatic conditions	134	515	3.84	2021.8
8	Low-cost building-integrated photovoltaic system and implementation technology	48	32	0.67	2021.4
9	Modular building structural system and its intelligent construction	45	119	2.64	2021.2
10	Autonomous unmanned system localization and mapping technology	23	66	2.87	2021.7

Table 6.16 Annual number of core patents published for the Top 10 engineering development fronts in civil, hydraulic, and architectural engineering

No.	Engineering development front	2018	2019	2020	2021	2022	2023
1	Intelligent scheduling technology and equipment for hydro-wind-photovoltaic-storage hybrid system	7	4	5	9	23	16
2	Intelligent simulation and resilience enhancement technology for urban drainage systems	15	15	28	49	65	57
3	Large scale 3D real scene modeling and dynamic updating	0	6	8	15	28	30
4	Intelligent coordination and safety assurance of low-altitude and ground transportation systems	17	22	24	31	41	69
5	Carbon reduction techniques for planning infrastructure renewal in urban areas	0	12	18	13	31	34
6	Structure-function integrated technology of organic composite materials in complex environments	15	16	19	22	17	27
7	Intelligent construction and maintenance of infrastructure under extreme climatic conditions	6	7	7	21	44	49
8	Low-cost building-integrated photovoltaic system and implementation technology	4	4	2	10	15	13
9	Modular building structural system and its intelligent construction	2	8	4	9	8	14
10	Autonomous unmanned system localization and mapping technology	0	3	2	2	7	9

include: ① high-precision integrated simulation and forecasting technology for hydro-wind-PV resources; ② multi-scale intelligent scheduling technology for basin hydro-wind-PV-storage complementarity; ③ real-time operation control technology for basin hydro-wind-PV-storage complementarity; ④ indigenous intelligent equipment for the operation and control of basin hydro-wind-PV-storage hybrid system; ⑤ bidding decision-making techniques for basin hydro-wind-PV-storage under the electricity market

environment; ⑥ new operation management modes and technical standards for hydro-wind-PV-storage integration. As the construction scale, number, and scope of multi-energy complementary bases continue to expand, the scheduling and operation of the system will transform from the current experience-driven planned scheduling to data-driven intelligent scheduling, forming a new management model and technical standards for hydro-wind-PV-storage complementary scheduling. This will comprehensively enhance the system's forecasting, decision-making, control, and management capabilities as well as the level of intelligence, promoting the development of integrated renewable energy in river basins. Between 2018 and 2023, 64 patents relevant to this research front were identified. These patents received 1 778 citations with an average of 27.78 citations per patent.

(2) Intelligent simulation and resilience enhancement technology for urban drainage systems

Urban drainage systems are essential for managing stormwater and wastewater, including the collection, conveyance, treatment, and reuse processes. The development of resilient and secure systems is vital for public health and social stability. By harnessing advanced technologies, such as AI, big data, and sophisticated modeling, we can enhance the resilience and intelligence of these systems across their entire lifecycle. These technologies enable the dynamic simulation and optimization of operations, risk management, and environmental impacts. Real-time intervention through control devices improves monitoring, fault diagnosis, process control, and pollution prevention, thereby bolstering the capacity of the system to handle extreme weather and unexpected events. Key development areas include: ① Advanced Monitoring and Warning Systems, implement intelligent systems for real-time monitoring and dynamic alerts at critical nodes; ② Simulation and Control Platforms, develop platforms for optimized simulation, decision support, and smart control to ensure safe operations; ③ Pollution Prevention and Adaptive Strategies, create adaptive scheduling and overflow pollution control measures; ④ Digital Resilience Planning, focus on digital planning, construction, and evaluation of resilient infrastructure. The future of technological development lies in designing adaptable models for extreme climatic conditions and the complexities of urban environments. This includes establishing intelligent networks for monitoring and data transmission, implementing adaptive controls for essential components such as drainage networks and pump stations, and creating integrated management and decision support systems to enhance preventive maintenance and rapid recovery capabilities. Between 2018 and 2023, 229 patents relevant to the research front were registered. These patents received 1 176 citations, with an average of 5.14 citations per patent.

(3) Large scale 3D real scene modeling and dynamic updating

3D real scene is an irreplaceable new type of national infrastructure that reflects and expresses spatiotemporal information on production, life, and ecological space in a realistic, three-dimensional, and temporal manner. In recent years, under the background that the country continues to build a 3D realistic geospatial scene, large-scale 3D real scene modeling and dynamic updating technology have become the forefront of development in this field. Development trends in this research front include: ① large-scale 3D real scene modeling, including geographic scene acquisition and fusion technology, IoT perception data access and fusion technology for real-world 3D, geographic entity semantic modeling technology, etc.; ② 3D real scene database management and dynamic updates, including basic geographic entity and geographic scene adaptation technology, 3D real scene data scale correlation and linkage maintenance technology, quality control technology for basic geographic entity results, etc.; ③ application services, including 3D real scene data interface and service publishing technology, lightweight processing technology for 3D real scene data, security service processing technology for 3D real scene data, etc. Future development trends include automation of large-scale 3D real scene modeling, intelligence updating of 3D real scene dynamics, and smart services of 3D real scenes. Eighty seven patents relevant to this research front were registered between 2018 and 2023. These patents received 468 citations, with an average of 5.38 citations per patent.

(4) Intelligent coordination and safety assurance of low-altitude and ground transportation systems

The low-altitude and ground transportation system refers to an integrated air-ground traffic network within low-altitude airspace and ground road networks, where manned aircraft, unmanned aerial vehicles (UAVs), and ground vehicles operate together. Compared with medium- and high-altitude airspaces, low-altitude airspaces have limited resources, diverse operational scenarios,

high traffic density, strong platform heterogeneity, and complex electromagnetic, magnetic, and wind environments. Their strong coupling with ground transportation systems adds further complexity, making the operation of low-altitude and ground transportation systems highly complex, with severe safety challenges. Research on intelligent coordination of low-altitude and ground transportation systems is of great significance for ensuring traffic safety and promoting the development of low-altitude economies. The main research directions include: ① integrated air-space-ground intelligent sensing of the operational situation and multitarget collaborative monitoring of air–ground transportation system; ② ultra-real-time simulation and risk reduction of digital twins in air–ground transportation system; ③ proactive collision avoidance and coordinated operation among manned aircraft, UAVs, and ground vehicles; ④ intelligent decision-making and risk control in air–ground transportation system management based on digital twin technology. Future development trends focus on achieving precise sensing and risk deduction for multitarget collaborative operations in low-altitude and ground transportation systems, optimizing system safety, and developing prevention strategies through digital twin technology. On this basis, integrating multi-source air-space-ground information will enable dynamic prediction and proactive risk prevention for air-ground transportation system operations, promote intelligent and automated airspace management, accelerate the construction of emergency response systems, and build an intelligent and collaborative safety management system for air-ground transportation. Between 2018 and 2023, 204 patents relevant to the research front were registered. These patents received 4 611 citations, with an average of 22.60 citations per patent.

(5) Carbon reduction techniques for planning infrastructure renewal in urban areas

Infrastructure planning and carbon reduction technology refers to technology that achieves the carbon emission reduction target throughout the entire life cycle of infrastructure, from planning and construction to operation and maintenance, through rational spatial layout, active policy guidance, and fine management. Unlike engineering techniques, planning carbon reduction techniques consider carbon emission reduction from a strategic and global perspective, focusing more on the carbon emissions of the entire life cycle of infrastructure. The implementation methods favor the adjustment of the spatial layout of various types of facilities as well as the formulation of various policies and indicators. Infrastructure, which is the backbone of urban operations, plays a crucial role in maintaining urban functions. In recent years, many energy consumption and carbon emission problems in the system operation and planning and construction of infrastructure exist, and it is of great significance to study the planning and carbon reduction technologies for the renewal of existing infrastructure in the context of “dual-carbon” and sustainable development goals. Currently, the main technical directions of this technology include: ① the entire life cycle carbon footprint assessment of infrastructure; ② the spatial layout and regulation control optimization of distributed integrated energy peaking facilities; ③ the scale, utilization, and spatial layout of renewable energy sources, such as solar energy, wind power generation, and ground-source heat pumps; ④ the optimization of recycling and management systems for solid waste; ⑤ the application and spatial reservation of green infrastructures for water supply and treatment; ⑥ the establishment of a support system for intelligent governance of carbon emissions throughtout the entire life cycle of infrastructure. Currently, the research and practice of carbon reduction technologies for infrastructure renewal in existing urban areas mainly focus on three core areas: carbon footprint assessment, optimization of the spatial layout of facilities, and establishment of intelligent governance systems. Future development trends will further clarify the carbon footprint of the entire life cycle of infrastructure, promote the deep integration of facilities and urban spaces, and endeavor to build comprehensive infrastructure that integrates multiple systems. Simultaneously, smart technologies will be strengthened for accurate carbon emission forecasting and spatial and temporal regulation of energy, as well as for the formulation of more effective policies and standards to realize green, low-carbon, and sustainable renewal of urban infrastructure. A total of 108 patents relevant to this research front were registered between 2018 and 2023. These patents received 2 360 citations, with an average of 21.85 citations per patent.

(6) Structure-function integrated technology of organic composite materials in complex environments

The structure-function integrated technology of organic composite materials in complex environments is an advanced approach that combines structural and functional properties. It was designed to satisfy the demands of multi-functionality, durability, and adaptability in civil engineering applications exposed to complex conditions. This technology integrates the mechanical performance of organic composites with functionalities, such as self-healing, corrosion resistance, electrical conductivity,

and thermal insulation. Consequently, it ensures long-term stability and performance in challenging environments, including marine conditions, extreme temperatures, high humidity, and corrosive atmospheres. The key technological directions, include four aspects: ① Self-healing technology, which introduces microcapsules or self-healing mechanisms, allowing the material to autonomously heal cracks and minor damage caused by external forces; ② Interface enhancement and multi-functional surface modification technology, which improves the interfacial bonding strength and surface functionality of organic composites through the incorporation of nanomaterials (such as carbon nanotubes or graphene) and the application of multi-functional surface coatings (e.g., corrosion resistance, wear resistance, and UV protection); ③ Conductive and sensing composite technology, which embeds conductive fibers or conductive polymers to endow the material with sensing and monitoring capabilities; ④ Flame retardant and thermal insulation technology, where the use of flame retardants or phase change materials enables organic composites to maintain effective thermal and fire resistance under high-temperature conditions. The development of structure-function integrated organic composites relies increasingly on the convergence of high-performance materials and advanced fabrication processes. Techniques, such as 3D printing, biomimetic design, nanotechnology, and intelligent manufacturing, further enhance their multi-functionality. This technology is expected to have profound impacts across sectors such as marine engineering, aerospace, and infrastructure construction. A total of 116 patents relevant to this research front were registered between 2018 and 2023. These patents received 319 citations, with an average of 2.75 citations per patent.

(7) Intelligent construction and maintenance of infrastructure under extreme climatic conditions

The intelligent construction and maintenance of infrastructure under extreme climatic conditions (extremely high and low temperatures, heavy precipitation, snowstorms, and typhoons) refers to the use of advanced information technologies, theories, and equipment, such as integrated sensing, machine learning, intelligent analysis, and complex system modeling, to establish models that analyze, learn, and reason based on multi-source real-time data. This enables a full-scale simulation of disaster response, condition evolution, and resilience recovery of the infrastructure, thereby ensuring its overall safety, reliability, functionality, and resilience under extreme climatic conditions. The research directions include: ① real-time sensing and integrated identification technologies for multi-dimensional and multi-modal infrastructure states based on complex multi-sensor networks; ② foundational theories for intelligent construction of infrastructure in extreme climatic environments; ③ data, knowledge, and physics-coupled digital twin modeling methods for complex infrastructure systems; ④ mechanisms of chain disasters and spatiotemporal evolution patterns of infrastructure under typical extreme climatic conditions; ⑤ online sensing and event-driven real-time evaluation, intelligent optimization, and online decision-making methods for infrastructure maintenance strategies. Future development trends focus on elucidating the disaster development mechanisms of large-scale distributed infrastructure under extreme climatic conditions; identifying and predicting risks through integrated and distributed sensing methods; and exploring new models of design, construction, and operation and maintenance that are resilient, recoverable, controllable in disaster impact, and sustainable. Between 2018 and 2023, 134 patents relevant to this research front were identified. These patents received 515 citations, with an average of 3.84 citations per patent.

(8) Low-cost building-integrated photovoltaic system and implementation technology

Low-cost building-integrated photovoltaic (BIPV) systems and implementation technologies involve close integration of photovoltaic power generation systems with the design and construction of buildings. Embedding solar cells into building envelope structures, such as roofs, walls, and windows, achieves a high level of integration between functionality and aesthetics while also reducing system costs. Compared with traditional photovoltaic systems, BIPV not only provides energy but also serves as building materials that offer insulation, soundproofing, and waterproofing. BIPV enables building envelopes to meet basic functional requirements while generating electricity, thereby achieving energy self-sufficiency and contributing to carbon neutrality in the building sector. The main technological directions include: ① developing new, high-efficiency, low-cost photovoltaic materials; ② lightweight and flexible photovoltaic modules adaptable to curved or irregular building facades and roofs; ③ integrated BIPV module design and modular efficient construction techniques; ④ BIPV/T combined technologies for various applications; ⑤ energy management systems for flexible energy use in building complexes. The focus of BIPV technology involves further improvement of energy conversion and utilization efficiency, significantly reducing production and construction

costs, and promoting widespread application and rapid adoption of this technology while ensuring efficient energy production and intelligent distribution. Forty-eight patents relevant to this research front were registered between 2018 and 2023. These patents received 32 citations with an average of 0.67 citations per patent.

(9) Modular building structural system and its intelligent construction

A modular building structural system and its intelligent construction technology refer to the process of dividing a building into several modular units and efficiently completing construction processes of structure, decoration, water and electricity, equipment pipelines, bathroom facilities, etc., of a module on an intelligent production line of a modern factory. Intelligent equipment is used on-site to quickly and reliably assemble various modules into an entire building. This technology moves the building construction process from the site to the intelligent factory, which significantly shortens the construction period, reduces construction difficulty, and achieves the goal of "building a house, such as a car". It is currently the most industrialized green and intelligent construction method in the construction industry. Intelligent modular buildings have achieved standardized design, intelligent production, green construction, integrated decoration, and digital management in construction, fundamentally overcoming the shortcomings of traditional construction methods, effectively eliminating common problems in traditional buildings, and connecting the entire construction process of design, processing, decoration, and construction. They have realized highly specialized collaboration upstream and downstream in the construction industry chain, promoting the transformation and upgrading of the construction industry toward refinement, low carbonization, and intelligence in all aspects of construction. The main technical directions of modular building structural systems and their intelligent construction include: ① high-performance structural systems and resilient disaster prevention for modular buildings; ② collaborative design and construction technologies for the entire process of modular buildings; ③ efficient connection technologies for modular buildings; ④ intelligent manufacturing and construction technologies for modular buildings. The technical focus is on fully utilizing information technologies, such as big data, AI, BIM, and construction robots, to develop new connecting technologies, structural systems, equipment, and algorithms involved in key processes, such as design, processing, decoration, and construction, to achieve resilient, low-carbon, and intelligent construction of modular building structures. Forty-five patents relevant to this research front were registered between 2018 and 2023. These patents received 119 citations, with an average of 2.64 citations per patent.

(10) Autonomous unmanned system localization and mapping technology

Accurately constructing maps and locating in dynamic unknown environments is a major challenge faced by autonomous unmanned systems such as drones, unmanned vehicles, and unmanned boats. Autonomous unmanned system location and map construction technology iteratively construct a map that expresses the spatial characteristics of the surrounding environment using onboard sensors and estimates the position information of the unmanned system relative to nearby points of interest/obstacles within the map. The development trends in this research front include: ① visual simultaneous localization and mapping (SLAM), the sensor types mainly including monocular, binocular, and RGB-D cameras; ② LiDAR SLAM, which is more robust to lighting conditions than visual SLAM; ③ Multi sensor fusion SLAM, typical sensor fusion techniques including particle filters, Kalman filters, and factor graphs optimized via nonlinear least-squares optimizers. Future development trends include: ① Semantic SLAM, which extracts environmental semantic information based on deep learning methods to enhance the perception and understanding ability of SLAM technology in complex scenes; ② Multi robot SLAM. Twenty-three patents relevant to this research front were registered between 2018 and 2023. These patents received 66 citations, with an average of 2.87 citations per patent.

6.2.2 Interpretations for three key engineering development fronts

6.2.2.1 Intelligent scheduling technology and equipment for hydro-wind-photovoltaic-storage hybrid system

The basin hydro-wind-photovoltaic (PV)-storage complementary system represents both China's innovative model and wisdom in contributing to the global energy transition as well as a key direction for the future development of China's hydropower and the low-carbon transformation of its energy system. Currently, major hydropower bases along Yalong, Jinsha, and Lancang rivers have

already proposed integrated planning schemes and have begun pilot construction. Once completed, the total installed capacity is expected to reach two to ten times the currently planned hydropower capacity, forming several 10-million-kilowatt or even 100-million-kilowatt hydro-wind-PV-storage clean energy bases. These bases are 10-million-kilowatt multi-source and multi-grid hybrid power generation systems comprising more than 100 power stations of different types, scales, and transmission modes. Hydropower, wind, PV, and energy-storage power stations are closely coupled through complex hydraulic and topological power structures. They possess the new characteristics of cascade hydraulic circulation connections and multi-energy mutual feedback transformation. Significant changes have occurred in the system structure, mutual feedback relationships, and operational rules. Scientifically determining the scheduling methods of various power sources and efficiently managing and controlling multiple types of units and equipment are unprecedented in China and worldwide. It is critical to promote the integrated development of renewable energy and aid in achieving the "dual carbon" goals.

The cutting-edge research and development directions for intelligent scheduling technology and equipment for basin hydro-wind-PV-storage complementarity currently include the following:

1) High-precision integrated simulation and forecasting technology for hydro-wind-PV resources, including "space-air-ground" collaborative intelligent perception technology for hydro-wind-PV resources, high-precision and high-resolution integrated simulation technology for hydro-wind-PV resources suitable for complex terrain conditions in southwest and northwest China, and AI-based multi-scale forecasting and error correction technology for hydro-wind-PV integration.

2) Multi-scale intelligent scheduling technology for basin hydro-wind-PV-storage complementarity, including water–energy coupling mechanism and mutual feedback transformation relationship of the multi-energy complementary system, flexibility quantification and enhancement technology for hydropower under high-proportion new energy conditions, multi-scale intelligent scheduling technology for multi-energy complementarity oriented to power and energy balance, scheduling risk conduction mechanism and optimization control technology of the multi-energy complementary system, and efficient high-dimensional nonlinear optimization technology for hydro-wind-PV-storage complementarity scheduling.

3) Real-time operation control technology for basin hydro-wind-PV-storage complementarity, including stability analysis technology for basin hydro-wind-PV-storage complementary operation, core algorithms for automatic generation control of basin hydro-wind-PV complementarity, and intelligent control technology for the frequency and voltage of hydro-wind-PV-storage multi-type power sources under a high proportion of new energy and power electronic equipment.

4) Indigenous intelligent equipment for operation and control of basin hydro-wind-PV-storage hybrid system, including a fully indigenous intelligent control and management platform for the integrated operation of the basin hydro-wind-PV-storage system, core equipment, industrial control software for intelligent power generation control of multi-energy complementarity, intelligent decision-making systems for integrated operation management of hydro-wind-PV-storage systems, etc.

5) Bidding decision-making techniques for basin hydro-wind-PV-storage in the electricity market environment, including a mechanism design for multi-energy complementary systems to participate in the electricity market, electricity market supply demand forecasting technology based on large AI models, volume-price bidding technology for the joint participation of basin hydro-wind-PV-storage systems in multiple electricity markets, and decision-making technology for basin hydro-wind-PV-storage complementary scheduling considering participation in multiple electricity markets.

6) New operational management modes and technical standards for hydro-wind-PV-storage integration, including grid-source-coordinated intelligent operational management modes for basin hydro-wind-PV-storage, business systems for complementary operational management of basin hydro-wind-PV-storage complementarity, and technical standards for integrated operational management of basin hydro-wind-PV-storage complementarity.

As listed in Table 6.15, 64 patents related to this topic were registered, with each patent cited 27.78 times on average. The countries that registered the most patents were China, the USA, and Argentina (Table 6.17). China was at the forefront of development, contributing 71.88% of its patents. The number of citations per patent for Chinese patents was 4.70.

The three institutions that produced the most patents were Resilience Financing, Inc., Enrique Menotti Pescarmona, and Hohai University (Table 6.18). Resilience financing, Inc. in the USA mainly studies the use of AI and data analysis to improve engineering management. Hohai University mainly researches the capacity configuration of water-wind-light-storage complementary pump stations, multi-energy complementary scheduling methods, the optimal capacity configuration of multi-energy complementary systems.

The future development of this frontier in the coming ten years will involve multi-energy complementary system resource forecasting, scheduling methods, real-time operation, control equipment, power trading, management models, and technical standards. As the capacity and coverage of multi-energy complementary bases in river basins continue to expand, the contradiction between new energy consumption and the safe and stable operation of power systems is becoming increasingly prominent. This research can effectively overcome difficulties such as power and energy imbalances in multi-energy complementary systems, serious wind and solar power curtailment, and unit regulation delays. It can achieve coordinated scheduling, operational decision-making, and intelligent management of over hundred different types of power stations and thousands of different units, demonstrating enormous development potential (Figure 6.10).

Table 6.17 Countries with the greatest output of core patents on "intelligent scheduling technology and equipment for hydro-wind-photovoltaic-storage hybrid system"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	46	71.88	216	12.15	4.70
2	USA	11	17.19	822	46.23	74.73
3	Argentina	5	7.81	740	41.62	148.00
4	Indonesia	1	1.56	0	0.00	0.00
5	Republic of Korea	1	1.56	0	0.00	0.00

Table 6.18 Institutions with the greatest output of core patents on the "intelligent scheduling technology and equipment for hydro-wind-photovoltaic-storage hybrid system"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Resilience Financing, Inc.	9	14.06	452	25.42	50.22
2	Enrique Menotti Pescarmona	6	9.38	1 110	62.43	185.00
3	Hohai University	4	6.25	36	2.02	9.00
4	China Three Gorges Corporation	3	4.69	3	0.17	1.00
5	State Grid Corporation of China	2	3.12	27	1.52	13.50
6	Institute of Agricultural Resources and Regional Planning, CAAS	2	3.12	25	1.41	12.50
7	Wuhan University	2	3.12	18	1.01	9.00
8	Shenyang University	2	3.12	9	0.51	4.50
9	Sichuan University	2	3.12	4	0.22	2.00
10	Institute of Geographic Sciences and Natural Resources Research, CAS	2	3.12	3	0.17	1.50

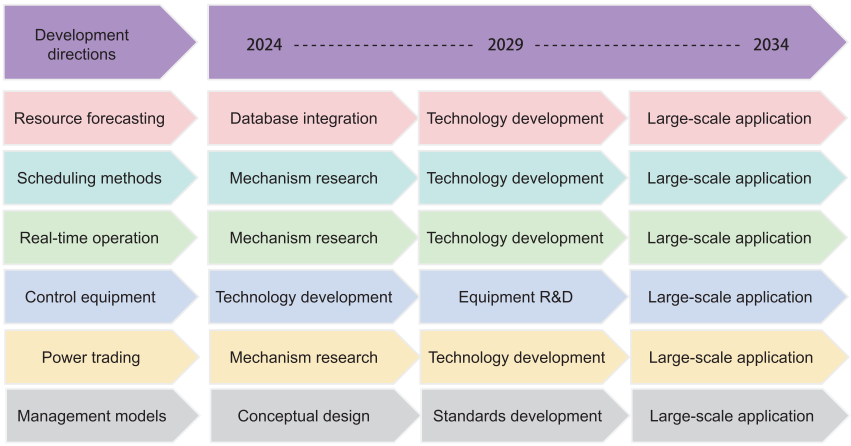


Figure 6.10 Roadmap of the engineering development front of "intelligent scheduling technology and equipment for hydro-wind-photovoltaic-storage hybrid system"

6.2.2.2 Intelligent simulation and resilience enhancement technology for urban drainage systems

Extreme weather events, particularly intense rainfall, pose a critical threat to urban safety and the reliability of drainage systems. Challenges, such as outdated design standards, aging infrastructure, and limited automation, result in high energy consumption, carbon emissions, and low resilience, restricting the ability to manage extreme weather and floods. To address these issues, it is crucial to systematically gather and analyze historical data across various scales to develop climate-adaptive designs and operational models. This includes creating sophisticated monitoring and control methods tailored to the complexity of urban drainage systems, and establishing sustainable management techniques to enhance preventive maintenance and rapid recovery.

New strategies for smart management have emerged owing to advancements in AI, big data, and modeling. Key development areas include: ① Advanced monitoring: Implementation of integrated sensors for water metrics and IoT devices; Optimize the acquisition of unstructured data and the strategic placement of sensors for critical nodes like drainage networks and flood-prone areas. ② Innovative diagnosis and repair: Employ precise technologies for identifying and repairing issues in mixed or damaged drainage networks, utilizing non-invasive detection and repair methods. ③ Adaptive scheduling systems: Develop real-time feedback control mechanisms and optimize system compatibility at various levels, incorporating both local and global strategies for integrated watershed management and comprehensive. ④ Pollution control: Utilization of bioretention, rainwater collection, and advanced storage and treatment systems. Implement predictive control technologies to manage pollution from source to endpoint. ⑤ Resilient Infrastructure Planning. Focus on green infrastructure to manage runoff and pollution, ensure lifecycle water quality, and integrate systems for comprehensive water management. ⑥ Unify simulation and management platforms: Develop precise models for integrated systems by combining advanced simulation software with comprehensive platforms that enhance resilience and operational management.

As listed in Table 6.15, 229 patents related to this front were registered, with each patent cited 5.14 times on average. China, India, and the USA registered the most patents (Table 6.19). China was at the forefront of development, contributing 93.45% of the patents. The number of citations per patent for Chinese patents was 2.03. Cooperation between these countries is rare (Figure 6.11).

The three institutions that produced the most patents were Enrique Menotti Pescarmona, Chongqing City Investment Infrastructure Construction Co., Ltd., and the Power Construction Corporation of China (Table 6.20). In Argentina, Enrique

Menotti Pescarmona mainly studies the hydrological analysis and management processes and systems of river basins, involving networks of meteorological stations, artificial drainage systems, management of natural and artificial reservoirs, and simulation calculations of hydrological maps. Chongqing City Investment Infrastructure Construction Co., Ltd. primarily researches the methods and structures of intelligent anti-drainage systems, including maintainable design, BIM-technology-based pressure monitoring management modules, and configurations of side drainage pipes and annular blind drainage pipes. The Power Construction Corporation of China mainly studies urban intelligent drainage systems, including rainwater and sewage collection, sponge city rainwater discharge, and plant-network-river integrated intelligent scheduling methods, all integrated with sensors and automated control technologies.

The development of this front in the coming ten years involves smart monitoring, smart diagnosis, smart scheduling, facility construction, and integrated management (Figure 6.12).

Table 6.19 Countries with the greatest output of core patents on "intelligent simulation and resilience enhancement technology for urban drainage systems"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	214	93.45	434	36.90	2.03
2	India	9	3.93	2	0.17	0.22
3	USA	4	1.75	370	31.46	92.50
4	Argentina	3	1.31	370	31.46	123.33
5	Ecuador	1	0.44	0	0.00	0.00
6	Spain	1	0.44	0	0.00	0.00
7	Philippines	1	0.44	0	0.00	0.00
8	Saudi Arabia	1	0.44	0	0.00	0.00

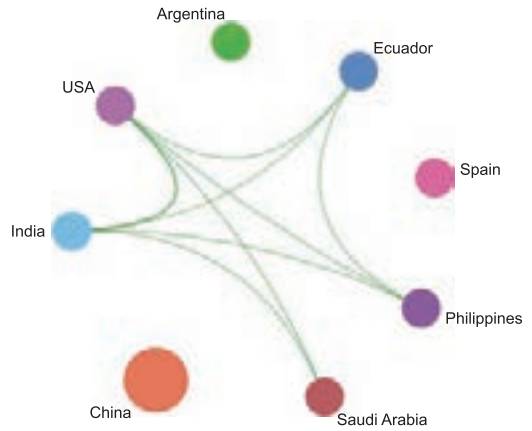


Figure 6.11 Collaboration network among major countries in the engineering development front of "intelligent simulation and resilience enhancement technology for urban drainage systems"

Table 6.20 Institutions with the greatest output of core patents on the "intelligent simulation and resilience enhancement technology for urban drainage systems"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Enrique Menotti Pescarmona	4	1.75	740	62.93	185.00
2	Chongqing City Investment Infrastructure Construction Co., Ltd.	4	1.75	5	0.43	1.25
3	Power Construction Corporation of China	4	1.75	5	0.43	1.25
4	Nanjing Gaoli Construction Machinery Co., Ltd.	3	1.31	27	2.30	9.00
5	Guangzhou Railway Polytechnic (Guangzhou Railway Machinery School)	3	1.31	0	0.00	0.00
6	Hohai University	3	1.31	0	0.00	0.00
7	China State Construction Engineering Corporation	2	0.87	16	1.36	8.00
8	China Metallurgical Group Corporation	2	0.87	10	0.85	5.00
9	Shandong University	2	0.87	10	0.85	5.00
10	Zhejiang University	2	0.87	9	0.77	4.50

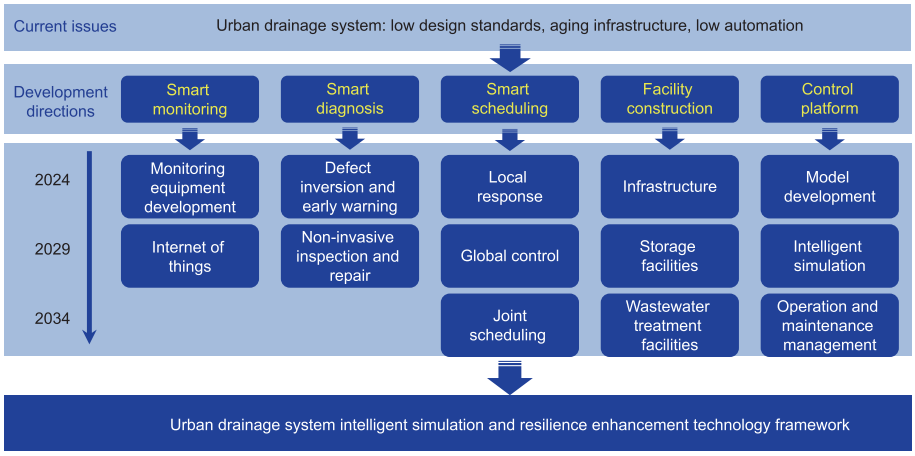


Figure 6.12 Roadmap of the engineering development front of "intelligent simulation and resilience enhancement technology for urban drainage systems"

6.2.2.3 Large scale 3D real scene modeling and dynamic updating

3D real scene is an irreplaceable new type of national infrastructure that reflects and expresses spatiotemporal information on production, life, and ecological space in a realistic, three-dimensional, and temporal manner. The data products can be divided into three levels: terrain-level 3D real scenes, city-level 3D real scenes, and component-level 3D real scenes. In recent years, under the background that the country continues to build a 3D realistic geospatial scene, large-scale 3D real scene modeling and dynamic updating technology have become the forefront of development in this field. The development trends on this research front include the following:

1) Large-scale 3D real scene modeling automation, including geographic scene acquisition and fusion technology, IoT perception data access, fusion technology for real-world 3D, and geographic entity semantic modeling technology. Space satellite photography, aerial photography, ground laser scanning, Internet of Things perception, volunteer mobile phone shooting, and other means of building space-air-ground-human multi-source data acquisition technology are used to achieve large-scale real three-dimensional data acquisition and modeling by multi-source data fusion and intelligent processing.

2) Intelligent management and dynamic updating of the 3D real scene database, including basic geographic entities and geographic scene adaptation technology, stepless mapping techniques for basic geographic entities, spatiotemporal analysis technology for 3D real scenes, data scale correlation and linkage maintenance technology for 3D real scenes, and quality control technology for basic geographic entity results. Integrating diverse data from various geographic scenarios, establishing a distributed database and management system with distributed storage of massive heterogeneous data resources and centralized logic, and achieving the collaborative maintenance of geographic entities, geographic scenes, and other 3D real scene data.

3) Smart services include 3D real scene data interfaces and service publishing technology, lightweight processing technology for 3D real scene data, and security service processing technology for 3D real scene data. Supported by the information infrastructure of cloud network integration and cross-domain interconnection, it provides service capabilities such as spatiotemporal connectivity, spatiotemporal computing, and spatiotemporal intelligence through the construction of dynamic service computing and open technology ecology.

Research institutions that produced the most achievements in this field include Chinese Academy of Surveying & Mapping, National Geomatics Center of China, Wuhan University, Shenzhen University and Southwest Jiaotong University, etc. The three organizations that produced the most patents were Wuhan University, Chinese Academy of Surveying & Mapping and National Geomatics Center of China.

As listed in Table 6.15, 87 patents related to this front were registered, with each patent cited 5.38 times on average. China and the USA registered the most patents (Table 6.21). China was at the forefront of development, contributing 97.70% of the patents. The number of citations per patent for Chinese patents was 4.67.

The three institutions that produced the most patents were Wuhan University, the State Grid Corporation of China, and Wuhan Center China Geological Survey (Central South China Innovation Center for Geosciences) (Table 6.22). Wuhan

Table 6.21 Countries with the greatest output of core patents on “large scale 3D real scene modeling and dynamic updating”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	85	97.70	397	84.83	4.67
2	USA	2	2.30	71	15.17	35.50

Table 6.22 Institutions with the greatest output of core patents on the “large scale 3D real scene modeling and dynamic updating”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Wuhan University	5	5.75	13	2.78	2.60
2	State Grid Corporation of China	5	5.75	2	0.43	0.40
3	Wuhan Center China Geological Survey (Central South China Innovation Center for Geosciences)	3	3.45	57	12.18	19.00
4	Terra Creating Digital Technology (Beijing) Co., Ltd.	3	3.45	21	4.49	7.00
5	China State Construction Engineering Corporation	3	3.45	18	3.85	6.00
6	China Railway Construction Corporation	2	2.30	22	4.70	11.00
7	China Railway Group Limited	2	2.30	13	2.78	6.50
8	Wuhan Dashi Wisdom Technology Co., Ltd.	2	2.30	11	2.35	5.50
9	Changjiang Spatial Information Technology Engineering (Wuhan) Co., Ltd.	2	2.30	5	1.07	2.50
10	Guangdong South Digital Technology Co., Ltd.	2	2.30	3	0.64	1.50

University mainly studies technologies such as the 3D reconstruction of indoor and urban structures based on 2D videos, air-ground image consistency feature learning, building extraction from live-action 3D models, orthographic image generation, panoramic data, and automatic separation of ground and non-ground models. The State Grid Corporation of China mainly researches 3D realistic modeling and construction quality detection technologies for power systems based on point cloud data fitting, GIS platforms, power infrastructure construction systems, air-ground integrated joint modeling methods, and fatigue life analysis of oil buffers in SF6 circuit breaker operating mechanisms. The Wuhan Center China Geological Survey (Central South China Innovation Center for Geosciences) primarily studies the input of remote-sensing interpretation marks into catastrophe evolution identification models for potential landslide hazard points. Cooperation between these institutions is rare (Figure 6.13).

The future development of this front in the coming ten years involves precision spatial geodetic data processing technology, nonlinear motion modeling of reference stations, a combination of spatial geodetic technology, and geocentric motion modeling (Figure 6.14).

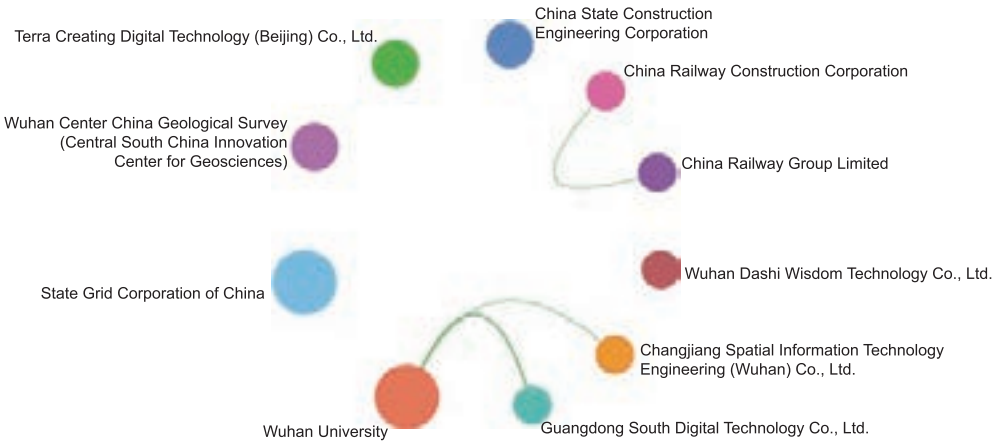


Figure 6.13 Collaboration network among major institutions in the engineering development front of “large scale 3D real scene modeling and dynamic updating”

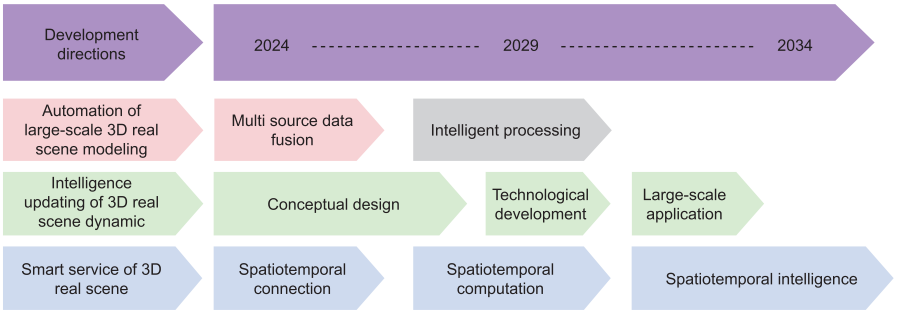


Figure 6.14 Roadmap of the engineering development front of “large scale 3D real scene modeling and dynamic updating”

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