IX. Engineering Management

1. Engineering research fronts

1.1 Trends in Top 10 engineering research fronts

In the field of engineering management, the global Top 10 engineering research frontiers this year are "research on human–machine symbiotic intelligent manufacturing under Industrial 5.0 environment", "research on unmanned aerial vehicle dispatching and path optimization in logistics", "research on symbiotic logic and governance of major engineering innovation ecosystems", "research on enhancing and ensuring the resilience of transportation networks", "research on evolution and governance of public safety incidents driven by big data", "research on product quality and reliability technology in a big data environment", "research on interactive mechanism and coordinated development rules of energy economy and environmental systems", "research on intrinsic mechanism of digital empowerment value creation in manufacturing enterprises", "research on precision medical process optimization", and "research on pricing and revenue sharing mechanism of digital elements". Citations to seminal articles pertinent to these topics can be found in Tables 1.1.1 and 1.1.2. Among these domains, particular attention is accorded to "research on human–machine symbiotic intelligent manufacturing under Industrial 5.0 environment", "research on unmanned aerial vehicle dispatching and path optimization in logistics" and "research on symbiotic logic and governance of major engineering innovation ecosystems". Succeeding sections will offer a robust analysis of their extant developmental trajectories and prospective orientations.

(1) Research on human–machine symbiosis intelligent manufacturing under the Industrial 5.0 environment

Industrial 5.0 heralds a novel phase in the evolution of manufacturing, building upon the foundations laid by the 4.0 stage, with an

Table 1.1.1 Top 10 engineering research fronts in engineering management

No.	Engineering research front	Core Papers	Citation	Citations per paper	Mean year
1	Research on human–machine symbiotic intelligent manufacturing under Industrial 5.0 environment	29	2 270	78.28	2021.2
2	Research on unmanned aerial vehicle dispatching and path optimization in logistics	45	4 913	109.18	2018.9
3	Research on symbiotic logic and governance of major engineering innovation ecosystems	45	986	21.91	2020.1
4	Research on enhancing and ensuring the resilience of transportation networks	4	227	56.75	2020.0
5	Research on evolution and governance of public safety incidents driven by big data	13	870	66.92	2018.2
6	Research on product quality and reliability technology in a big data environment	17	99	5.82	2019.8
7	Research on interactive mechanism and coordinated development rules of energy economy and environmental systems	11	144	13.09	2021.2
8	Research on intrinsic mechanism of digital empowerment value creation in manufacturing enterprises	25	628	25.12	2019.2
9	Research on precision medical process optimization	31	383	12.35	2019.8
10	Research on pricing and revenue sharing mechanism of digital elements	15	230	15.33	2020.1

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

No.	Engineering research front	2017	2018	2019	2020	2021	2022
1	Research on human–machine symbiotic intelligent manufacturing under Industrial 5.0 environment	0	1	3	3	4	18
2	Research on unmanned aerial vehicle dispatching and path optimization in logistics	5	11	15	11	3	0
3	Research on symbiotic logic and governance of major engineering innovation ecosystems	3	4	6	7	10	13
4	Research on enhancing and ensuring the resilience of transportation networks	0	1	0	1	2	0
5	Research on evolution and governance of public safety incidents driven by big data	4	4	3	2	0	0
6	Research on product quality and reliability technology in a big data environment	3	1	5	1	1	6
7	Research on interactive mechanism and coordinated development rules of energy economy and environmental systems	0	1	0	2	1	7
8	Research on intrinsic mechanism of digital empowerment value creation in manufacturing enterprises	6	4	5	3	3	4
9	Research on precision medical process optimization	3	4	4	11	3	6
10	Research on pricing and revenue sharing mechanism of digital elements	1	3	2	2	1	6

emphasis on human-centered approaches designed to realize more sustainable and resilient production processes. At the heart of Industrial 5.0 lies the concept of Human–Machine Symbiosis Intelligent Manufacturing, an integrated system comprising human–human, human–machine, and machine–machine interactions. These interactions are orchestrated to operate in harmony across both physical and virtual domains, leveraging the collaboration and coevolution of human beings and intelligent machines. The system combines the precision and strength of robotics with the advanced cognitive abilities and flexibility of humans, allowing adaptation to perpetually evolving circumstances and demands.

Contemporary advancements in front-end technologies, such as intelligent sensing, brain–machine interfaces, and the Internet of Things, along with foundational technologies, including cloud computing, big data, large models, and artificial intelligence, have led to machines progressively manifesting intelligent and autonomous characteristics. The traditional unifunctional nature of machine operations has metamorphosed into multifaceted processes encompassing perception, comprehension, planning, decision-making, and execution. Machines have advanced from being controlled entities to autonomous intelligent agents, and the human–machine relationship has matured from a “supportive, subordinate” level to stages of “collaborative, equal”, and “integrative, symbiotic” interaction.

Unlike the traditional realm of human–machine interaction, which predominantly concentrates on machine adaptation to human needs for effective collaboration, human–machine symbiosis intelligent manufacturing extends this paradigm. It emphasizes the exploration of three technological strata: human–machine mutual perception–cognition–trust, human–machine collaborative organization–planning–decision–making, and human–machine collaborative interaction–control–evolution. The overarching goal is the scalable, flexible, and automated production of personalized and highly complex products.

Looking forward, the rapid advancement of human–machine symbiosis intelligent manufacturing will undoubtedly catalyze the emergence of innovative business models and value chains within the manufacturing industry.

(2) Research on unmanned aerial vehicle dispatching and path optimization in logistics

In densely populated urban regions, there is a serious deficiency in land resources available for road construction, which leads to increasingly acute problems of traffic congestion and pollution. Concurrent with the rapid advancement of logistics unmanned aerial vehicles (UAVs) and the exploration of three-dimensional space, the transition from ground logistics transport to aerial transport has emerged as a new trend in the development of urban logistics. Many domestic and international logistics companies have recognized the efficiency advantages of drone delivery and have commenced comprehensive verification.

International logistics titan Amazon has deployed Prime Air drones, with an emphasis on the development of last-mile delivery from warehouses to suburban customers. Concurrently, DHL is dedicated to establishing drone stations to facilitate the delivery of goods in remote areas. In 2019, UPS partnered with CVS Pharmacy to transport home medical supplies in suburban and rural areas, while Wing focused on commercial food delivery drone research. China's Rapid Ant Technology Co., Ltd. began with suburban postal delivery and then gradually transitioned to urban delivery and medical reagent transport. Meituan, capitalizing on its resources in food delivery, has aggressively pursued urban drone instant delivery. JD.com has centered its efforts on the "last mile" in rural areas while simultaneously expanding a three-tier drone transport network encompassing trunk, branch, and terminal levels.

Compared to traditional ground logistics transportation, drone logistics transport offers a significant increase in speed but is not without its drawbacks. These include a low single-drone payload, short flight range, and the frequent necessity for battery replacement. Therefore, unique research problems have arisen in drone logistics following its emergence, which distinguishes it from ground logistics scheduling. These include challenges related to drone logistics path planning, coordination of transport path planning between drones and ground vehicles, and scheduling optimization.

(3) Research on the symbiotic logic and governance of major engineering innovation ecosystems

Mega-projects refer to large-scale public initiatives characterized by substantial investment, extended implementation cycles, technical complexity, and far-reaching impacts on society, economy, and the ecological environment. Within the context of innovation-driven high-quality development, mega-projects serve as pivotal platforms for fostering peaks of innovation, and the construction of a symbiotic and prosperous mega-project innovation ecosystem represents one of the research frontiers in the field of project management. A mega-project innovation ecosystem is a tightly interconnected and co-evolving network formed by various innovation actors—including project owners, designers, constructors, consulting agencies, academic institutions, research organizations, and governmental departments—in the pursuit of effective systemic solutions to the technical challenges faced by mega-projects. The notion of "symbiosis" within this innovation ecosystem refers to the mutually beneficial and interdependent relationships established among different types of innovation actors as they collaborate to overcome technical challenges and seek solutions. Investigating governance strategies for the symbiotic logic among innovation actors within the mega-project innovation ecosystem can facilitate the efficient operation of the ecosystem and the synergistic development of its constituent actors, thereby providing insights for optimizing innovation management in mega-projects.

(4) Research on the enhancement and safeguarding of transportation network resilience

With the rapid expansion of transportation demands and the frequent occurrence of various disasters and unexpected events, ensuring and enhancing the transportation capacity and efficiency of the transportation network has gained significant importance. Maintaining and bolstering the resilience of the transportation network has emerged as a critical and pressing issue within the realm of engineering management. Transportation network resilience pertains to the transportation system's ability to withstand or absorb the impacts of external disturbances or attacks and subsequently return to normal operational levels.

In accordance with the concept and definition of transportation network resilience, ongoing research primarily engages in safeguarding and enhancing network resilience through the following avenues. First, it delves into measurement methods and an assessment index system for network resilience grounded in network topology structure and system performance. Second, through the monitoring of disaster factors within the road network, simulations of disaster early warnings, analyses of network redundancy, assessments of traffic capacity, and the optimization design of capacity, research investigates methods and technologies for pre-event transportation network resilience enhancement.

Third, it explores the augmentation of the network's resistance and absorptive capacity during disaster impacts. This includes identifying and managing critical infrastructure, optimizing the allocation of emergency resources within the network, making network response decisions, and implementing network emergency controls. Finally, research undertakes the optimization of restoration strategies for the network, resource allocation for restoration, and the enhancement of system function recovery. This addresses post-event network recovery decision-making and the optimization of resource allocation, thereby ensuring the dependable and swift enhancement of the resilience of the transportation network system.

Ongoing research still requires innovative work in data mining and mechanism analysis related to characteristics of disaster intensity distribution, the evolution and mutation rules of travel demand, the coupling of multimodal transportation systems, and the collaborative optimization of complex systems, among others. In the foreseeable future, this research frontier is poised to generate novel growth opportunities in the domains of integrated transportation, collaborative efforts between vehicles and roadways, the integration of multiple networks, big data technology, intelligent control, and more. These developments bring forth challenges and prospects for research in transportation infrastructure operation and management.

(5) Research on the evolutionary law and governance of social public safety incidents driven by big data

Amidst the swift progression of the social economy and the ongoing intensification of urbanization, diverse incidents impacting public safety have found a fertile ground to develop. These incidents encompass natural calamities, industrial mishaps, traffic collisions, criminal activities, contagious ailments, and other unforeseen emergencies. Gradually, they are evolving into tangible menaces that undermine urban security, hinder economic advancement, and disrupt societal equilibrium. Concurrently, as technology advances, significant opportunities have arisen through the integration of big data technologies like 5G, deep learning, and cloud services. This integration holds immense potential for studying and managing social public safety incidents.

Big data technology, encompassing the comprehensive collection, analysis, and application of voluminous data from multiple sources, has witnessed extensive implementation across domains such as finance, manufacturing, and public services. In recent years, its utilization has penetrated deeply into the realm of social public safety incident research and management. Research endeavors span all phases of big data utilization, including collection, analysis, and application. Key areas of investigation encompass: the acquisition, aggregation, and retention of significant data related to social public safety incidents, driven by innovative technologies like 5G and blockchain; the application of data mining, deep learning, artificial intelligence, and analogous algorithms to discern the genesis and progression of these incidents; leveraging the advancements in Internet of Things and data infrastructure to develop big data-driven technologies for managing social public safety incidents, while simultaneously conceptualizing suitable administrative frameworks.

As the evolution of smart cities continues, the horizon for the application of big data technology within the realm of social public safety incident research and management expands significantly. Future research trajectories are expected to intertwine closely with the multi-tier structure of smart cities. This encompasses the assimilation of big data perception, analysis, and application, grounded in the city information model (CIM). Additionally, research efforts will be informed by iterative optimizations based on insights drawn from established smart cities, thereby setting a trajectory for future advancements.

(6) Research on product quality and reliability technology in the big data environment

With the progression of science and technology, especially in the realm of information technology, industrial big data has undergone explosive growth. This growth provides the requisite data support environment and conditions for the analysis, control, and enhancement of product quality and reliability. Industrial big data not only encapsulates the entire life cycle processes of product design, manufacturing, maintenance, scrapping, recycling, and remanufacturing but also encompasses information related to the product usage environment and user perception. It significantly facilitates the comprehensive application of artificial intelligence in product manufacturing, usage, and maintenance. The research on product quality and reliability within the big data environment can be categorized into two primary aspects.

First, the foundation of product quality analysis theory and methods relies on the digitization of the entire “design–manufacture–sale–use” process. Key research directions in this area include the horizontal and vertical integration of quality and reliability industrial big data across the product life cycle and supply chain. Data fusion and intelligent quality management within manufacturing systems. Precise tracing of product quality throughout the entire lifecycle, leveraging IoT, blockchain, and identification resolution technologies. Digital quality control is propelled by multimodal fusion and digital twin technology. Intelligent maintenance services are fortified by intelligent sensing, knowledge graphs, and natural language processing. Networked supply chain quality control incorporating blockchain technology. Personalized custom product intelligent design and quality control, employing industrial big model technologies. Complex product reliability analysis theory and methods concentrate on intricate equipment reliability modeling, analysis, assessment, and optimization. These transcend the constraints of the independent unit statistical assumption, taking into account unit correlation ubiquity, data and model-driven complex equipment remaining life prediction, and maintenance analysis theory and methods.

Second, the emphasis is placed on human–machine integration as the cornerstone of product quality and reliability analysis theory and methods. Key research directions here include human–machine (intelligent machines) collaborative product quality control and management techniques. Reliability modeling, analysis, and optimization theory and methodologies for human-integrated intelligent product systems.

(7) Research on the interactive impact mechanism and coordinated development laws of energy economy and environmental systems

Presently, global economic, social, and energy–environment systems are undergoing profound transformations. The interplay between climate governance, energy security, environmental enhancement, and socioeconomic developmental goals is deepening. Notably, the prominence of cascading, compounded, and uncertain factors affecting decision outcomes and risk propagation is growing. Consequently, there is an escalating emphasis on comprehensively considering the interconnectedness of system components within simulation models of the energy-environment-economy complex system. This approach is pivotal in ensuring the stability of the environmental-economic system and prudently advancing dual carbon objectives. The ongoing principal research directions encompass the following aspects. ① Complex system modeling and evolutionary trend analysis with dual carbon orientation: this entails coupling diverse energy models with meteorological and land-use models to construct intricate comprehensive assessment models. A notable example is IIASA’s MESSAGEix-GLOBIOM model. These models facilitate a spectrum of scenario simulations, and they play a fundamental role in guiding path decisions. ② Research on multielement coordinated development paths driven by pollution and carbon reduction objectives: rooted in the modeling of the energy-environment-economy complex system, this research integrates multielement constraint functions. The goal is to optimize paths that coordinate pollution reduction and carbon reduction in accordance with principles that maximize coordinated benefits and public welfare while minimizing policy costs. ③ Measurement and modeling of adaptive behavior: within the intricate web of decisions concerning pollution reduction and carbon reduction, entities exhibit adaptability. They formulate targeted adjustment strategies in response to alterations in policy and market environments, thereby influencing system evolution. Quantifying adaptive behavior facilitates a cross-simulation of behavior, climate, and economy. The process of selecting effective adaptive approaches stands as a current critical frontier. Furthermore, the decision-making associated with pollution and carbon reduction contends with uncertainties emanating from various sources. These encompass outcomes from predictive models, occurrences of extreme climate events, and leaps in technological costs. In the future, a key developmental trajectory is navigating robust decision-making within the energy-environment-economy system amidst profound uncertainty. This necessitates integrating diverse stakeholder perspectives into decision-making and exploring the tripartite equilibrium between risk, cost, and resilience across diverse plausible scenarios.

(8) Study on the intrinsic mechanism of value creation through digital empowerment in manufacturing enterprises

Value creation through digital empowerment in manufacturing enterprises entails leveraging technologies such as artificial intelligence, digital twins, and edge computing. This process follows a systematic sequence of data perception, intelligent cognition, dynamic decision-making, and precise execution. It necessitates establishing effective perception mechanisms to sense objects and gather data and subsequently employing system analysis models to translate voluminous data into valuable insights and knowledge for comprehending objects. The application of dynamic decision-making comes into play across diverse scenarios, harmonizing a range of resources, including data, materials, human resources, and finances. This fosters the streamlined and efficient execution of manufacturing enterprise activities. Drawing from the outcomes of dynamic decisions, the meticulous execution of action plans materializes, accompanied by real-time feedback and proficient control. This engenders a cycle of reducing costs, enhancing quality, boosting efficiency, and ultimately yielding efficient value creation. To elaborate further, manufacturing enterprises heighten their operational capacities by seamlessly integrating digital technology into strategic decision-making, research and development, materials procurement, production, marketing services, and organizational management. This expansion enhances their competence in describing, diagnosing, predicting, deciding, and overseeing operational conditions. This holistic integration markedly elevates the impact, efficiency, and benefits of value creation. Moreover, digital technology serves as a catalyst for the integration of industrial chains, value chains, innovation chains, and capital chains. This augments collaboration and cooperation between enterprises, nurturing transformations across industrial elements, organizational structures, innovation systems, and business models. In turn, this impels the evolution and advancement of the manufacturing industry. Finally, while embarking on the journey of value creation through digital empowerment in manufacturing enterprises, critical concerns such as privacy breaches, data rights validation, algorithmic biases, and technology misuse must be addressed. These efforts are vital for ensuring enterprise security and industrial stability. This imperative calls for continuous enhancements at both the policy and technical levels.

(9) Research on precision medical process optimization

Precision medicine epitomizes a personalized medical paradigm grounded in data-driven methodologies. It furnishes patients with tailored preventive and treatment strategies based on their genetic, environmental, and lifestyle particulars. The chief pursuits of precision medicine encompass the personalized calibration of treatment regimens, early ailment detection, drug innovation, and biomarker identification, among others.

At its core, precision medicine draws strength from extensive, multidimensional, and high-quality biomedical data, including genomic and vital sign information. These data are gleaned through sequencing technologies and wearable devices. This profusion of data renders possible personalized, exact, and cost-effective disease prevention, diagnosis, and treatment. The COVID-19 pandemic underscored this when large-scale sequencing data and population mobility insights facilitated precise disease control strategies.

Precision medicine harnesses methodologies such as mathematical modeling and optimization algorithms to formulate optimal treatment decision protocols rooted in patients’ health status and treatment outcomes. These protocols can account for both immediate and delayed treatment impacts, or they can optimize diverse anticipated objectives such as treatment effects and patient quality of life. Notably, for chronic conditions such as cancer and Alzheimer’s disease, the shift from traditional maximum tolerable dose approaches to precision medicine has been proposed by experts.

Furthermore, precision medicine leverages the “virtual physiological human (VPH)” to simulate a myriad of physiological processes and organ functions within the human body. It also capitalizes on extensive language models for retrieving biomedical information. The domains of cancer, Alzheimer’s disease, infectious diseases, and beyond hold vast potential for precision medicine applications. By delving into the mechanisms underlying disease initiation, which entails identifying disease-associated biological targets and assessing treatment outcomes via biomarkers, precision medicine stands poised to deliver more effective and safer therapeutic interventions.

By harnessing big data analysis and artificial intelligence, precision medicine enhances the timeliness and convenience of diagnostic services. Through wearable devices and smartphones, it furnishes personalized and continuous health management. The arena of precision medicine is thriving, emerging as one of the most vigorously pursued investment domains in both academia and industry. Crucially, the optimization of the precision medicine process assumes a pivotal role across numerous levels, encompassing data collection and organization, model construction, and decision analysis, and necessitates interdisciplinary collaborations between scholars in the medical, information science, and management science fields. This collaborative impetus is pivotal in further elevating the health and hygiene landscape within our nation.

(10) Research on the pricing and revenue sharing allocation mechanism of digital elements

One of the fundamental strategies for fully unlocking the value inherent in data elements rests upon the circulation of these elements. Similarly, a pivotal aspect contributing to the active circulation of data elements lies in the effective implementation of pricing mechanisms and allocation strategies for revenue sharing. At present, notable advancements have been made in the exploration of mechanisms and approaches for pricing data elements, as well as methods for distributing revenue, within diverse domains encompassing computer science, data science, management studies, and economics.

In the domain of data element pricing, the realm of computer science is primarily engaged in investigating strategies for pricing data based on its contributions to AI models, along with methodologies for pricing rooted in privacy compensation. In parallel, data science and economics have proffered techniques for pricing data grounded in principles such as equity, revenue optimization, absence of arbitrage discrepancies, and information entropy. The realm of management studies has proposed diverse data pricing methodologies, including expert assessment scoring, hierarchical analysis, and supply-demand alignment tailored to distinct contextual settings.

In the realm of revenue-sharing allocation for data elements, management studies have predominantly concentrated on the exploration of multiparty revenue distribution within Internet service platforms. Meanwhile, economics has placed significant emphasis on research aligned with the marginal contribution stemming from data.

As China accelerates the establishment of fundamental data element frameworks, coupled with the systematic progress of the data element circulation market, along with its supporting technological infrastructure, the evolution toward data productization will continue to mature. It is imperative that the examination of pricing and revenue-sharing allocation mechanisms for data elements be comprehensively and thoroughly pursued. Prospective directions for development within this sphere encompass: ① a comprehensive consideration of the novel attributes exhibited by data elements in the formation of market-based pricing frameworks, including underlying theories and methodologies; ② an interconnected analysis of the complete lifecycle of data elements, entailing the investigation of revenue-sharing allocation mechanisms and regulations embodying the principle of “market-assessed contribution, remuneration determined by contribution”, underpinned by state-of-the-art technology within the realm of data element circulation; and ③ an alignment with the structural configuration of data element property rights, necessitating research into data pricing and revenue-sharing allocation methodologies contingent on application scenarios. This includes a thorough exploration of varied pricing techniques and revenue-sharing allocation regulations pertaining to the authorized utilization of public data.

1.2 Interpretations for three engineering research fronts

1.2.1 Research on human–machine symbiosis intelligent manufacturing under the Industrial 5.0 environment

Human–machine engineering was first conceptualized as far back as the mid-nineteenth century, with its primary focus being the harmonization of human, machine, and environmental elements during operations, enabling the efficient and safe utilization of machinery. With the widespread adoption of computers in the 1980s, human–machine interaction primarily centered around enhancing feedback loops between machines and humans, aiming to enhance machine adaptability to human needs. Since 2008, driven by the imperative of personalized manufacturing, the idea of human–machine collaboration has gained consensus within industrial manufacturing. This collaboration envisions the sharing of resources and capabilities between humans and machines during the manufacturing process. This phase initially explored non-semantic perception and shallow intelligence. Subsequently, with the emergence of cognitive computing, large-scale models, knowledge evolution, and similar advancements, human–machine collaboration has evolved toward symbiosis, initiative, and integration within the context of the Industrial 5.0 paradigm.

Contemporary research into human–machine symbiotic intelligent manufacturing predominantly centers on three key aspects. ① The foundation of human–machine symbiosis lies in mutual perception, cognition, and trust. This is realized through technologies such as the Internet of Things and digital twins, offering a comprehensive understanding of machine task execution.

Additionally, through knowledge acquisition and ergonomics analysis, machines are enabled to perceive and interpret human intentions. ② The core of human–machine symbiosis is the collaborative organization, planning, and decision-making processes between humans and machines. This entails self-organization within the broader system, the planning of human–machine movements and system resource allocation, and the application of intelligent decision-making during production. ③ At the heart of human–machine symbiosis is collaborative interaction, control, and evolution. This involves rich interactions between humans and machines, introducing human cognitive models into machine intelligence through methodologies such as deep learning. This enhances machine skill strategy optimization, imbuing machines with higher-level intelligence and capability for more intricate collaborative tasks.

Although human–machine symbiotic intelligent manufacturing is progressing from interactive collaboration to deeper bidirectional cognition and higher-level intelligent integration, it remains at an early stage. Numerous challenges persist, such as real-time human–machine–environment perception analysis, fostering human–machine trust and addressing machine psychological concerns, allocating tasks to multiple individuals and machines in abnormal situations, creating plug-and-play scalable human–machine AI agents, and more. Despite these challenges, human–machine symbiotic intelligent manufacturing is in the ascendant phase, steadily advancing toward comprehensive, diverse, and systematic integration as it gains momentum in various industrial applications.

In the front of "research on human–machine symbiotic intelligent manufacturing under the Industrial 5.0 environment", the foremost countries based on core paper count are the USA, China, and Sweden (Table 1.2.1). Leading institutions in terms of core paper output include KTH Royal Institute of Technology, Hong Kong Polytechnic University, and University of Patras (Table 1.2.2). Analyzing the main collaborative network among countries (Figure 1.2.1), the USA emerges as a prominent collaborator with various nations. Examining major institutional collaborations (Figure 1.2.2), it is evident that the KTH Royal Institute of Technology, Hong Kong Polytechnic University, University of Patras, and Beijing Institute of Technology have established close collaborative ties. As indicated in the Table 1.2.3, the USA ranks first, followed by China in terms of citing paper counts. Notably, the key institutions for citing paper counts include KTH Royal Institute of Technology, George Washington University, and University of Oulu (Table 1.2.4).

The Figure 1.2.3 illustrates the developmental trajectory of the front of "research on human–machine symbiosis intelligent manufacturing under the Industrial 5.0 environment". Fueled by the imperative for personalized, intricate product scaling, flexibility, and automation in production, pivotal technologies such as human–machine mutual perception–cognition–trust, human–machine collaborative organization–planning–decision, and human–machine collaborative interaction–control–evolution are being innovated. This evolution marks a shift from "individual intelligence integration" toward "collective intelligence integration" and "intelligent coevolution", culminating in a novel manufacturing paradigm characterized by the mutual and symbiotic coexistence of humans and machines.

Table 1.2.1 Countries with the greatest output of core papers on "research on human–machine symbiosis intelligent manufacturing under the Industrial 5.0 environment"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per aper	Mean year
1	USA	13	44.83	633	48.69	2021.5
2	China	7	24.14	569	81.29	2021.7
3	Sweden	5	17.24	446	89.20	2021.4
4	Greece	5	17.24	183	36.60	2022.0
5	India	4	13.79	493	123.25	2020.8
6	Republic of Korea	3	10.34	402	134.00	2021.7
7	Australia	3	10.34	392	130.67	2020.7
8	Germany	3	10.34	297	99.00	2021.7
9	Italy	3	10.34	283	94.33	2020.3
10	Turkey	3	10.34	242	80.67	2020.7

Table 1.2.2 Institutions with the greatest output of core papers on "research on human–machine symbiosis intelligent manufacturing under the Industrial 5.0 environment"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	KTH Royal Institute of Technology	4	13.79	366	91.50	2021.8
2	Hong Kong Polytechnic University	3	10.34	177	59.00	2022.0
3	University of Patras	3	10.34	112	37.33	2022.0
4	University of Auckland	2	6.90	285	142.50	2021.5
5	University of Johannesburg	2	6.90	278	139.00	2022.0
6	Beijing Institute of Technology	2	6.90	81	40.50	2022.0
7	Zhejiang University	2	6.90	81	40.50	2022.0
8	George Washington University	2	6.90	73	36.50	2022.0
9	Berlin School of Economics and Law	2	6.90	71	35.50	2022.0
10	Deakin University	1	3.45	281	281.00	2019.0

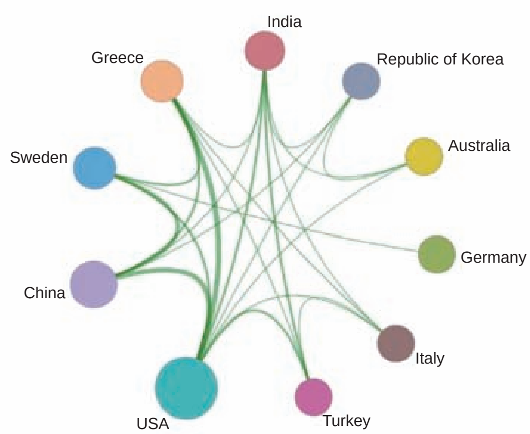

Figure 1.2.1 Collaboration network among major countries in the engineering research front of "research on human–machine symbiosis intelligent manufacturing under the Industrial 5.0 environment"

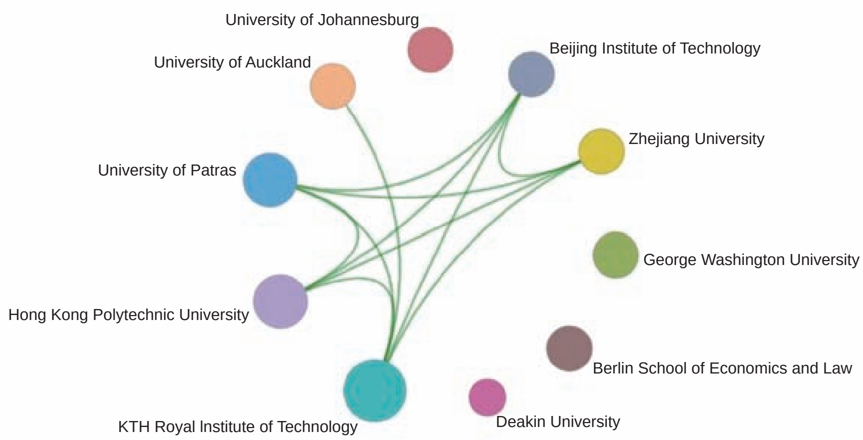

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "research on human–machine symbiosis intelligent manufacturing under the Industrial 5.0 environment"

Table 1.2.3 Countries with the greatest output of citing papers on “research on human–machine symbiosis intelligent manufacturing under the Industrial 5.0 environment”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	USA	31	17.32	2021.4
2	China	29	16.20	2021.5
3	UK	21	11.73	2021.2
4	India	21	11.73	2021.2
5	Italy	15	8.38	2020.5
6	Kingdom of Saudi Arabia	11	6.15	2021.6
7	Sweden	11	6.15	2021.5
8	Canada	11	6.15	2020.6
9	Germany	10	5.59	2021.3
10	Brazil	10	5.59	2020.9

Table 1.2.4 Institutions with the greatest output of citing papers on “research on human–machine symbiosis intelligent manufacturing under the Industrial 5.0 environment”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	KTH Royal Institute of Technology	6	13.95	2021.8
2	George Washington University	5	11.63	2021.6
3	University of Oulu	4	9.30	2021.5
4	Ismaili Muslim University	4	9.30	2020.8
5	Velore Institute of Technology	4	9.30	2022.0
6	University of Johannesburg	4	9.30	2021.2
7	Hong Kong Polytechnic University	4	9.30	2022.0
8	Taif University	3	6.98	2021.7
9	Berlin School of Economics and Law	3	6.98	2022.0
10	Deakin University	3	6.98	2021.3

1.2.2 Research on unmanned aerial vehicle dispatching and path optimization in logistics

In recent years, researchers both domestically and internationally have been exploring various logistical elements related to unmanned aerial vehicles (UAVs), ground take-off and landing facilities, and logistics warehouses. These investigations encompass a range of topics, including path planning, scheduling optimization, trajectory optimization, and operational management.

(1) UAV logistics path planning in urban scenarios

Research in this area encompasses topics such as the traveling salesman problem with drones (TSP-D), the vehicle routing problem

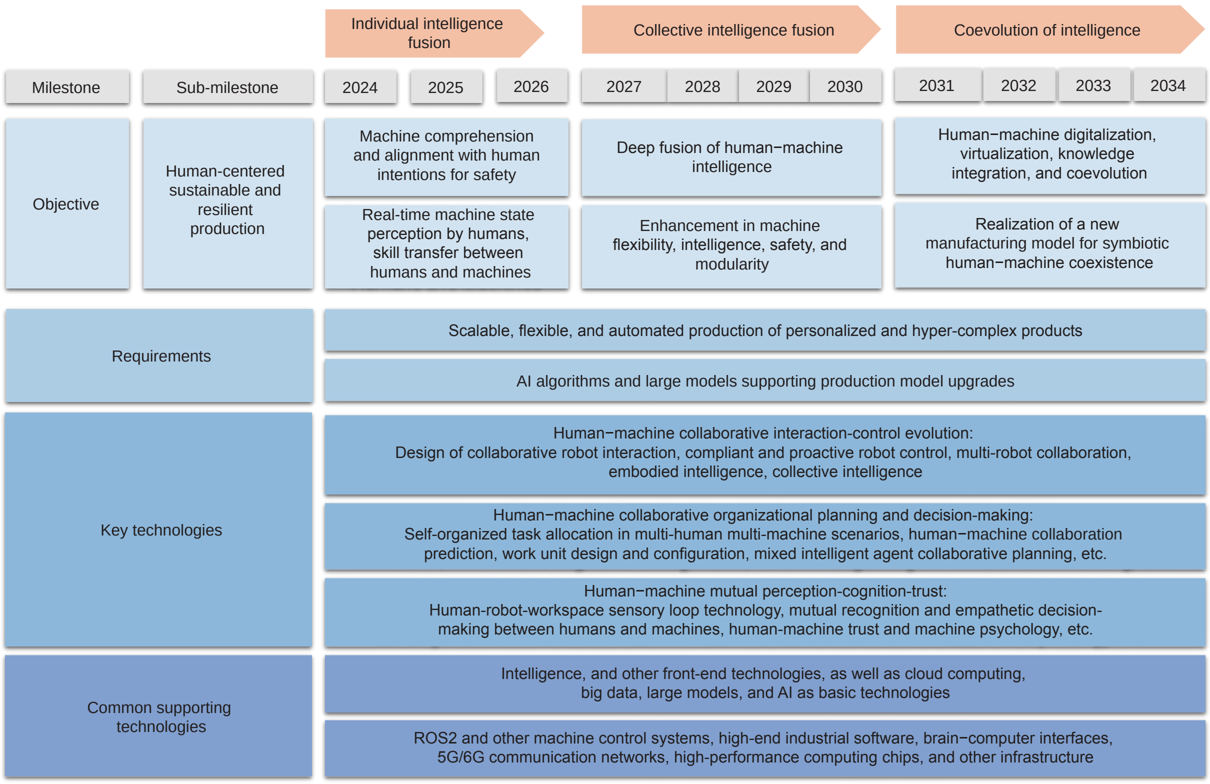

Figure 1.2.3 Roadmap of the engineering research front of “research on human–machine symbiosis intelligent manufacturing under the Industrial 5.0 environment”

with drones (VRP-D), and various aspects of vehicle-drone joint path problems. Addressing limitations such as UAVs’ restricted flying distance due to battery capacity and shorter flight ranges, researchers have turned their attention to joint delivery route planning involving both vehicles and drones. This approach leverages the advantages of both ground vehicles and aerial drones. This has resulted in the formulation of multiple problem models, including vehicle-assisted drones, drone-assisted vehicles, independent delivery, and parallel delivery. Current research incorporates multiple objective optimizations, considering factors such as cost, path efficiency, time windows, energy consumption, and carbon emissions. In addition to drawing from classical path-planning techniques, contemporary studies integrate dynamic factors found in urban settings, such as flight restrictions, public safety and privacy concerns, and changes in demand for last-mile delivery. This integration ensures more practical and feasible outcomes, signifying the future trajectory of UAV logistics delivery path research.

(2) Drone scheduling challenges

Drone scheduling builds upon path planning and focuses on the real-time allocation of multi-drone delivery tasks and the arrangement of ground support resources. The process involves comprehensive considerations of factors such as available delivery time, support facility capacity, and charging station layout. This includes mixed scheduling involving both vehicles and drones, scheduling for drone fleets, and the optimization of charging stations, warehouses, and take-off and landing facility layouts. Recent studies have introduced unpredictable urban environmental factors such as wind fields, tall obstructions, no-fly zones, and risks associated with falling objects into constraint conditions. In the future, integrating variables such as logistics warehouse locations, fleet size, battery charging, nonlinear energy consumption, and drone malfunctions into more complex scheduling optimization models will likely become new research foci.

(3) Trajectory optimization and operational management

Unlike path planning, which focuses on two-dimensional route design, trajectory optimization is concerned with designing three-dimensional space trajectories. Optimization models aim not only to minimize flight time and energy consumption but also to accommodate constraints imposed by various air restriction zones and ground obstacles. Operational management research delves into factors influencing UAV logistics, encompassing policy, technological environments, market size, business models, and more.

Algorithms addressing the aforementioned logistics delivery path and scheduling optimization challenges can be categorized into two main types: exact algorithms and heuristic algorithms. Exact algorithms and solvers are commonly applied for precise solutions to small-scale problems, while heuristic algorithms are employed for nearly optimal solutions to larger-scale problems. The research focused of heuristic algorithms centers on solution quality, convergence speed, and potential for improvement. As model complexity increases, enhancing algorithm efficiency and accuracy becomes a renewed priority. As the field advances, establishing systems for validating algorithms will emerge as a new research area.

Electrically driven zero-emission drones align seamlessly with sustainable development trends. Research evaluating logistics carbon emissions from a socioecological perspective represents a prominent current research direction. The assessment typically involves ground trucks, electric vehicles, and motorcycles. For UAV logistics transportation, a new research direction revolves around the "green routing" problem, aiming to reduce CO_2 emissions from combined vehicle-drone delivery systems. Future exploration may also delve into incorporating clean energy sources such as solar and wind power into the charging network, as well as investigating the relationship between drone delivery system efficiency and charging layout. Additionally, due to drones flying at low altitudes, issues such as noise pollution, risks from falling objects, and infringement of public privacy also hold significant research value.

In the front of "research on unmanned aerial vehicle dispatching and path optimization in logistics", the countries with the highest core paper counts are the USA, China, and Germany (Table 1.2.5). Noteworthy producing institutions include Northeastern University, Massachusetts Institute of Technology, and Portland State University (Table 1.2.6). Analyzing major country collaboration networks (Figure 1.2.4), there is substantial collaboration between Canada, the USA, China, and other nations. Within major institution collaboration networks (Figure 1.2.5), close collaboration is observed between institutions such as Northeastern University, Massachusetts Institute of Technology (MIT), and Binghamton University in the USA. As highlighted in Table 1.2.7, China leads in citing paper count. Likewise, Table 1.2.8 demonstrates that the institutions with the

Table 1.2.5 Countries with the greatest output of core papers on "research on unmanned aerial vehicle dispatching and path optimization in logistics"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	17	37.78	1 641	96.53	2019.2
2	China	5	11.11	444	88.80	2019.0
3	Germany	4	8.89	294	73.50	2018.2
4	Turkey	3	6.67	481	160.33	2018.0
5	Singapore	3	6.67	309	103.00	2019.3
6	Italy	3	6.67	295	98.33	2019.0
7	Canada	3	6.67	250	83.33	2019.0
8	India	3	6.67	169	56.33	2020.0
9	Denmark	2	4.44	206	103.00	2018.0
10	Spain	2	4.44	201	100.50	2019.5

Table 1.2.6 Institutions with the greatest output of core papers on “research on unmanned aerial vehicle dispatching and path optimization in logistics”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Northeastern University, USA	3	6.67	231	77.00	2020.7
2	Massachusetts Institute of Technology	3	6.67	223	74.33	2020.0
3	Portland State University	3	6.67	218	72.67	2018.7
4	National University of Singapore	2	4.44	259	129.50	2019.5
5	Friedrich Schiller University Jena	2	4.44	177	88.50	2019.5
6	State University of New York at Binghamton	2	4.44	111	55.50	2020.0
7	Institute of Science and Technology of Porto	1	2.22	564	564.00	2017.0
8	University of Trás-os-Montes and Alto Douro	1	2.22	564	564.00	2017.0
9	Galatasaray University	2	6.90	71	35.50	2022.0
10	Catholic University of Leuven	1	3.45	281	281.00	2019.0

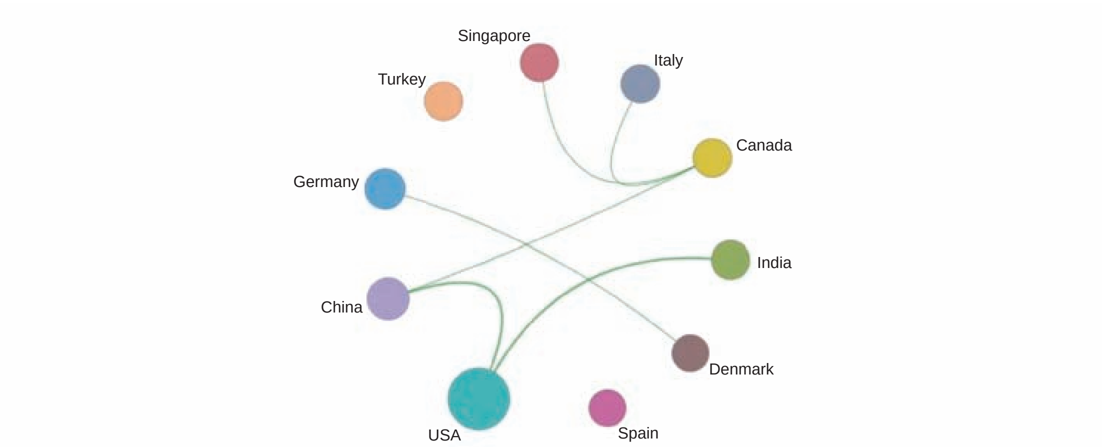

Figure 1.2.4 Collaboration network among major countries in the engineering research front of “research on unmanned aerial vehicle dispatching and path optimization in logistics”

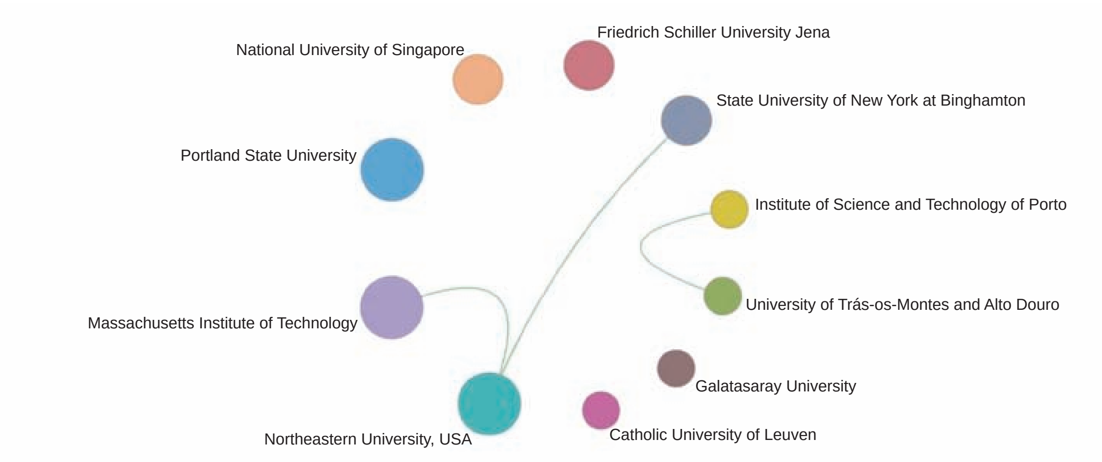

Figure 1.2.5 Collaboration network among major institutions in the engineering research front of “research on unmanned aerial vehicle dispatching and path optimization in logistics”

Table 1.2.7 Countries with the greatest output of citing papers on "research on unmanned aerial vehicle dispatching and path optimization in logistics"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	98	24.69	2020.3
2	USA	82	20.65	2019.9
3	UK	46	11.59	2020.1
4	Germany	27	6.80	2019.7
5	Republic of Korea	26	6.55	2019.7
6	France	24	6.05	2020.0
7	Italy	23	5.79	2020.2
8	Spain	22	5.54	2019.4
9	India	18	4.53	2020.7
10	Canada	16	4.03	2020.5

Table 1.2.8 Institutions with the greatest output of citing papers on "research on unmanned aerial vehicle dispatching and path optimization in logistics"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Sejong University	6	13.95	2021.8
2	Chinese Academy of Sciences	5	11.63	2021.6
3	University of Derby	4	9.30	2021.5
4	Southeast University	4	9.30	2020.8
5	National University of Singapore	4	9.30	2022.0
6	Hong Kong Polytechnic University	4	9.30	2021.2
7	Zhejiang University	4	9.30	2022.0
8	University of Macau	3	6.98	2021.7
9	Rongxuan University	3	6.98	2022.0
10	Kyung Hee University	3	6.98	2021.3

highest citing paper counts are Sejong University in Republic of Korea, Chinese Academy of Sciences, and University of Derby in the UK. Figure 1.2.6 visually represents the developmental trajectory in the front of "research on unmanned aerial vehicle dispatching and path optimization in logistics".

1.2.3 Research on the symbiotic logic and governance of major engineering innovation ecosystems

In light of the current state of research and practical management of mega-projects, the frontier areas of study in the symbiotic logic and governance of mega-project innovation ecosystems primarily include the following two aspects.

(1) Symbiotic evolution and value co-creation in mega-project innovation ecosystems

In recent years, the challenges associated with technological innovation in the context of mega-projects have been escalating. On

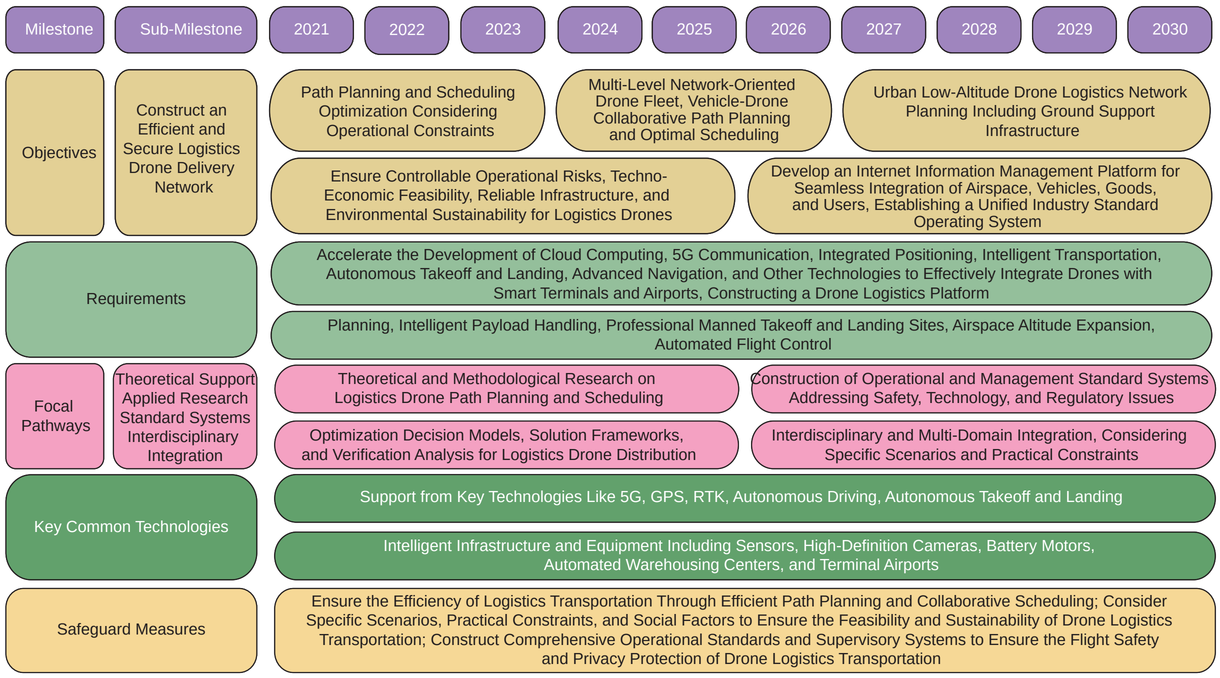

Figure 1.2.6 Roadmap of the engineering research front of "research on unmanned aerial vehicle dispatching and path optimization in logistics"

one hand, the diversified demands of various stakeholders, the transformative impact of emerging technologies, and the trend towards digital empowerment have accentuated the strategic importance of innovation in mega-projects, rendering it a critical determinant of project success. On the other hand, innovation activities within mega-projects confront a unique set of challenges, including distinct innovation contexts, rigid target requirements, dynamic phase evolution, and complex technological integration, which involve managerial issues divergent from those in conventional corporate technological innovation. In light of these considerations, the focal point of research in mega-project innovation management needs to shift from traditional technological innovation systems to innovation ecosystems.

An innovation ecosystem is a vibrant and evolving platform formed based on engineering innovation practices. It integrates the origins and processes of innovation, the participating actors and environmental elements, and the aggregation of resources and emergence of force fields into a systemic framework. This ecosystemic approach holds the potential to overcome the limitations of singular, linear, static, and closed research paradigms. The formation of such an ecosystem is predicated upon the establishment of relationships among various actors within the system, resulting in a tightly interconnected and co-evolving entity. These actors collaborate based on a consensus for value co-creation, thereby forming a value community.

In relation to the symbiotic evolution and value co-creation within mega-project innovation ecosystems, several research questions warrant further exploration: the self-organization and inter-organizational learning aimed at enhancing innovation capabilities in mega-projects; the dynamic evolutionary mechanisms of mega-project innovation ecosystems; the behavioral patterns of value co-creation within mega-project innovation ecosystems under the backdrop of digital transformation; and the orchestration and allocation of resources and value in mega-project innovation ecosystems based on symbiotic and mutually beneficial relationships.

(2) Governance mechanisms in mega-project innovation ecosystems

Compared to conventional projects, mega-projects exhibit multi-dimensional, multi-level, and multi-phase complexities, and their management practices face a myriad of intricate challenges. Given the need to marshal resources for problem-solving within a constrained timeframe, the governance of mega-projects is often closely associated with national systems. Consequently, governance research for mega-projects primarily revolves around specific aspects or systemic mechanisms, such as the "corporate-government–society" governance framework oriented towards social responsibility in mega-projects, or the "government–market" dual governance mechanisms targeting organizational models in mega-projects. The fundamental components of an innovation ecosystem are species (innovation actors), which form various communities through connections. These species and communities drive the overall evolution of the system through symbiotic competitive cooperation. Therefore, governance aimed at mega-project innovation ecosystems should adopt a complex systems perspective, combining the interactive relationships and deep characteristics among different types of innovation actors to design targeted governance strategies. This promotes the efficient and coordinated symbiotic evolution of the mega-project innovation ecosystem, forming a crucial platform that supports high-quality, high-level, and high-impact innovation outcomes, diffusion, and transformation. Currently, several research questions requiring further exploration include: the co-evolutionary governance of mega-project innovation ecosystems; governance of mega-project innovation ecosystems under a national system; and platform governance strategies for mega-project innovation ecosystems.

Existing research indicates that in the front of "research on the symbiotic logic and governance of major engineering innovation ecosystems", the top three countries in terms of the number of core papers are China, the UK, and Australia, as shown in Table 1.2.9. The countries with the highest citations per paper are Singapore, Australia, and the USA (Table 1.2.9). Within the network of core paper-producing countries (Figure 1.2.7), Chinese scholars have extensive collaborations with their counterparts in Australia, the USA, and the Netherlands. Specifically, Chinese scholars have constructed theoretical frameworks for the formation, evolution, and governance of mega-project innovation ecosystems, drawing upon significant projects such as the Hong Kong-Zhuhai-Macau Bridge. These frameworks delineate the role of ecosystem integrators and elucidate the mechanisms for value co-creation within innovation ecosystems. Relying on major projects like the London Underground, Heathrow Airport Terminal, and the Bang Na Expressway, international scholars have explored various facets of mega-project innovation ecosystems, including significance construction, "windows of opportunity", incremental and open innovation, and cross-organizational learning.

In the front of "research on the symbiotic logic and governance of major engineering innovation ecosystems", the top three institutions in terms of the number of core papers are Tongji University, University College London, and Shanghai Jiao Tong University (Table 1.2.10). Within the network of core publication-producing institutions (Figure 1.2.8), collaborations are particularly frequent among Tongji University, Chongqing University, and Huazhong Agricultural University, as well as between Aalto University and the University of Oulu. Table 1.2.11 reveals that China, the UK, and Australia lead in the number of citing papers. Table 1.2.12 shows that the top three institutions in terms of the number of citing papers are Tongji University, University

Table 1.2.9 Countries with the greatest output of core papers on "research on the symbiotic logic and governance of major engineering innovation ecosystems"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	21	46.67	397	18.90	2020.4
2	UK	12	26.67	241	20.08	2020.2
3	Australia	6	13.33	311	51.83	2018.0
4	USA	4	8.89	192	48.00	2017.8
5	Finland	4	8.89	106	26.50	2019.8
6	Germany	2	4.44	62	31.00	2019.0
7	Canada	2	4.44	60	30.00	2020.0
8	Norway	2	4.44	20	10.00	2021.0
9	Netherlands	2	4.44	8	4.00	2021.5
10	Singapore	1	2.22	57	57.00	2018.0

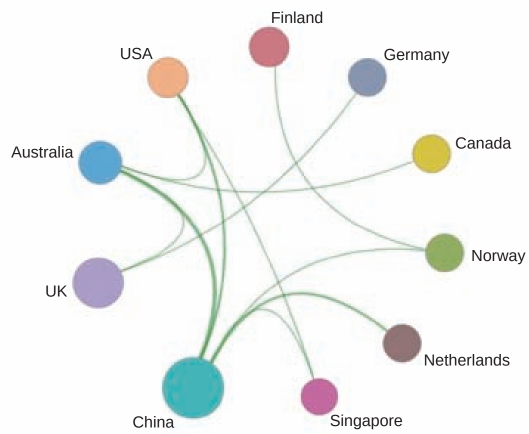

Figure 1.2.7 Collaboration network among major countries in the engineering research front of "research on the symbiotic logic and governance of major engineering innovation ecosystems"

Table 1.2.10 Institutions with the greatest output of core papers on "research on the symbiotic logic and governance of major engineering innovation ecosystems"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Tongji University	9	20.00	180	20.00	2020.3
2	University College London	4	8.89	143	35.75	2018.8
3	Shanghai Jiao Tong University	3	6.67	162	54.00	2019.0
4	Aalto University	3	6.67	98	32.67	2019.3
5	Chongqing University	3	6.67	24	8.00	2021.3
6	Nanjing University	2	4.44	76	38.00	2020.5
7	University of Leeds	2	4.44	55	27.50	2020.5
8	University of Oulu	2	4.44	49	24.50	2019.5
9	Huazhong Agricultural University	2	4.44	47	23.50	2019.5
10	University of Sussex	2	4.44	30	15.00	2020.5

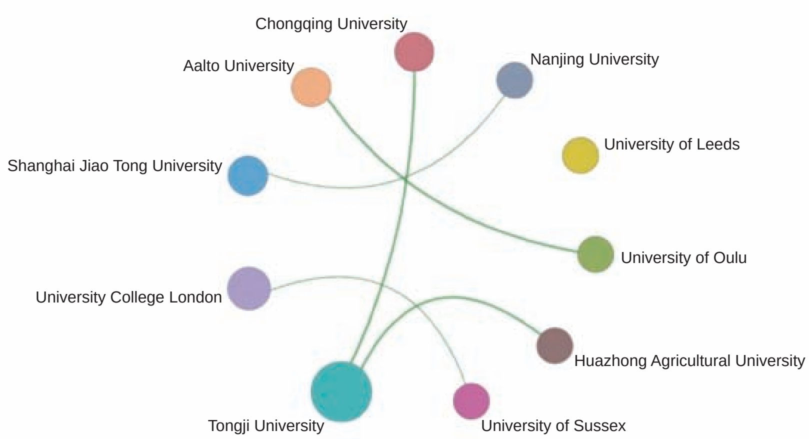

Figure 1.2.8 Collaboration network among major institutions in the engineering research front of "research on the symbiotic logic and governance of major engineering innovation ecosystems"

Table 1.2.11 Countries with the greatest output of citing papers on "research on the symbiotic logic and governance of major engineering innovation ecosystems"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	233	34.37	2021.1
2	UK	108	15.93	2020.6
3	Australia	101	14.90	2020.6
4	USA	60	8.85	2021.0
5	Italy	33	4.87	2021.7
6	Canada	29	4.28	2021.0
7	India	25	3.69	2021.2
8	Finland	25	3.69	2021.0
9	Norway	25	3.69	2020.4
10	Netherlands	22	3.24	2021.4

Table 1.2.12 Institutions with the greatest output of citing papers on "research on the symbiotic logic and governance of major engineering innovation ecosystems"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Tongji University	45	19.91	2021.0
2	University College London	27	11.95	2020.2
3	Shanghai Jiao Tong University	26	11.50	2020.9
4	University of Leeds	22	9.73	2020.8
5	The Hong Kong Polytechnic University	19	8.41	2020.6
6	Chongqing University	18	7.96	2021.6
7	Politecnico di Milano	15	6.64	2021.8
8	Nanjing Audit University	14	6.19	2021.0
9	University of Technology Sydney	14	6.19	2020.3
10	Deakin University	13	5.75	2020.5

College London, and Shanghai Jiao Tong University. Figure 1.2.9 outlines the developmental trajectory of the front of "research on the symbiotic logic and governance of major engineering innovation ecosystems".

2 Engineering development fronts

2.1 Trends in Top 10 engineering development fronts

In the domain of engineering management, the top ten global fronts in engineering development for the current year include "linear and integer programming solvers", "intelligent factory operation and maintenance systems based on industrial internet and big data", "methods and systems for automatic building design generation based on deep learning", "smart home health care systems for the elderly", "comprehensive urban safety risk monitoring and early warning platform", "supply chain risk management

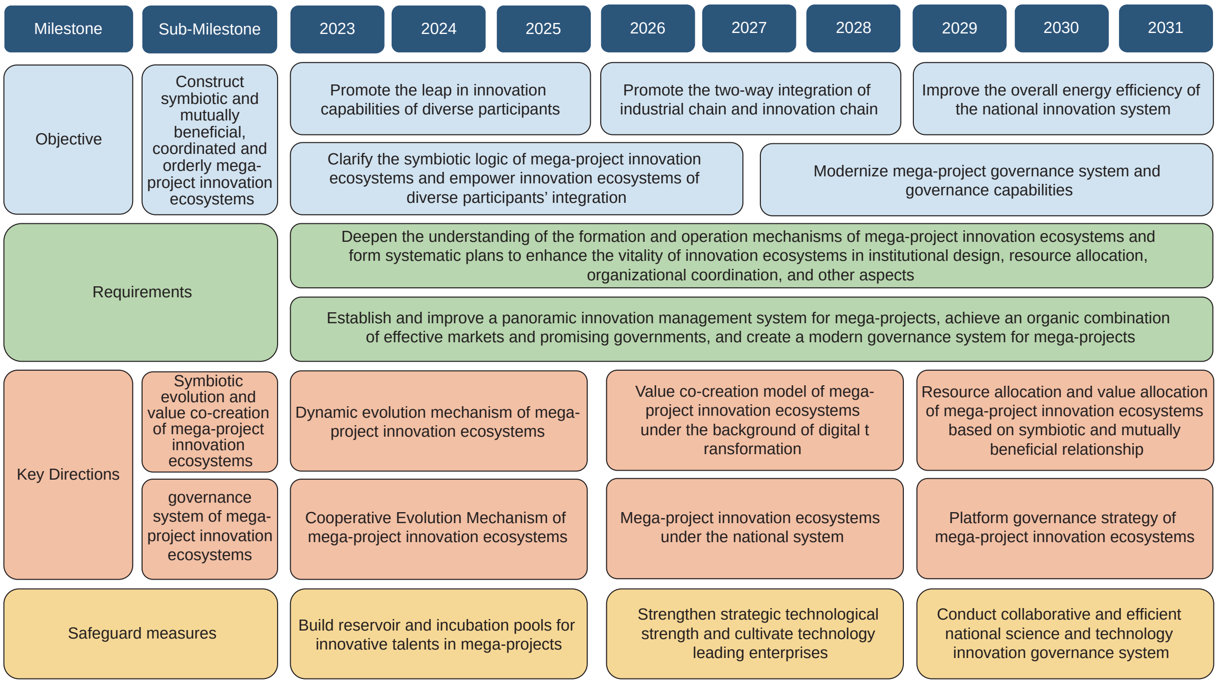

Figure 1.2.9 Roadmap of the engineering research front of "research on the symbiotic logic and governance of major engineering innovation ecosystems"

platform based on intelligent simulation", "industrial equipment health monitoring and data fusion analysis system", "prediction and early warning system for external shocks and internal disturbances in energy systems", "financial risk management system based on federated learning", and "network audio-visual recommendation algorithms and content supervision intelligent platform". The core patent statuses for these fronts are detailed in Tables 2.1.1 and 2.1.2. These ten engineering development fronts span a multitude of disciplines, including medicine, architecture, transportation, and computer science. Among them, "linear and integer programming solvers", "intelligent factory operation and maintenance systems based on industrial internet and big data", and "methods and systems for automatic building design generation based on deep learning" are identified as the focal fronts. Subsequent sections will provide a comprehensive analysis of their current developmental trajectories and future trends.

(1) Linear and integer programming solvers

Linear and integer programming solvers, utilized as engineering software, employ mathematical optimization algorithms to address extensive and intricate challenges faced by public institutions and commercial organizations. This technology has garnered widespread application across defense, energy, manufacturing, transportation, communications, finance, and other sectors, yielding substantial value. The research and development of these solvers demand elevated expertise in mathematical optimization theory and large-scale computer system engineering, combined with significant investments in time and capital, thereby presenting substantial risks. At present, the global dominant market for solvers is monopolized byproducts from three American companies (IBM, Gurobi, and FICO) with formidable barriers to market entry.

Since 2018, Chinese domestic research teams have sequentially introduced indigenous solvers, including the Chinese Academy of Sciences' open-source solver CMIP, Shanshu Technology's COPT, Alibaba Cloud's MindOPT, and Huawei's Tianchou (OPTV) solver, among others. Over the span of three decades of solver product development, research teams worldwide have consistently elevated performance, thereby enhancing computational efficiency and the aptitude to solve large-scale problems. Traditional solver advancement has predominantly relied upon mathematical programming theory and algorithms such as the simplex method, dual theory, branch-and-bound method, and heuristic algorithms, among others.

Table 2.1.1 Top 10 engineering development fronts in engineering management

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Linear and integer programming solvers	103	328	3.18	2020.3
2	Intelligent factory operation and maintenance systems based on industrial internet and big data	66	1 090	16.52	2020.9
3	Methods and systems for automatic building design generation based on deep learning	26	208	8.00	2020.0
4	Smart home health care systems for the elderly	53	177	3.34	2019.8
5	Comprehensive urban safety risk monitoring and early warning platform	94	237	2.52	2020.6
6	Supply chain risk management platform based on intelligent simulation	59	334	5.66	2020.9
7	Industrial equipment health monitoring and data fusion analysis system	23	379	16.48	2020.4
8	Prediction and early warning system for external shocks and internal disturbances in energy systems	16	121	7.56	2020.2
9	Financial risk management system based on federated learning	35	74	2.11	2021.5
10	Network audio-visual recommendation algorithms and content supervision intelligent platform	15	196	13.07	2019.1

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

No.	Engineering development front	2017	2018	2019	2020	2021	2022
1	Linear and integer programming solvers	6	15	9	16	24	8
2	Intelligent factory operation and maintenance systems based on industrial internet and big data	0	1	8	13	20	16
3	Methods and systems for automatic building design generation based on deep learning	1	4	5	7	2	34
4	Smart home health care systems for the elderly	4	11	11	5	8	13
5	Comprehensive urban safety risk monitoring and early warning platform	9	4	10	8	22	10
6	Supply chain risk management platform based on intelligent simulation	4	3	0	7	17	9
7	Industrial equipment health monitoring and data fusion analysis system	3	0	2	5	5	31
8	Prediction and early warning system for external shocks and internal disturbances in energy systems	2	2	1	3	2	66
9	Financial risk management system based on federated learning	0	0	0	4	9	30
10	Network audio-visual recommendation algorithms and content supervision intelligent platform	2	6	1	3	0	28

However, recent technological breakthroughs in computing, coupled with the evolution of artificial intelligence and machine learning algorithms, have introduced fresh avenues for research in the realm of linear and integer programming solvers. These avenues encompass but are not confined to large-scale distributed parallel computing, artificial intelligence, and quantum computing. Current developmental trajectories primarily center around expeditiously resolving extensive and intricate challenges to furnish superior global optimization decisions for institutions and corporations, augmenting their capacity to respond to unforeseeable changes.

(2) Intelligent factory operation and maintenance systems based on industrial internet and big data

As the industrial internet and big data technology continue to advance and deeply integrate with the manufacturing sector, intelligent factories have emerged, facilitating a close connection and interaction among production equipment, sensors, and other industrial components. The real-time collection, sharing, and analysis of extensive production data have become feasible. In this context, the maintenance management model within factories has progressively transitioned toward digitization, networking, and intelligence. This evolution has given rise to intelligent factory maintenance systems that are grounded in the comprehensive interconnection of people, machines, materials, methods, and the environment. These systems are supported by the collection and management of production data throughout the entire lifecycle. Leveraging artificial intelligence tools, this system can perform real-time monitoring of production processes, precisely manage equipment statuses, and intelligently issue maintenance instructions. Consequently, a new service-oriented maintenance system has been established, extending across the entire industrial and value chains.

The present research emphasizes several key areas: enhancing data management linkage, precision, and timeliness within the maintenance system; improving equipment control accuracy and responsiveness; and enhancing system operational reliability and integration. To achieve these goals, there is a strong emphasis on industrial big data collection and management technology, equipment fault diagnosis and maintenance technology driven by industrial big data, and technological integration and development at the system level.

However, challenges persist for intelligent factory maintenance systems, including insufficient levels of intelligence, high integration difficulty, and stringent data security requirements. As a result, there is a need for demand-driven custom development of maintenance systems, exploration of multisource heterogeneous data fusion technology, and optimization of encryption and authentication technology. These areas are likely to emerge as central focal points for future research and development efforts.

(3) Methods and systems for automatic building design generation based on deep learning

The automatic generation of architectural schemes entails the computer-based creation of architectural design concepts and plans. This process occurs through automated means, relying on factors such as project background, design objectives, and requirements. Parametric design technology plays a role in realizing this process. However, the resultant architectural schemes are contingent upon parametric models constructed independently by designers, thereby constraining the level of automation and intelligence achievable. While existing architectural design materials encapsulate designers' experience and expertise, their potential has not been fully harnessed in previous research due to their intricate attributes. These attributes encompass multidisciplinary intersections, diverse forms, and pronounced timeliness.

With the progressive enhancement of deep learning technology's capacity to extract features from multidimensional, multimodal, and multiscale data, approaches and systems for automatically generating architectural schemes, propelled by deep learning, have emerged as a pivotal driving force, a significant avenue, and a novel platform for expediting the intelligent transformation and advancement of the architectural design industry. Architectural design drawings constitute the core content within existing design materials and serve as the principal visual mode for presenting design concepts.

Recent scholarly investigations have drawn inspiration from thought paradigms within the realm of computer-generated imagery, with a specific focus on architectural scheme design. Key discussions have revolved around semantic representation of architectural schemes, architectural style transfer, amalgamation of multimodal features within architectural design, applications and refinements of deep generative models, as well as automated compliance assessments.

To further bolster the dependability of automatically generated architectural schemes and elevate the general level of intelligence within design systems, upcoming predominant research trajectories will encompass human–machine collaborative design modes that harmonize regularity and creativity. Additionally, research will delve into enhancing design data driven by intricate architectural parametric models, recognizing and autonomously verifying ambiguous design specifications, and cultivating methods and systems for generating architectural schemes that seamlessly integrate multidisciplinary engines and design principles.

(4) Smart home health care systems for the elderly

With the rapid proliferation of “inverted pyramid” and “empty nest” family structures, as well as a growing number of aging individuals with disabilities, the challenge posed by an aging population is intensifying. As of the conclusion of 2022, the demographic of individuals aged 65 and above has swelled to 210 million, constituting 14.9% of the total population. More than half of this group resides without children at home, a circumstance that thrusts many elderly individuals into the sphere of at-home care. To combat this predicament, the Intelligent Health Home Care System for the Elderly platform harmonizes contributions from medical institutions, communities, and corporations. It leverages advanced technologies such as the Internet of Things, cloud computing, big data, and artificial intelligence to comprehensively cater to the elderly’s requirements for at-home care.

The key research directions encompass: ① the development of innovative intelligent perception and real-time monitoring technologies; ② the creation of disease and risk prediction and management systems; ③ the establishment of intelligent early-warning and online diagnosis systems; and ④ the formulation of intelligent home interconnection systems.

Looking ahead, as the next wave of intelligent technology emerges and elderly home care becomes increasingly sophisticated, augmenting the comprehensiveness, precision, diversity, and integration of services will emerge as the industry’s future trends. These trends will interlace aspects of medical care, eldercare, community engagement, commerce, and governmental intervention, establishing an integrated platform for living, medical assistance, well-being, and recreational services. Precision advancement will harness emerging data analysis and artificial intelligence technologies to yield more precise prognostications and evaluations of the elderly’s health status. Diversified services will underscore individual distinctions and multifarious needs, catering to the varied and personalized requisites of the elderly to amplify their quality of life during later stages. Integrative development will spur the amalgamation and dissemination of technology and resources across various domains, leading to more effective and all-encompassing home care services.

(5) Comprehensive urban safety risk monitoring and early warning platform

The Integrated Urban Safety Risk Monitoring and Early Warning Platform refers to a digital infrastructure designed from a strategic perspective of overall urban safety and large-scale emergency response. This platform leverages modern information technologies such as the Internet of Things, cloud computing, big data, and artificial intelligence to construct a network that supports urban safety risk monitoring, disaster situational awareness, intelligent risk assessment, early warning, and coordinated response. It focuses on various types of risks, including natural disasters, public health incidents, accidental catastrophes, social safety events, and macro-environmental factors. The aim is to elevate the level of intelligent identification, prevention, mitigation, and management of urban risks, thereby ensuring the secure development of cities. Currently, the Integrated Urban Safety Risk Monitoring and Early Warning Platform in China has entered the pilot construction phase. However, rapid urbanization has led to an increase in urban population and an expansion of infrastructure systems, making urban systems increasingly complex. Concurrently, the frequency of extreme events under climate change, the aggregation of multiple types of disasters, and the prominence of disaster chains have escalated the composite and systemic safety risks that cities face. Against this backdrop, the construction and developmental directions of the Integrated Urban Safety Risk Monitoring and Early Warning Platform include: refining cross-departmental and cross-regional data sharing and coordinated response mechanisms; researching comprehensive urban sensing technologies that mutually calibrate the accuracy of space-based, aerial-based, and ground-based monitoring; employing advanced technologies such as artificial intelligence and digital twins to develop precise and intelligent identification, assessment, and prediction technologies for urban safety risks, particularly for multi-type cascading coupled risks; enhancing the dissemination of early warning information through multiple means, channels, and audiences; and improving the intrinsic resilience of monitoring and early warning hardware facilities, as well as strengthening the platform’s capabilities in information security risk prevention and control.

(6) Supply chain risk management platform based on intelligent simulation

Presently, the robust advancement of digitization and globalization has ushered in an abundance of data, information, and emerging technological resources to fortify supply chains. However, this progress simultaneously engenders heightened complexity within supply chains, accentuating uncertainty and escalating risk levels, all while hastening market fluctuations. This increasingly intricate and unsettled milieu presents more profound trials to the realm of supply chain risk management. In the era of digitalization, intelligent simulation research methods find themselves uniquely positioned to address these challenges.

The Intelligent Simulation-Based Supply Chain Risk Management Platform offers distinct advantages. By crafting a virtual supply chain environment, this platform not only mimics existing supply chain strategies but also models the behaviors, decisions, interactions, and potential occurrences and propagation of risk events among diverse participants. This enables a more precise emulation of the supply chain's intricacy, dynamism, and variability. Consequently, decision-makers are empowered to assess the impact of various risks on the supply chain and formulate corresponding strategies for risk response.

This platform showcases innovative features such as diverse risk event modeling, decision support, multiscale simulation, and collaborative decision-making. Its applications span risk assessment and prognostication, supply chain adaptation and optimization, emergency response planning, and risk management training and drills. Additionally, intelligent simulation systems frequently encompass distributed simulation models capable of functioning across assorted network environments, including cloud setups. This architecture permits agents to opt for residency or movement on distinct server platforms based on the available computational load, thus facilitating comprehensive, detailed simulations of large-scale supply chains and system-wide computational enhancements.

In the days ahead, the Intelligent Simulation-Based Supply Chain Risk Management Platform is poised to assimilate more advanced artificial intelligence technologies such as machine learning and deep learning. This integration aims to bolster the precision and timeliness of risk prediction. Simultaneously, the platform is progressing toward heightened customization to cater to the specific requisites of diverse industries, companies, and risk scenarios. This trajectory will provide users with personalized analysis and decision-making support. In essence, the Intelligent Simulation-Based Supply Chain Risk Management Platform is slated for rapid evolution, swiftly becoming an indispensable instrument in the digital era for effective supply chain risk management.

(7) Industrial equipment health monitoring and data fusion analysis system

The Industrial Equipment Health Monitoring and Data Fusion Analysis System harnesses advanced sensing, 5G technology, artificial intelligence algorithms, and expert systems. It seamlessly integrates cloud computing, fog computing, edge computing, and other data processing paradigms to achieve real-time perception of the health status of industrial equipment. This approach enables precise fault diagnosis and prediction, thus facilitating the implementation of preemptive maintenance strategies aimed at averting unforeseen breakdowns.

Presently, in the face of intricate industrial equipment structures, varying operational conditions, and limited fault instances, scholars have turned to big data and digital twin technologies to propose novel theories for data generation and fusion analysis. They have also devised methods for fault migration diagnosis and prediction. Correspondingly, they have explored optimal operation and maintenance strategies. This endeavor necessitates the high-level fusion of extensive multimodal monitoring data, entailing the determination of data fusion levels, assessment of priorities for multimodal data fusion, and the incorporation of human factors analysis and decision-making within complex industrial contexts. The ultimate aim is to maximize service availability, curtail unplanned downtime, and diminish operational and maintenance expenses. These objectives guide the formulation of optimal operation and maintenance protocols for industrial equipment.

The swift progress of the Industrial Equipment Health Monitoring and Data Fusion Analysis System has effectively overseen the well-being of high-value-added equipment, encompassing CNC machine tools, aerospace machinery, and industrial robots. This has led to notable economic and societal gains. In the future, this system will emerge as a pioneering frontier in multidisciplinary engineering research and development. This encompasses ensuring the privacy and security of monitoring data for industrial equipment via blockchain technology, executing on-site and off-site joint monitoring and health management founded on digital twin technology, economizing materials and expediting operation and maintenance time through 3D printing of spare parts, deploying generative AI technology to facilitate the formulation of preemptive maintenance strategies, and delving into other groundbreaking possibilities.

(8) Prediction and early warning system for external shocks and internal disturbances in energy systems

Significant emergent events often exert a non-negligible impact on energy security, with both external shocks and internal disturbances concurrently affecting the safety of energy systems. External shocks include energy trade conflicts, major public safety incidents, and geopolitical instability, among others. Internal disturbances include short-term meteorological fluctuations, extreme weather interference, and abnormal operational conditions of facilities. Energy supply and consumption systems of varying structures exhibit corresponding complexity and diversity in the transmission pathways and feedback mechanisms of external shocks and internal disturbances. The impacts on the safe operation of systems manifest significant spatiotemporal heterogeneity. In-depth research is urgently needed in risk measurement, pattern recognition, early warning and prediction, impact assessment, and response strategies.

Primary research directions include: ① meteorological prediction technologies for energy systems; ② transmission mechanisms, evolutionary laws, and diffusion principles of significant emergent events in energy systems; ③ key technologies for early identification and predictive warning of external shocks and internal disturbances in energy systems; ④ coordinated safety warning mechanisms, multi-faceted safety assurance mechanisms, emergency supply mechanisms, and risk response mechanisms for energy systems. Emerging trends in these domains include: ① meteorological disturbance prediction technologies: innovations in ultra-short-term weather forecasting, large-scale long-term wind energy prediction methods, atmospheric circulation stability and disturbance prediction correction techniques, and lightning warning systems; ② early warning mechanisms for energy system shocks: development of key indicator identification and warning systems based on statistical patterns, macro-crisis analysis tools leveraging big data analytics, and risk identification technologies for energy infrastructure based on satellite and remote sensing; ③ research on the diffusion mechanisms of energy system shocks: exploration of dynamic downscaling studies based on climate models and research on climate change transmission pathways informed by global atmospheric models.

(9) Financial risk management system based on federated learning

Federated learning is an algorithmic framework tailored for the construction of machine learning models. Within this framework, multiple data owners collaborate to fulfill the training objectives of machine learning models while upholding the privacy and security of their individual data. The models derived from this joint training can then be shared and adopted by all participating data owners. Throughout the model training process, the original data remain within the custody of the respective data providers, and encrypted information is transferred and exchanged among the involved parties. This methodology yields models whose performance can approximate that of models trained on complete data.

In the realm of financial risk management, financial institutions perpetually strive to amass and scrutinize diverse data sources to mitigate information asymmetry and curtail risk assumptions. However, many data assets crucial for financial risk management cannot be directly harnessed by financial institutions owing to data security and privacy limitations. This impairs the full realization of their commercial value. Federated learning resolves this conundrum by facilitating the integration of financial data with data from various other domains. This synergy fosters the creation of more precise and comprehensive algorithmic models, thereby offering a more holistic perspective for managing financial risks.

Contemporary research predominantly centers on the fusion of data from financial institutions and other enterprises. This fusion is employed for tasks such as constructing investor profiles, evaluating individual credit ratings and repayment capabilities, gauging the operational status and future potential of small and medium-sized enterprises, conducting risk assessments of financiers, developing risk warning models grounded in data related to loan repayment during the loan process, and fostering collaboration among multiple financial institutions for endeavors such as credit card fraud detection, anti-money laundering prewarning, and identification. Moreover, insurance companies are utilizing multiparty data tied to the insured to undertake pricing studies for insurance products.

Anticipated future research trajectories encompass delineating the structure and development model of a federated learning ecosystem tailored for financial risk management. This involves establishing substantial big data platforms tailored for federated learning within the context of financial risk management. Additionally, future research will delve into the selection decisions and measurement of contributions made by diverse data contributors within the framework of federated learning. Methodological advancements will be pursued for applying federated machine learning in financial risk management scenarios. Furthermore, the explainability of financial federated learning models, the creation of expansive financial risk cognitive maps founded on federated learning, and the integration of artificial intelligence generated content (AIGC) within financial vertical domains through federated learning will all likely constitute burgeoning domains of exploration.

(10) Network audio-visual recommendation algorithms and content supervision intelligent platform

Online audio-visual recommendation algorithms are data-driven technologies that predict and match personalized content based on user interests and behavior, thereby fostering the growth of the digital economy. These algorithms analyze user viewing records, searches, and social behavior and recommend content of interest from an extensive array of resources. With technological advancements, algorithms are now able to combine multimodal features, individual attributes, and domain information to attain more accurate personalized recommendations. This enhancement in service quality strengthens the competitiveness of internet platforms. The main aspects of this advancement are as follows:

1) Data analysis techniques: traditional algorithms rely on historical behavior to forecast interests, but the era of big data necessitates the integration of various media forms, such as news and videos. Algorithms that combine multimodal features can analyze associations and provide precise recommendations. Large language models, such as BERT, are applied to recommendation systems, processing multidimensional data, extracting rich semantic information, and offering a comprehensive recommendation experience.

2) Products and services intelligent recommendation techniques: it is vital that algorithms ensure fairness in recommendations, avoiding discrimination and information silos, while promoting positive values. Strategies to increase recommendation diversity, reduce information islands, and safeguard user privacy are crucial. Constructing robust data security measures and personal information protection policies is essential to mitigate information leakage issues.

3) System development for different business scenarios: e-commerce platforms must provide equitable and quality recommendations, avoiding inequality due to divergent consumer capabilities. Video websites should broaden the recommendation information range to prevent user information isolation. Social media platforms need to decrease viewpoint polarization, create accurate recommendation mechanisms, and guide healthy development.

In the global landscape, the USA and China are the main competitors, boasting numerous patents and high citation numbers. China's Foxconn leads in this field, with Chinese universities emphasizing theoretical innovation, while the industry centers on practical effects. Conversely, the USA is dedicated to enhancing user experience, focusing on personalized content recommendations for mobile intelligent terminals, encompassing deep learning and multimodal recommendation technology.

Future prospects indicate that online audio-visual recommendation algorithms will continue to evolve across various dimensions, reflecting a complex interplay between technology, ethics, commerce, and social considerations.

2.2 Interpretations for three key engineering development fronts

2.2.1 Linear and integer programming solvers

The research focused of linear and integer programming solvers centers on the amalgamation of mathematical programming theory and computer application technology. Mathematical programming theory constitutes the foundational basis of mathematical programming solvers. In 1947, George Dantzig, renowned as the “father of linear programming”, introduced the “simplex method”, which proficiently addressed linear programming problems. This method later garnered recognition as one of the most significant algorithms of the 20th century. In 1979, L. Khachiyan pioneered the ellipsoid algorithm, providing the inaugural proof that linear programming problems could be solvable in polynomial time. However, its computational efficiency proved inadequate, impeding practical application. In 1984, N. Karmarkar conceived the interior point algorithm, the premier practically applicable polynomial-time algorithm for linear programming. In the realm of integer programming, Ralph E. Gomory unveiled the primary general linear integer programming convergence algorithm, the cutting plane algorithm, in 1958. Subsequent scholars introduced algorithms such as branch and bound, as well as branch and cut. In the 1980s, concurrent with the advancement of computer technology, endeavors emerged to create solver software utilizing computers. The foremost commercial solvers worldwide encompass IBM CPLEX, Gurobi, and FICO Xpress. CPLEX, developed in 1988 by American mathematician Robert Bixby and colleagues, was acquired by ILOG in 1997 and subsequently by IBM in 2009. In 2008, core developers from the CPLEX solver team (Zonghao Gu, Edward Rothberg, and Robert Bixby) founded Gurobi. In 1983, Dash Optimization in Edinburgh created Xpress, which was acquired by the American credit enterprise FICO in 2008. In addition to these commercial solvers, global open-source solvers include Germany’s ZIB-developed SCIP, Google’s OR-Tools, and the COIN-OR foundation’s CBC. In recent times, domestic research groups have introduced self-developed solvers. In 2018, the team led by Dai Yuhong at the Chinese Academy of Sciences introduced the inaugural open-source integer programming solver, CMIP. In 2019, Shanshu Technology launched China’s first commercial linear programming solver, COPT. In 2020, Alibaba DAMO Academy’s Decision Intelligence Laboratory introduced the commercial solver MindOpt. Huawei debuted the Tianchou (OPTV) AI solver in 2021. As of the conclusion of June 2023, on the solver assessment platform offered by Professor Hans Mittelmann at Arizona State University, Shanshu Technology, Gurobi, and Huawei developed solvers ranked among the top three in linear programming. Notably, Gurobi and Shanshu Technology’s solvers ranked first and second, respectively, in integer linear programming evaluation.

During the course of solver development, the augmentation of computer hardware speed and the enhancement of solver algorithm efficiency have consistently elevated the overall efficacy of the solver, facilitating the resolution of increasingly extensive problems. Specifically, advancements in computer hardware speed encompass elevated CPU clock rates, heightened memory bandwidth, enhancements in processor physical architecture, upgrades to instruction sets, integration of multicore and multithreading technology, transition from 32-bit to 64-bit architecture, compiler improvements, and more. Optimization of the efficiency of linear programming and integer programming algorithms predominantly stems from algorithm parallelization (e.g., the barrier algorithm in linear programming, tree searching in MILP) and the application of heuristic integer programming algorithms (such as RINS, local branching, MCF cuts), among others.

Looking forward, with the advent of a new generation of computer technology and the amplification of computing power, research directions meriting attention and strategic planning include the following:

1) Distributed parallel computing: presently, mainstream commercial solvers such as CPLEX and Gurobi can solely accommodate 32-core concurrent computing. Mere augmentation of core numbers does not necessarily translate to enhanced solving efficiency. Future research ought to concentrate on optimizing solver algorithms to fully harness the computational capabilities of thousands of GPU cores in distributed services, thus accelerating the solution of large-scale problems.

2) Artificial intelligence algorithms: in recent years, researchers have endeavored to integrate AI technology into solver optimization algorithms to augment the efficiency of solving linear and integer programming problems. Existing machine learning algorithms necessitate training on existing problems. Further research is imperative to ascertain whether the model can ensure effective problem resolution for general scenarios amidst altering problem characteristics.

3) Quantum computing: quantum optimization, a burgeoning area in the realm of quantum computing, has garnered attention. It revolves around leveraging quantum computing to expedite optimization problem solving. Presently, for constrained optimization problems, quantum optimization theories encompass quantum simulated annealing, quantum interior-point methods, quantum linear programming, quantum semidefinite programming, and more. These theories await further validation subsequent to practical implementation of quantum computers.

In addition to linear and integer programming, which are the two most prevalent problems in practical applications, contemporary mathematical programming solvers are also dedicated to addressing more intricate problems. These encompass quadratic programming, second-order cone programming, semidefinite programming, mixed-integer nonlinear programming, and others.

Within the realm of the engineering research front of “linear and integer programming solvers” , the leading three countries in terms of core patent numbers are China, the USA, and Japan (Table 2.2.1). Pertaining to collaborative networks among these principal countries, cooperative efforts are observed between China and Germany, the USA, and the UK, as well as among the USA, the UK, France, and China (Figure 2.2.1). The main output organizations of the core patents include International Business Machines Corporation (IBM), State Grid Electronic Commerce Co., Ltd. and others (Table 2.2.2), etc., where State Grid Electronic Commerce Co., Ltd. and Tsinghua University have some cooperation (Figure 2.2.2).

Table 2.2.1 Countries with the greatest output of core patents on “linear and integer programming solvers”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	61	59.22	182	55.49	2.98
2	USA	26	25.24	75	22.87	2.88
3	Japan	8	7.77	8	2.44	1.00
4	Germany	5	4.85	54	16.46	10.80
5	Canada	2	1.94	2	0.61	1.00
6	Saudi Arabia	2	1.94	2	0.61	1.00
7	UK	2	1.94	0	0.00	0.00
8	Colombia	1	0.97	7	2.13	7.00
9	France	1	0.97	5	1.52	5.00

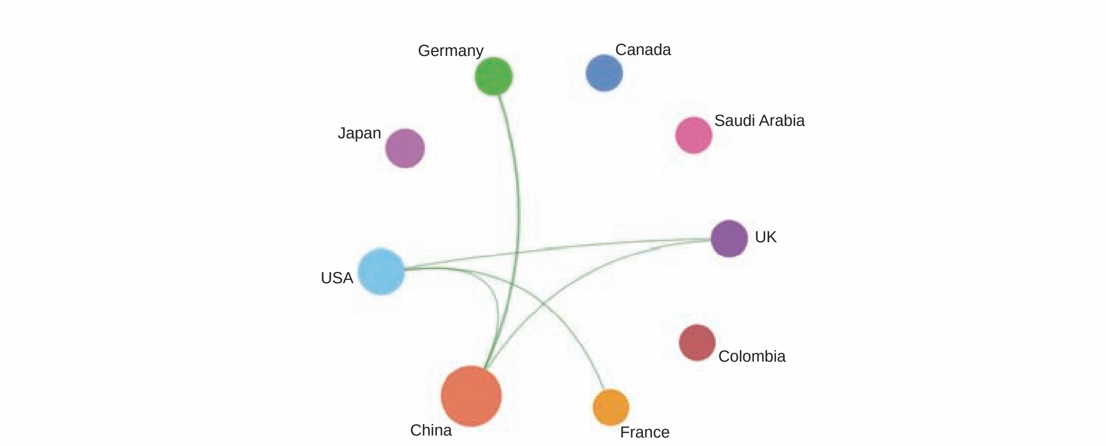

Figure 2.2.1 Collaboration network among major countries in the engineering development front of “linear and integer programming solvers”

China’s solver products have experienced rapid development in recent years, achieving international recognition and serving global enterprises. With China’s ongoing investment in solver research, a growing number of significant accomplishments are emerging. Domestically developed solver products are progressively approaching the technical caliber of world-class solvers and establishing a presence in the international market.

The evolution of linear and integer programming solvers unfolded in two phases: from theoretical research to solver development, optimization, and practical application. Future pivotal development trajectories encompass following two key aspects.

1) Expansion of problem scope: this entails broadening the scope of problems that can be addressed, extending beyond linear and integer programming to encompass challenges such as quadratic programming, second-order cone programming, semidefinite programming, and integer nonlinear programming.

2) Technical innovation: this involves integrating concepts from disciplines beyond mathematical optimization into the advancement of linear and integer programming solvers. This innovation aims to further heighten the solving efficiency and enlarge the array of application scenarios. Present research efforts primarily revolve around large-scale distributed computing, artificial intelligence, and quantum computing. Figure 2.2.3 illustrates its future pathway of the engineering development front of "linear and integer programming solvers".

Table 2.2.2 Institutions with the greatest output of core patents on "linear and integer programming solvers"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of Citations/%	Citations per patent
1	International Business Machines Corporation (IBM)	16	15.53	28	8.54	1.75
2	State Grid Electronic Commerce Co., Ltd.	9	8.74	21	6.40	2.33
3	Baidu Netcom Technology Co., Ltd.	8	7.77	49	14.94	6.12
4	Guangxi Electric Power Industry Group Co., Ltd.	6	5.83	8	2.44	1.33
5	China Jiliang University	5	4.85	14	4.27	2.80
6	Fujitsu Group	5	4.85	3	0.91	0.60
7	Tsinghua University	4	3.88	19	5.79	4.75
8	Siemens AG	4	3.88	4	1.22	1.00
9	Nippon Steel Corporation	3	2.91	6	1.83	2.00
10	Shandong University	2	1.94	26	7.93	13.00

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of "linear and integer programming solvers"

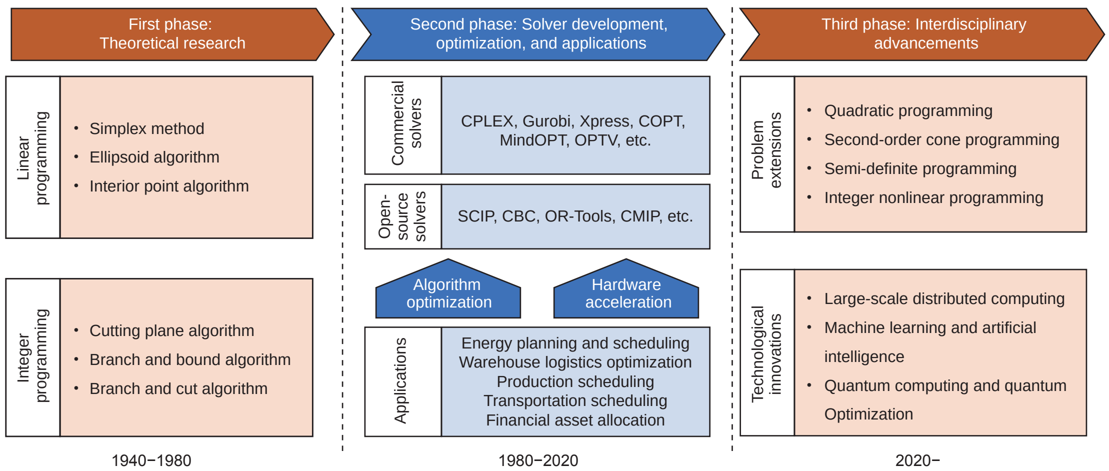

Figure 2.2.3 Roadmap of the engineering development front of "linear and integer programming solvers"

2.2.2 Intelligent factory operation and maintenance systems based on industrial internet and big data

The intelligent factory operation system, founded on industrial internet and big data, serves as a data-driven core for factory operations and maintenance management. This system gathers real-time and comprehensive data from the production process, meticulously extracts knowledge embedded within the data, and facilitates more accurate and timely monitoring and management of the operation process and production resources. Patent analysis underscores the pivotal research areas associated with this system, currently focusing on followings.

(1) Industrial big data collection and management technology

This encompasses the collection of operational data pertaining to production equipment, process flows, etc. It also involves the processing, analysis, and storage of the collected data, collectively supporting the oversight and maintenance activities of the production system. Research emphasis lies in intelligent sensor network design and deployment, assessment and optimization of data quality, and fusion processing of multisource heterogeneous data.

(2) Industrial big data-driven equipment fault diagnosis and maintenance technology

This technology diagnoses and pinpoints equipment faults through the analysis of equipment data collected via data mining, artificial intelligence, and related methods. It subsequently provides reference maintenance plans and strategies. Current areas of focus include constructing fault diagnosis models, conducting root cause analysis of faults, and managing maintenance plan information.

(3) Intelligent factory operation system based on industrial internet

Anchored in the industrial internet and incorporating big data collection, analysis, and application, this system attains intelligent operation and maintenance management for production processes and resources. It amalgamates several key enabling technologies and functional services, including data collection and management technology, equipment fault diagnosis and maintenance technology, real-time monitoring, and remote operation services. At present, technologies such as edge intelligence, cloud computing, and digital twin are evolving into essential catalysts for the system's intelligent enhancement.

From a core patent perspective, China leads in publicly disclosed patent numbers, while the USA claims the highest average citation count (Table 2.2.3). Collaborations are observed between Italy and Israel (Figure 2.2.4). Noteworthy patent-disclosing institutions encompass ioCurrents Company and Henan Sutong Boiler Co., Ltd. (Table 2.2.4), with no established cooperative relationships among different organizations.

Looking ahead, intelligent factory maintenance systems rooted in industrial internet and big data will advance toward heightened intelligence, integration, and security. Progress in artificial intelligence will facilitate more accurate autonomous prediction of equipment failure and production risk. Simultaneously, advancements in data fusion technology will amplify system integration, propelling a sophisticated leap across the entire value chain. Furthermore, enhancements in data encryption and authentication technology will fortify the privacy protection and security management of multiparty data, establishing a robust underpinning for the system's reliability and security. Figure 2.2.5 outlines the developmental trajectory for "intelligent factory operation and maintenance systems based on industrial internet and big data".

Table 2.2.3 Countries with the greatest output of core patents on "intelligent factory operation and maintenance systems based on industrial internet and big data"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	35	53.03	88	8.07	2.51
2	Republic of Korea	19	28.79	7	0.64	0.37
3	USA	11	16.67	976	89.54	88.73
4	Israel	1	1.52	19	1.74	19.00
5	Italy	1	1.52	19	1.74	19.00

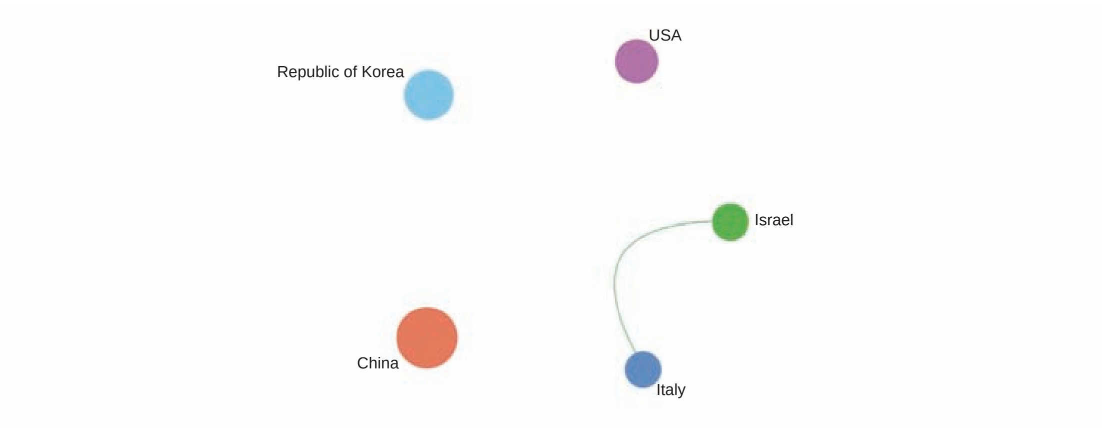

Figure 2.2.4 Collaboration network among major countries in the engineering development front of "intelligent factory operation and maintenance systems based on industrial internet and big data"

Table 2.2.4 Institutions with the greatest output of core patents on "intelligent factory operation and maintenance systems based on industrial internet and big data"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of Citations/%	Citations per patent
1	ioCurrents Corporation	6	9.09	720	66.06	120.00
2	Henan Sito Boiler Co., Ltd.	5	7.58	4	0.37	0.80
3	AiKEN Technology Co., Ltd.	4	6.06	32	2.94	8.00
4	Tsinghua University	4	6.06	9	0.83	2.25
5	DLIT Co., Ltd.	4	6.06	0	0.00	0.00
6	Korea Electronics Technology Institute	3	4.55	5	0.46	1.67
7	Wistron Technology	3	4.55	3	0.28	1.00
8	SFIP Corporation	2	3.03	237	21.74	118.50
9	Mobileye Vision Technologies Ltd.	2	3.03	38	3.49	19.00
10	Guangzhou Bote Intelligent Information Technology Co., Ltd.	2	3.03	18	1.65	9.00

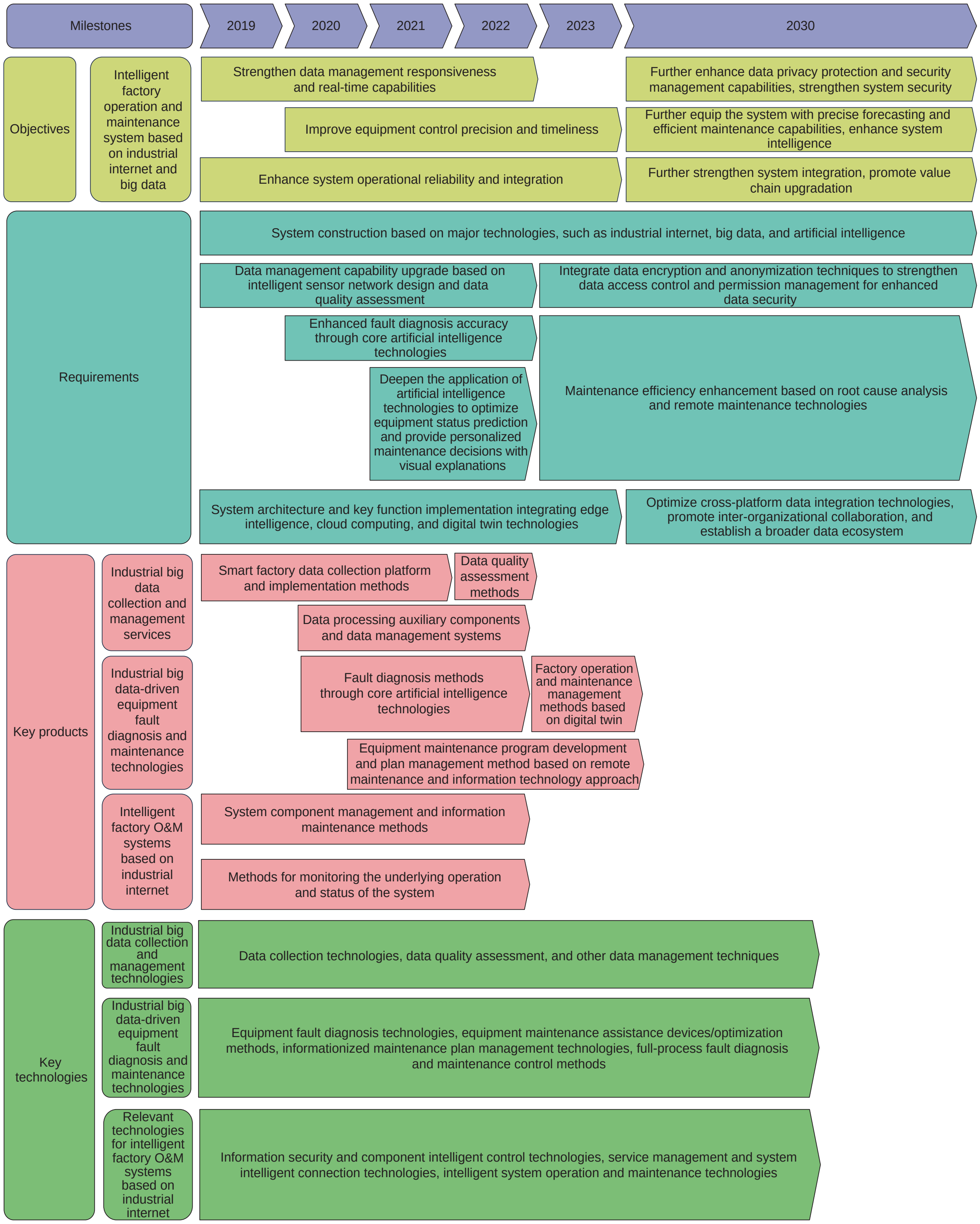

Figure 2.2.5 Roadmap of the engineering development front of “intelligent factory operation and maintenance systems based on industrial internet and big data”

2.2.3 Methods and systems for automatic building design generation based on deep learning

The primary goal of deep learning-based automatic building scheme generation is to leverage deep learning technology for the automated creation of architectural design plans. Its essence lies in extracting and learning the intrinsic rules of architectural design from existing materials, thereby fulfilling project requirements automatically. These methods and systems have the potential to enhance designers' productivity by freeing them to focus on higher-level creativity and significant decision-making. This can reduce uncertainties related to design quality and cost in traditional design models while further elevating the digitalization, automation, and intelligence levels of architectural design.

As the technological bedrock of this domain, deep learning models have played an indispensable supporting role in the advancement of key research directions. For example, the fully convolutional neural network, introduced in 2014 for image and semantic segmentation, has found wide-ranging application in the automatic semanticization of architectural schemes. In the same year, two deep generative models, variational autoencoders and generative adversarial networks, emerged as pivotal engines for image generation and style transfer. Nonetheless, these studies have predominantly centered on low- to high-rise buildings, with limited attention given to spatial structure and superhigh-rise constructions. In 2017, graph convolutional networks were introduced to solve spatial arrangement challenges in generating beams, columns, walls, and more. The transformer model, also introduced in 2017, has been used for automated compliance checking, ensuring the generated scheme's adherence, safety, and quality. However, it has not yet effectively addressed the recognition and processing of ambiguous design clauses.

By focusing on the creation of secure, efficient, and stable design systems via an array of automatic generation methods, the provision of high-quality customized services to designers becomes feasible. While automatic generation methods themselves face numerous challenges in terms of feasibility and reliability, the research and development of associated systems are still in their nascent stages. Apart from automatic generation methods, existing automatic generation systems often lack the integration of critical functional modules, including automatic compliance checks, interactive scheme modification, scheme evaluation, multiperson collaboration, user privacy protection, file encryption, model rendering, and intelligent optimization.

In the engineering development front of "methods and systems for automatic building design generation based on deep learning", the overall status of core patents is shown in Tables 2.2.5 and 2.2.6. Specifically, the top three countries in terms of the number of core patents are the USA, Republic of Korea, and China. The primary institutions responsible for the output of core patents include Azova Inc. in the USA, SureSoft Technologies Inc. in Republic of Korea, and International Business Machines Corporation (IBM), among others. At the national level, there is currently limited collaboration among countries. At the institutional level, however, there exists a collaborative relationship between ChangSoft I&I in Republic of Korea and Yonsei University (Figure 2.2.6). The absence of extensive international collaboration may be attributed to regulatory measures concerning artificial intelligence technologies and divergent research orientations among institutions.

To elevate the feasibility, reliability, and diversity of autonomously generated architectural proposals, Figure 2.2.7 articulates the avant-garde trajectory of this scholarly endeavor. By extensively employing next-generation digital interaction technologies coupled with deep generative models, the investigation seeks to amplify and refine collaborative human–machine design methodologies, thereby harmonizing the prescriptive and inventive dimensions of design frameworks. Grounded in ontological paradigms, the research explores strategic amalgamations of multi-disciplinary analytical engines with design conventions, culminating in the conception of congruent systems for the self-generating architecture blueprints. To address the challenges posed by data-deficient complex architectures, supplementary analyses are executed through the medium of parametric modeling and cloud-based computational techniques, thereby facilitating data augmentation. Furthermore, the study categorizes the latent ambiguities present within design stipulations, advances methodologies for their identification and rectification, and coherently integrates these elements into extant frameworks for automated compliance verification.

Table 2.2.5 Countries with the greatest output of core patents on “methods and systems for automatic building design generation based on deep learning”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of Citations/%	Citations per patent
1	USA	15	57.69	206	99.04	13.73
2	Republic of Korea	9	34.62	2	0.96	0.22
3	China	1	3.85	0	0.00	0.00
4	Japan	1	3.85	0	0.00	0.00

Table 2.2.6 Institutions with the greatest output of core patents on “methods and systems for automatic building design generation gased on deep learning”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Azova Inc.	4	15.38	12	5.77	3.00
2	SureSoft Technologies Inc.	4	15.38	0	0.00	0.00
3	International Business Machines Corporation (IBM)	3	11.54	15	7.21	5.00
4	Google Inc.	2	7.69	86	41.35	43.00
5	TIBCO Software Inc.	2	7.69	38	18.27	19.00
6	Nuance Communications Inc.	1	3.85	50	24.04	50.00
7	Advanced Micro Devices, Inc.	1	3.85	5	2.40	5.00
8	ChangSoft I&I Co., Ltd.	1	3.85	1	0.48	1.00
9	Samsung Electronics Co., Ltd.	1	3.85	1	0.48	1.00
10	Yonsei University	1	3.85	1	0.48	1.00

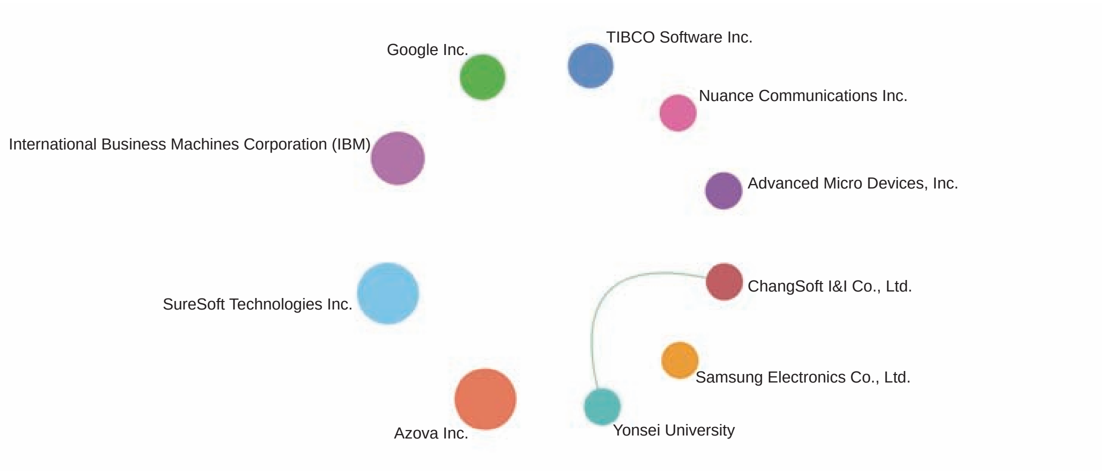

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of “methods and systems for automatic building design generation based on deep learning”

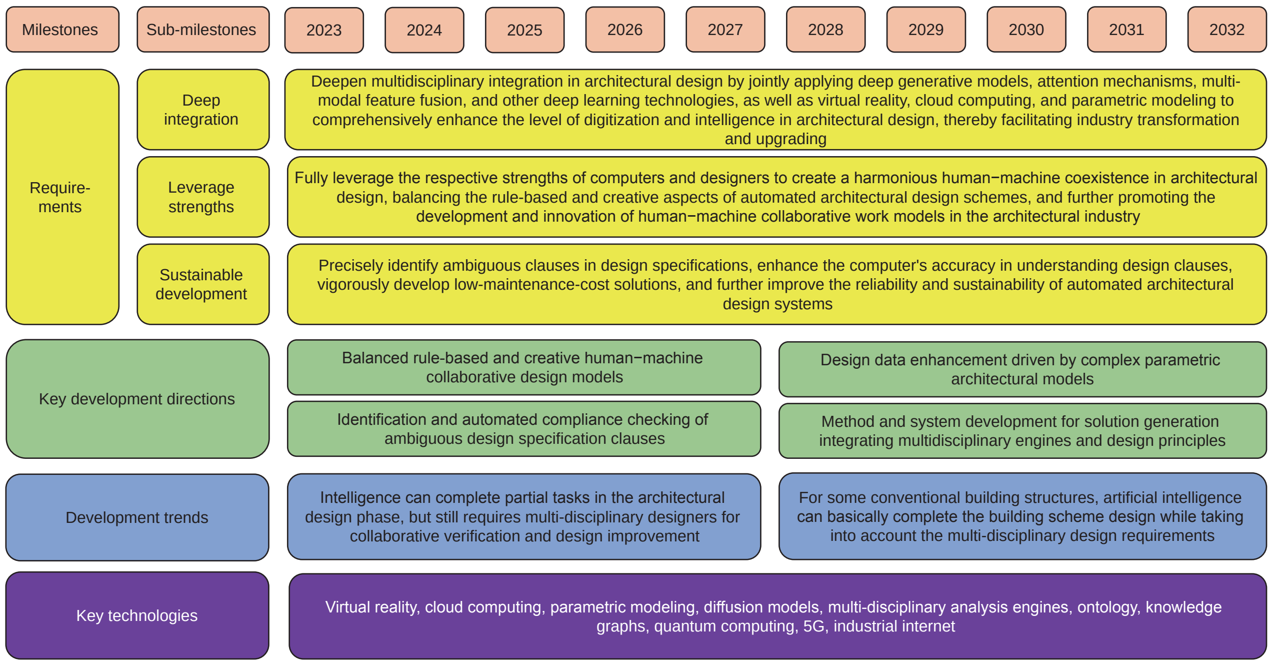

Figure 2.2.7 Roadmap of the engineering development front of “methods and systems for automatic building design generation based on deep learning”

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