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The Evolutionary Characteristics of Technological Innovation in the Construction Industry Based on the Perspective of Technology-Social System

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Abstract: *Modern engineering and technology science are an indispensable bridge between scientific principles and industrial development, and engineering research and development. This article studies the scientific and technological awards in the field of civil construction in China from the perspective of the Social Shaping of Technology (SST) theory from 2000 to 2020. It constructs an evolutionary framework of "four systems, two mechanisms, and one nature" for technological innovation in China's construction industry. Using LDA topic model, it analyzed the development trend of scientific and technological achievements. The study found that the evolutionary development of the technological system in the construction industry is a complex process of self-organization and collaboration. The external manifestation of the evolutionary process of the construction industry's technological system is "self-creation." The accumulation of technology and cross-disciplinary integration continuously provide momentum for the self-organizing evolution of the technological system. The "random fluctuations" caused by the synergy of technology, demand, industry, and policies have promoted the sustainable and rapid development of the construction industry. Technology innovation and economic reciprocity are driven by market demand, guided by major national strategies, and the expansion of the industry broadens the boundaries of technology innovation.*

Keywords: *Technological innovation; Civil construction industry; Evolutionary features; Science and technology awards*

1. Introduction

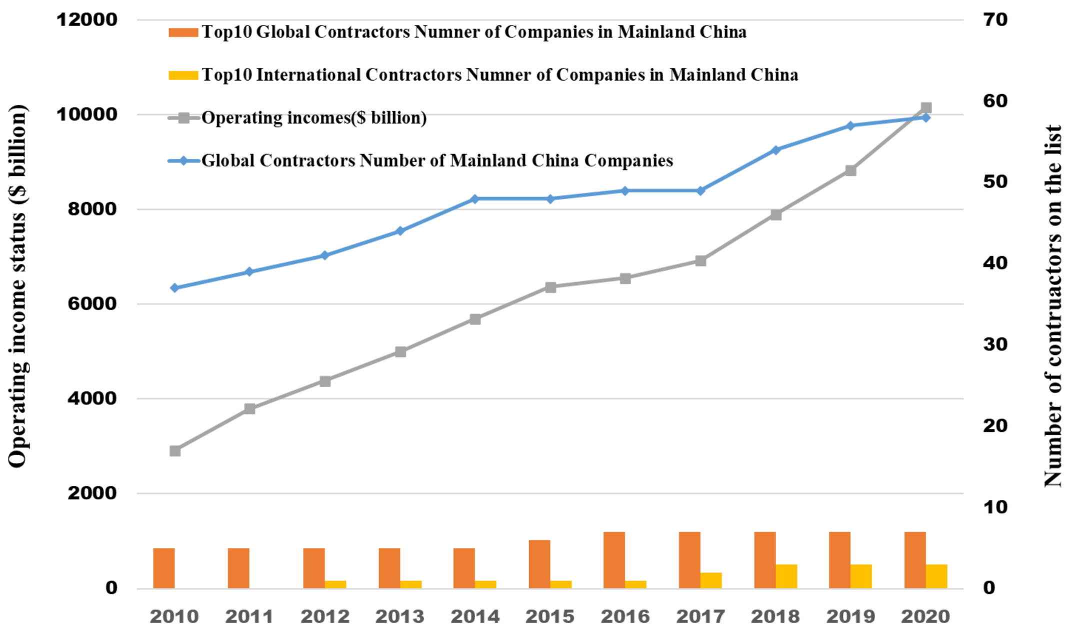

Figure 1: Top 225/250 Global Contractors from 2010-2020 in Chinese Mainland Companies and Related Policies

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China has more than half of the world's super-tall buildings, as well as super projects such as the Qinghai-Tibet Railway, the Three Gorges Dam, and the Hong Kong-Zhuhai-Macau Bridge, which have created many world firsts and earned China the nickname "Infrastructure Maniac." Since 2010, the number of Chinese companies in the ENR Global Contractors Top 225/250 has increased from 37 to 58, and their revenue has increased from 291.55 billion USD to 1.0151 trillion USD. Since 2016, seven Chinese mainland companies have remained in the top 10 Global Contractors, and three Chinese mainland companies have remained in the top 10 International Contractors, as shown in Figure 1. A new round of technological revolution and industrial transformation is progressing rapidly, and the paradigm of scientific research is undergoing profound changes. Interdisciplinary integration is constantly developing, and the integration of science and technology with economic and social development is accelerating. The development of the construction industry and the creation of engineering miracles are the results of the combined efforts of multiple factors, such as the industry's own development, industry policy support, market demand, and technological innovation, with innovation being the main driving force. This article takes the National Science and Technology Progress Award in the field of civil construction in the past 20 years as a case study to analyze the main characteristics and evolutionary mechanisms of technological innovation in civil construction, and to study the relationship between innovation and policy, economy, and industry. It seeks to more accurately grasp the laws of technological evolution in the construction industry, explore new application paths for scientific and technological innovation in the construction industry, and promote the sustainable development of the industry.

2. Theoretical and analytical framework

The Social Shaping of Technology (SST) explores the influence of social factors on technology, using sociology, systems theory, and other methods to explain technological activities. It emphasizes that technological activity is a process and result of the overlapping of technological possibilities and social demands. The theory holds that the formation of technology is a social phenomenon, not simply a technical issue. Market, social culture, system, and economic factors are closely related to technological activities, and only by placing technological innovation in the social environment can we gain a deeper understanding of the essence of innovation.

2.1. Technology-society system evolution process

The development of technology is driven by both the "internal force" of scientific technology and scientific methods, and the external environment composed of economic, political, and social factors. Hughes believed that the main driving force for the evolution of technology systems comes from the "inertia" momentum (technological momentum) inherent in the system [1]. The symbiotic, coupling, and embedding effects between various technological elements provide the conditions for the self-creative behavior of technology. The underlying factors of different technologies, such as knowledge, information, intelligence, technological elements, etc., interact with each other to produce technologies or combinations of technologies with new structures and functions[2]. However, the endogeneity of technology itself only provides the internal conditions for the implementation of technology. Without good social conditions such as policies, economic conditions, and social demands, i.e., the external environment, any excellent technology is difficult to sprout and grow and can only remain in the potential technology stage [3]. Fluctuation is one of the basic characteristics of the system. When the change value of a certain parameter of the system reaches or exceeds a certain threshold value, the expansion effect of the randomness of the system will cause the system to mutate. The system will transition from the original chaotic and disordered state to a higher-level ordered state in time, space, and function. The formation of fluctuation is often the embodiment of the non-equilibrium relationship between multiple subsystems [4]. Hughes called such "non-equilibrium" states in the technology system "reverse salients," and "fluctuations" will push the technology system to transition, forming a dynamic evolutionary process of "order-disorder-order."

2.2. Construction Industry "Technology-Society System" Evolutionary Framework Construction

The synergistic development of science, technology, and society has promoted a profound change in the knowledge production model. The needs of industry and practice have promoted a new model of knowledge production, Knowledge Production Model II. Henry Etzkowitz proposed the Triple Helixes as a model for the dynamics of Knowledge Production Model II, which forms a network of University-Industry-Government (UIG) relationships. The interactions between the UIGs show the static

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characteristics of a triple helix, while the vertical evolution and horizontal circulation show the dynamic characteristics of a triple helix[5].

Based on the Triple Helix theory and combined with the "technology-society system" framework, a "four systems, two mechanisms, and one property" analysis framework is constructed for the technological evolution of the construction industry. The "four systems" include the technological system, as well as the social demand subsystem, the policy promotion subsystem, and the industry expansion subsystem, all of which are collectively referred to as the social system. The two mechanisms are the endogenous momentum mechanism, which means that the internal momentum of the technological evolution system comes from the self-creative behavior of the technological subsystem. The second is the external environment driving mechanism, which means that social demand, industry expansion, or policy promotion provide the technological evolution system with forward momentum. The one property is fluctuation, which refers to the amplification of small fluctuations into large fluctuations under certain conditions in non-equilibrium and non-linear systems. This allows the technological system to achieve the transformation from disorder to order.

There is interaction, intersection, overlap, and integration between the technological system and the social system, as shown in Figure 2

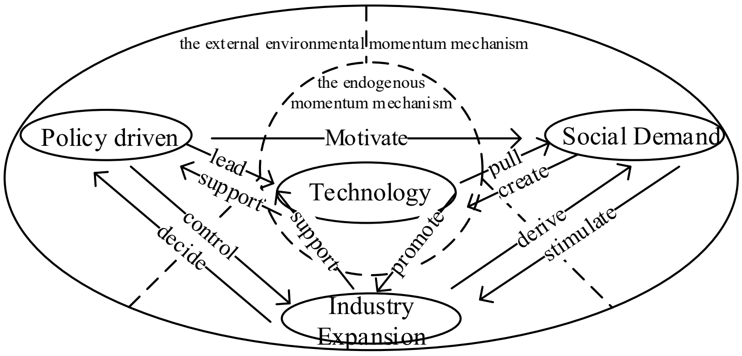

Figure 2: Static linkage of "technology-social system"

(1) There is a mutual influence between social demand and technology, and meeting social demand is both the main driving force and the ultimate goal of technological innovation. As social demand evolves from meeting basic needs to higher-level or new needs that existing technology cannot satisfy, conflicts arise between technology and demand, putting pressure on industry, academia, and research to develop new technologies. This leads to the development of new technologies.

(2) Industrial expansion refers to the process by which an industry grows by absorbing other industries that are structurally redundant and by leveraging the various resources provided by society. In industrial expansion, market demand increases, requiring large-scale production, which in turn requires equipment to be larger and production to be more specialized. Large-scale production stimulates technological innovation, especially in process innovation. In turn, process innovation enables the rapid standardization of products produced during the expansion phase of the industry, allowing for the aggregation of vast resources and the formation of economies of scale.

(3) Governments use the allocation effects and incentive effects of industrial policies to strongly influence the way resources are allocated and production factors flow, thus determining the efficiency and innovative power of the entire construction industry system. It can be said that institutional innovation by the state and government determines the extent to which various vested interest organizations play their roles and ultimately determines the operating efficiency of the entire industry.

The various elements of the technology system and social system interact, overlap, and merge dynamically, and can adjust their positions and roles based on changes in the environment. This promotes continuous adjustment of organizational forms and operational modes to meet the needs of scientific knowledge production, forming a four-spiral structure that promotes technological innovation, as shown in Figure 3, the dynamic "four-spiral" system framework of the "technology-social system" of the construction industry. The spiral lines represent the energy of the various elements of technology, market demand, policy promotion, and economic strength, and their fluctuations form the total kinetic energy of the four-spiral technology system's advancement. The "technology transformation system framework" model has the following characteristics: point "A" of the evolution and development of the construction industry's technological transformation is not static, but rather evolves upward over time; some

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subsystems in the social and technology subsystems develop steadily, while others fall behind, creating "reverse inflection points" far from equilibrium.

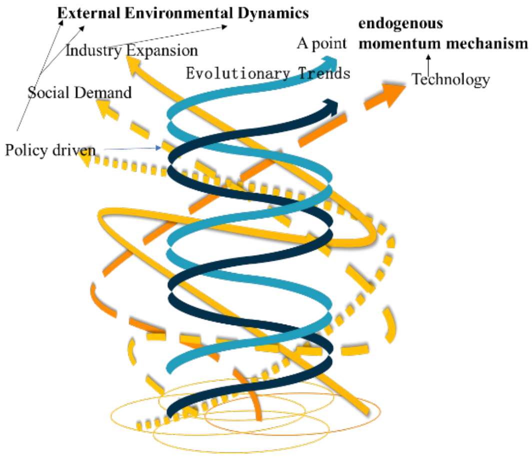

Figure 3: A dynamic "quadruple helix" system framework of "technology-social system"

3. Evolutionary trends of technological innovation in the last two decades

3.1. Data source

According to the results of the National Science and Technology Awards (NSTPA) from 2000 to 2020, as announced on the website of the Ministry of Science and Technology, there were a total of 163 awards in the field of civil engineering and architecture (J221). In addition, based on the "China Science and Technology Project Innovation Achievement Appraisal Opinion Database" (CNKI version), this article selected 154 registration forms whose project names and completion personnel matched the projects that won the National Science and Technology Awards.

3.2. Number, grade, and time distribution

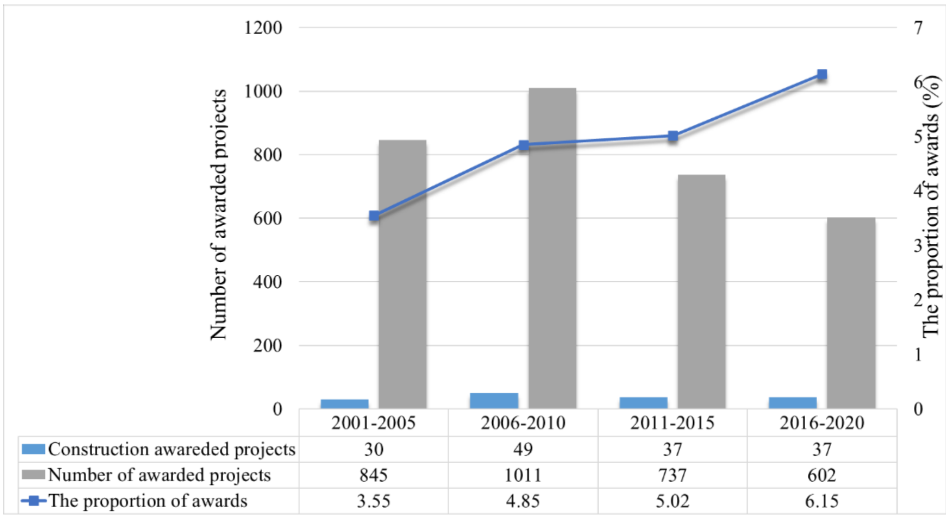

Figure 4: Percentage of awards in the field of civil engineering and construction

From 2000 to 2020, a total of 3,532 National Science and Technology Progress Awards were granted, including 15 Special Prizes, 222 First Prizes, 3,272 Second Prizes, and 23 Innovative Teams. In the field of civil engineering and architecture, there was one Special Prize, accounting for 6.7% of the total Special Prizes (15); 15 First Prizes, accounting for 6.8% of the total First Prizes (222); 146 Second Prizes, accounting for 4.5% of the total Second Prizes (3,272); and one Innovative Team, accounting for 4.3% of the total Innovative Teams (23), with a total of 163 awards. Due to the limited number of awards each year and the implementation of a quota-based evaluation system since 2017, the number of awards has been significantly reduced. Therefore, this article presents the award-winning projects according to the time periods of China's "Five-Year Plans". It can be observed that while the number of National Science and Technology Awards is gradually decreasing, the proportion of awards in the field of civil engineering and architecture continues to increase, with a 2.6% growth in the proportion of awards from the Tenth Five-Year Plan period to the Thirteenth Five-Year Plan period, as shown in Figure 4.

3.3. Award-winning institutions

The core of the technological system is composed of organizational elements such as enterprises, companies, and research institutions [6]. This article uses the completing unit as the basis for statistics, and out of the 163 national science and technology awards, 454 units were awarded, including 65 universities, 5 research institutes, and 387 enterprises. Among them, universities or research institutes as the first completing units won 8 first prizes and 77 second prizes, accounting for 52.1% of the total number of awards (163). As shown in Table 1, the top 5 institutions in terms of total awards (accounting for 1% of the total number of institutions receiving awards) participated in 45% of the project research over the past 21 years, mainly consisting of universities and technology-oriented enterprises. We can observe that the type of award-winning project is closely related to the disciplinary advantages and technology mastered by the completing unit, for example, Southwest Jiaotong University, born and developed due to railways, has won awards for research on bridge engineering or tunnel engineering necessary for railway construction.

Table 1: The top 10 institutions involved in award-winning research projects in the 2000-2020

Institution	Frequency	Year																				
		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Southwest Jiaotong University	20	2			1		2		2	2	1	2	1	1		1			2	2		1
Southeast University	18						1	2		2		2	1	1	1	2					3	3
Tongji University	18	1					1	1	1	2	2	1		2	1	2	1	1	1			1
Tsinghua University	17				1	2				1	4		2	1				1	1	2	1	1
Zhejiang University	15									1	2		3	1	1				1	2	1	3
China Academy of Building Research	13		1						1			1			3	1		1	2	1	1	1
China Academy Of Railway Sciences	11			1	1		1	1	1	2					1	1		1				1
Central South University	11			1	2	1	1		1	1			1						1		2	
Harbin Institute of Technology	11				1			1	1				1		1	1	1	1		1	1	1
Beijing University Of Technology	11				1			1		2	1	2		1			1		1		1	

3.4. Thematic evolution of NSTPA in the construction industry

3.4.1. Theme identification model construction

This passage describes the use of Latent Dirichlet Allocation (LDA) topic modeling to identify the themes of scientific and technological achievements, using the content of the national scientific and technological achievement registration form corresponding to the field of civil engineering and architecture. LDA is a topic generation model that evolved from Latent Semantic Indexing (LSI)[7]. It is a three-layer Bayesian probability generation model that represents documents as a probability distribution of latent topics and topics as a probability distribution of vocabulary. Since topics represent a collection of document content, the model can effectively model semantic information in large-scale corpus.

3.4.2. Description of technical result topics

As shown in Table 2, according to the clustering of topic words in each topic, the core topics in the

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field of civil engineering mainly include the construction of large-scale transportation projects in complex environments, green construction and environmental protection, design and construction of various types of bridges, structural vibration control, geotechnical and foundation engineering, new structural and new material structures, engineering geology, environment, and disasters, civil engineering machinery and equipment, and safety and health monitoring technology, large-span and high-rise buildings.

Table 2: Theme of NSTPA in the field of civil engineering and construction for the time period of 2000-2020

Topic Category	number	Topic	Topic Vocabulary
1Application Scenarios	Topic#1-1:	High-rise buildings	steel structure, Shanghai World Financial Center, TV Tower, specially shaped column
	Topic#1-2:	Large-span construction	long-span, steel roof, National Stadium, curve sliding, movable technology large jig, prestressed structure
	Topic#1-3:	Bridge Engineering	Cable-stayed bridges, three cable planes, highway-railway, suspension brige, continuous Rigid-Frame Bridge, cable launching method
	Topic#1-4:	Railroad Engineering	CRTSIII ballastless track, Long Stator and Normal Conducting
	Topic#1-5:	Tunnel Engineering	Large-section tunnels; overlapping Tunnels, tertiary water-rich and weakly cemented sandstone tunnel, underwater tunnel
	Topic#1-6:	Highway Engineering	Thaw settlement; desert region; aeolian sand; special soil
2 Technology	Topic#2-1:	Green Building and Environmental Protection	Thermal environment; Energy saving; Waste concrete; ecological city
	Topic#2-2:	Structural Health Monitoring	Intelligent detection of structural cracks, Damage Controlled Structure Theory, Optical fiber grating, six-direction pressure sensor, Carbonation corrosion rate model
	Topic#2-3:	Structural Vibration Control	low modulus and high damping compound; elastomeric isolator for buildings, Analytical model of seismic wave propagation, Earth Dam Reinforcement, steel reinforced high-strength concrete
	Topic#2-4:	Foundation and Foundation Engineering	Constant thickness steel cement-soil wall; Unsupported foundation pit; fully-grouted bolt; Isolation pile; prestressed anchor without middle beam
	Topic#2-5:	New Structure and New Material Structure	Steel-concrete; FRP sheets; Bidirectional electro-migration rehabilitation; Structure for aged offshore; Polyester fibers; Nodes analysis
	Topic#2-6:	Engineering Geological Environment and Disaster	Soft rock roadway; Frozen soil mechanics; Remote sensing interpretation of sliding sand slope; vibration wave of explosion
	Topic#2-7:	Civil Engineering Machinery and Equipment	Large maintenance machinery; Salvage crane vessel; Large crawler crane; Tailing machine; Road header
	Topic#2-8:	Digital Technology	Integrated Construction Control System for Rail Transit Projects; Digitalization of the whole process of concrete pouring; Submerged pipe floating command navigation; Safety control technology for soft soil tunnel construction
	Topic#2-9:	Artificial Intelligence Technology	Tunnel fan steering control; Structural damage assessment; Intelligent fully hydraulic bulldozer driving system; Intelligent weighing system for excavators

3.4.3. Analysis of technology development trend

Describing the distribution of each topic over time can better demonstrate the development process of technical research in the civil engineering and architecture fields, as shown in Figure 5, which corresponds to the time indicators of scientific and technological achievements extracted by the document-topic based on the LDA model. Firstly, from the perspective of application scenarios, high-rise buildings, large-span buildings, bridge engineering, and tunnel engineering have been consistently awarded in the past 20 years. Secondly, in terms of technology, the research in the first decade mainly focused on machinery, structural materials, and vibration. In the second decade, research mainly focused on foundation, engineering geology, and structural monitoring. In particular, research on green buildings, digital technology, and artificial intelligence technology has grown rapidly in recent years and has made great progress on this basis. The productivity of technology must be fully reflected in engineering practice, such as the development of technologies like foundation and foundation engineering, new steel structures, and structural vibration, which are closely related to the emergence of high-rise buildings in China. With the rise of bridge engineering, China's civil engineering machinery and equipment has also entered a golden period of development.

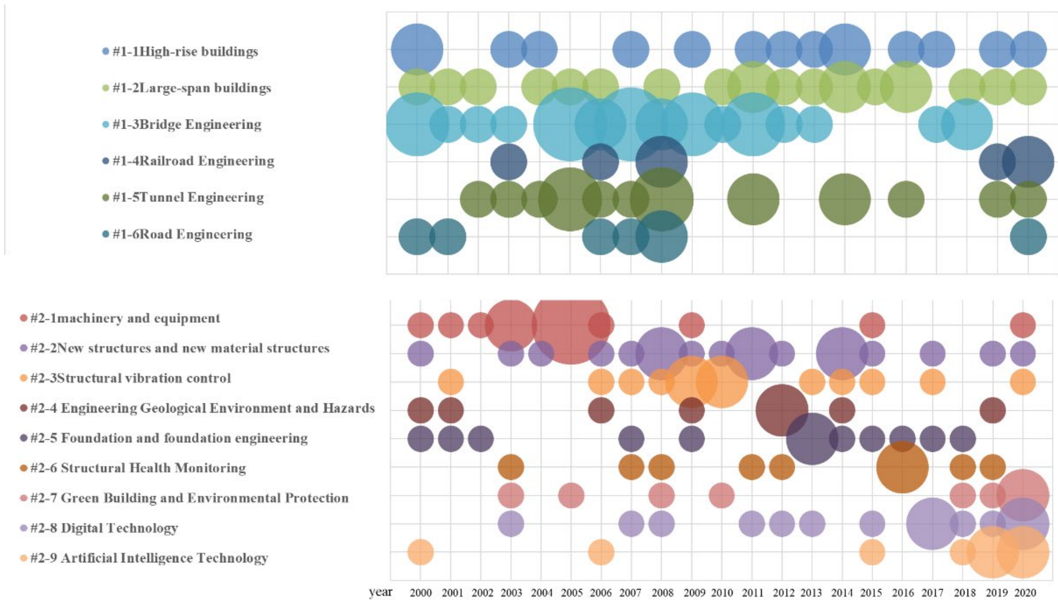

Figure 5: Theme development trend bubble distribution map

4. Characteristics and paths of technological evolution in the construction industry

According to the above framework of "technology-society system" analysis in construction industry, combined with the achievements of national scientific and technological progress in the past 20 years, this section analyzes the forms and paths of technological evolution in construction industry as follows.

4.1. The coupling between different technologies drives the "self-generated" evolution of technology systems

The technical momentum mechanism is a "self-creation" evolutionary mechanism, in which the underlying factors of technology come from the experimental conditions, R&D resources, and technological accumulation of research institutions. It is the interaction among these factors that drives different technologies to match and couple with each other in a compatible way, providing conditions for the stable growth of the "technology-society system" in the construction industry.

4.1.1. Technology accumulation drives technology coupling

Scientific research institutions rely on long-term experience and exploration to achieve different levels of change and supplementation in technology, while at the same time creating new knowledge through coupling and replacing old knowledge. This provides new and broader opportunities for gathering technological resources and searching for knowledge and offers new technological solutions for previously unsolvable problems [8]. From the award-winning situation in the construction industry, we found that the top 10 organizations accounted for 45% of the research on technological innovation achievements, of which 7 universities belonged to the national key construction universities in civil engineering. They have accumulated most of the technological resources in the field of construction and are the main force driving technological innovation in China's construction industry. Their knowledge stock continues to accumulate dynamically in a way that is "path-dependent", leading to a "cumulative advantage effect" within the technical system. Under this effect, different technologies interact and couple with each other, and the new technologies produced are applied to existing or new application areas, thereby causing replacement or termination of relevant existing technologies.

The Engineering Structural Innovation Team at Tsinghua University is currently the only team in the field of civil engineering to have won the National Science and Technology Progress Award (Innovation

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Team). The team has long been committed to the research and practice of steel-concrete composite structures. From 2013 to 2017, team members undertook a total of 103 projects with a funding of more than 1 million yuan, published more than 520 SCI papers, applied for 74 invention patents, authorized 111 patents, and achieved 26 technology transfers. The team also revised 14 national standards and 13 industry/local standards. In combination with the significant demand for large-span heavy-duty structures in China's infrastructure, such as bridges, tunnels, and exhibition centers, the team has brought significant technological and economic benefits and social benefits to China's bridge and construction industries[9].

4.1.2. Cross-disciplinary fusion facilitates technological coupling.

From the perspective of the history of scientific development, the continuous differentiation and coupling of disciplines are two fundamental trends that often play a role, and modern science has developed along the trajectory of coupling, differentiation, and then coupling again. Award-winning projects in the field of civil engineering not only involve a large number of civil engineering disciplines, but also involve cross-system and interdisciplinary applications.

Intra-system cross-coupling refers to the cross-coupling within the primary discipline system. The technological innovation of intra-system disciplines often originates from major discoveries of new scientific principles, or from the fusion of interdisciplinary and cross-disciplinary technologies. The breakthrough and transformation of such technologies can spur new industries and potentially huge markets, trigger significant changes in product manufacturing, industrial organization, and business operations, and reshape industry or industrial competition patterns. For example, the improvement of concrete process performance and the breakthrough of construction technology rely on high-quality admixtures, especially high-efficiency water-reducing agents. With the advent of carboxylic acid polymer, the third generation of new polymer water-reducing agent, significant breakthroughs have been made in the research of ultra-high-performance concrete UHPC. It is considered to be the most innovative cement-based engineering material in the past 30 years. Currently, about 80 bridges in China use UHPC material[10]. The Aizhai Extra Large Suspension Bridge in the NSTPA uses ultra-high-performance concrete RPC as the bonding medium at both ends of the anchor rod to form a new anchor system based on high-performance materials[11].

Cross-system cross-coupling refers to the cross-coupling between primary discipline systems. The embedding and combination of technology implementations across unrelated fields or across different cognitive structures can spur new functions and applications, providing new technological tracks for cross-technology innovation and a new horizontal and vertical fusion for different technologies, thereby promoting the evolution of breakthrough technological innovation[12]. For example, wind tunnel testing, as a method of simulating the interaction between engineering objects and air flow, was initially applied in the aerospace field and is now widely used in the field of bridge design[13]. The award-winning project "Key Technologies and Engineering Applications for Large-Span Cable-Stayed Bridges' Wind Resistance" in 2018 was based on wind tunnel testing and studied the optimal inclination range (14°-18°) of the streamlined box girder lower belly plate, establishing aerodynamic design guidelines for streamlined box girders[14].

4.2. The collaboration of social subsystems is the driving force of technological system evolution

The result of the evolution and development of the technological system in the construction industry is the maximum synergy and consistency with external social subsystems such as market demand, policy promotion, and industry expansion, such as the increasing demand for infrastructure, changes in product and industry structure due to technological progress, changes in national policies, and the improvement of building environmental quality requirements. However, during the process of technological evolution, when the deviation value of fluctuations exceeds a certain range, such as when existing technology cannot meet market demand or when achieving expected goals requires significant resource consumption, "micro-fluctuations" through the nonlinear interaction between the technological subsystem and the social subsystem of feedback regulation lead to the "macro-fluctuations" of the technological system, causing the structure of the entire system to change, thereby forming a new, orderly system.

4.2.1. Mutual symbiosis of technological innovation and economy driven by market demand

The scaling of the industrial economy has generated a strong demand for industrial technology, attracting relevant technology providers and innovators to enter the industry. The refinement of division of labor within the industry and the interaction between industries also creates new opportunities for technological innovation. With the rapid development of the economy and society, the huge demand for large-scale infrastructure construction in China has provided a rare historical opportunity for the

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development of construction industry technology, as shown in Figure 6. Investment in fixed assets of railway, highway, and waterway infrastructure in China has continued to grow, with total investment in the transportation industry increasing by more than 12 times in the past 21 years. After the release of relevant policies by the government, investment in transportation infrastructure has significantly increased, indicating the positive and important role of policy in the development of the industry. According to the China Science and Technology Statistics Yearbook and the China Construction Industry Statistics Yearbook published by the National Bureau of Statistics, R&D investment in the construction industry has increased more than fivefold from 59.96 million yuan in 2004 to 331.77 million yuan in 2020.

The productivity of science and technology needs to be reflected through engineering activities. Under such huge demand, many key technologies are bound to emerge, such as the "rail-slip method," the main achievement of the Aizhai Extra Large Suspension Bridge with a total investment of 1.4 billion yuan, which is recognized worldwide as the fourth method for the erection of the main beam of a suspension bridge. It has driven the progress of suspension bridge erection technology in China and can also be applied to the construction of main beams of middle and lower hanger-type arch bridges, with strong vitality and broad applicability. Therefore, the goal of China's major engineering technological innovation is not only to meet the needs of engineering construction but also to stimulate market demand and generate key common technological innovation achievements at the industry and even national levels.

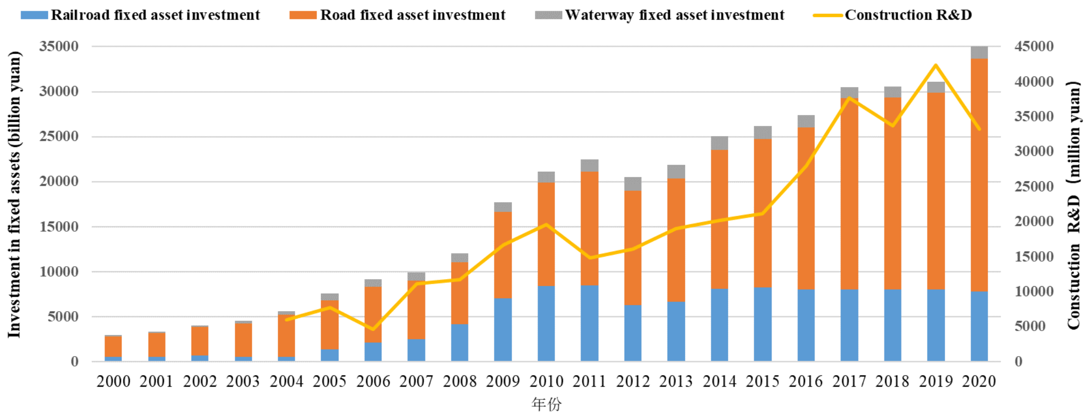

Figure 6: China's transportation industry fixed asset investment from 2000 to 2020

4.2.2. Major national strategies as the guide for technological innovation

Arrow pointed out the phenomenon of market failure in the process of technological innovation. Due to the indivisibility of inventions, externalities of R&D benefits, and market uncertainty, the investment in invention and research by free enterprise economies may be lower than socially optimal investment[15], and market mechanisms may not lead to optimal choices of technical standards, but rather may lead to the selection of incorrect technical standards[16]. Based on these considerations, the government, according to the needs of macroeconomic and social development, uses administrative measures to formulate plans and incentive policies, establish an industrial policy system through industry selection and planning, and establish technical standards through government standardization organizations or government-authorized standardization organizations. This can compensate for the insufficient R&D investment by enterprises, reduce their R&D risks, and thus help to enhance their technological innovation capabilities.

At the macro level, the strategic decision-making of a country plays a guiding role in the technological innovation of its industries. Since the reform and opening up, China has gradually incorporated technological innovation into its important national development strategies. The 18th National Congress pointed out that technological innovation is a strategic support for improving social productivity and comprehensive national strength, and must be placed at the core of national development. In 2013, the State Council issued a notice on the "Twelfth Five-Year Plan for National Independent Innovation Capability Building", which emphasized the need to strengthen government coordination and planning guidance, and further enhance the market's fundamental role in resource allocation to guide active participation of social innovation entities. The deep integration of industry and information technology should be promoted, and the intelligent and digital applications of manufacturing processes should be strengthened to improve the integration and innovation of automation and information technology such as distribution control and digital control.

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Technology standards are valuable technical achievements and also internationally and domestically recognized basic requirements for product quality. They are the crystallization of experts' long-term experiments, research, and discussions. The process of standard formulation, implementation, and revision is in fact a process of innovation and dissemination of experience and technology, leading to further innovation. Therefore, enterprises that fully understand and adopt these standards can make their products competitive in domestic and foreign markets, and further promote product research and development [17]. The "Regulations on Seismic Management of Construction Projects" stipulate that "public buildings such as new schools, kindergartens, hospitals, nursing homes, emergency command centers, and emergency shelters located in high-intensity fortification areas and earthquake key monitoring and defense areas should adopt seismic isolation and mitigation technologies." The promulgation of this regulation will further promote the rapid development of this technology in China. For example, in the award-winning project "Key Technologies and Engineering Applications of High-performance Seismic Isolation Buildings" in 2020, the project team developed high-performance rubber bearings that are at the international leading level; developed viscous dampers with adjustable performance parameters that can effectively control the deformation of buildings in earthquakes; and proposed for the first time a flexible pipe parameter design method for seismic isolation layers, and compiled a national industry standard, filling a gap in this field.

4.2.3. Expanding industries widen the boundaries of technological innovation

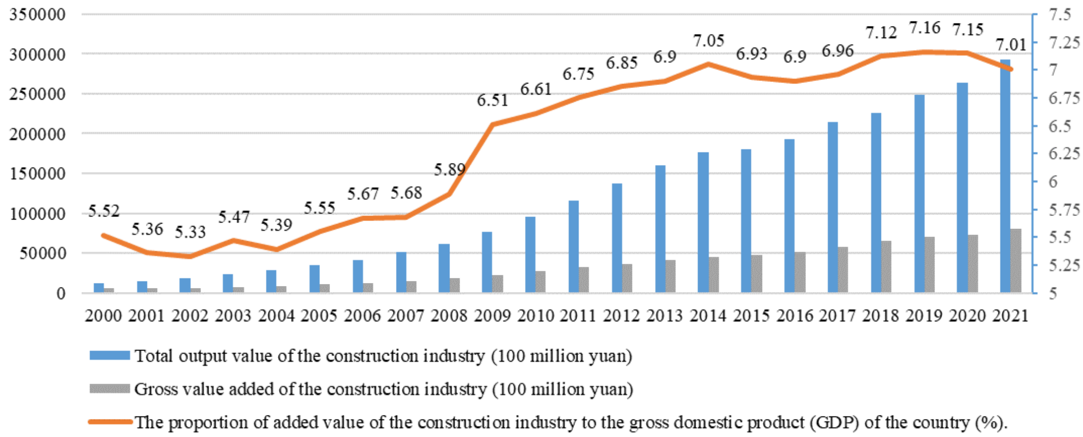

Figure 7: Total output value and value-added of China's construction industry, and the proportion of GDP from 2000 to 2021.

By seeking technological knowledge through cross-disciplinary approaches, enterprises can not only increase differentiation in their technical elements and bring forth more innovative ideas, but also break through the initial technological limitations and create potential solutions in a more radical way by combining internal and external knowledge to form breakthrough technological innovations [18]. With the rapid development of the construction industry, enterprises in various industries have been integrating their leading technologies with construction technology to gradually expand the boundaries of technological innovation in the construction industry. As shown in Figure 7, as China's urbanization process deepens, the output value of the construction industry continues to expand, with a total output value of 29.31 trillion yuan in 2021, a year-on-year increase of 11.04%. Since 2012, the proportion of value added by the construction industry to GDP has remained above 6.85%, reaching 7.01% in 2021 despite a slight decrease, and the construction industry remains a pillar industry of the national economy. In 2015, the "Beijing-Shanghai High-speed Railway Project" won an award, with China Water Resources and Hydropower Construction Group Co., Ltd. as a participating unit. In 2009, China Water Resources and Hydropower Construction Group made great strides in the new field of railway construction and won a 142.7 billion yuan contract for 266.6 kilometers of the Beijing-Shanghai High-speed Railway, and subsequently won contracts for the Gui-Guang Railway, Nan-Guang Railway, and Ning-Hang Railway Passenger Dedicated Line projects. In fact, in 2008, the company's non-hydropower construction bidding contract amount accounted for 34% of the total contracting amount of the group, and non-hydropower construction has become a new business area that the company is focusing on expanding. In 2016, the award-winning project "Key Technologies and Applications of Mobile Integrated Lifting Equipment for Large-scale Engineering Construction" led to Xugong developing eight super-large crawler cranes and trailer equipment ranging from 650 to 3600 tons, fundamentally transforming the traditional production mode of the construction industry. The 1,000-ton crawler crane has also proven its worth in many

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important projects, lifting deep-sea pipelines weighing over 650 tons and reaching up to 96 meters high, and connecting them to main structural components over 200 meters away under a 90% load, successfully challenging the limits of marine engineering construction and becoming the only domestically produced thousand-ton-level product to enter the marine engineering construction field.

5. Conclusion

This article examines the award-winning situation of the National Science and Technology Progress Award in the civil engineering field since 2000. It constructs a "technology-society system" evolutionary framework for the construction industry and identifies the themes of technological changes in the construction industry using LDA topic modeling. The study investigates the evolutionary characteristics of technological innovation in the construction industry and reaches the following conclusions:

(1) From a systemic perspective, this article defines the connotation of the technological evolution of the construction industry and analyzes its technological evolution mechanism, pointing out that the technological system of the construction industry is an evolutionary mechanism that combines self-organization and synergistic effects.

(2) The self-organizing manifestation of the evolutionary process of the technological system in the construction industry is "self-creation." Based on the dynamic development mode of "path dependence" of technological knowledge accumulation and the cross-disciplinary integration, technological coupling continuously provides momentum for the self-organizing evolution of the technological system. In scientific and technological innovation, science and technology are closely integrated, and new scientific discoveries directly guide technological innovation. This type of scientific discovery may direct technological innovation to closely follow scientific discoveries and enter the forefront of scientific and technological progress.

(3) The "random fluctuations" caused by the synergistic effect between the social subsystem and the technological system have played a promoting role in technological innovation in the construction industry. Technological innovation is driven by market demand and mutual benefit between technology and the economy, guided by major national strategies, and expanded by industrial expansion to broaden the boundaries of technological innovation.

Efforts should be made to strengthen interdisciplinary integration in modern engineering and technological scientific research, drive the development of basic science and engineering technology, and form a complete modern scientific and technological system. Accelerate the construction of innovation consortia led by leading enterprises, supported by universities and research institutes, and coordinated by various innovative entities to develop an efficient and powerful common technology supply system and improve the effectiveness of the transfer and transformation of scientific and technological achievements.

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