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RESEARCH ARTICLE

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Adaptability evolution of financing systems of mega projects

Abstract Mega projects require large funding, which often reaches tens or even hundreds of billions of yuan. In the state-oriented financing system, the huge fund gap has generally become an important factor restricting the development of mega projects worldwide. Since the 1980s, China's long-span bridge projects have developed rapidly as typical mega projects as their financing systems have also undergone a series of changes and shown a high adaptability to complexity. However, the existing literature based on the perspective of evolution lacks focus on the complexity of mega project financing systems and its causes. Therefore, the complexity of the financing methods employed in the financing systems for China's long-span bridges is analyzed in this work from the dimensions of time and regions through investigation and interviews. On the basis of the results and complex adaptive systems theory, the causes of the complexity are further explored in terms of the clustering effects of financing subjects and the deep uncertainty of financing environments. Then, the evolution rules of financing systems of mega projects are established from the aspect of financing subjects, financing environments, and financing methods. The research results can enrich decision-makers' understanding of the essential attributes and formation mechanism of the financing systems of mega projects and provide powerful support for decision-making in financing.

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Keywords adaptability evolution, financing methods, long-span bridges in China, mega projects

1 Introduction

Mega projects require large investments (Jia et al., 2011), and project financing tasks are difficult. After World War II, many countries started mega projects on a large scale by means of financial allocation, government loans, and loans from financial institutions. However, in the 1970s, the international debt crisis worsened due to the large debts incurred by developing countries. With the increase in project investment, governments could not easily allocate adequate funds to meet the increasing demand for mega projects (Lo and Naraharisetti, 2013). Hence, exploring and innovating financing channels for mega projects has become a primary issue for mega projects in all countries (Osei-Kyei and Chan, 2015).

Long-span bridges are typical mega projects. By the end of 2017, China had successfully completed 96423 long-span bridges with a total length of 32510.9 km (with a single span measuring more than 150 m or a total length of more than 1000 m). In addition to their remarkable progress and innovation in design, construction, science and technology, and management, China's long-span bridge projects have achieved innovation in financing channels in engineering. Over the past 40 years, China's mega projects, which are represented by long-span bridge projects, have interacted with financing systems and the financing environment while financing methods have undergone considerable changes (Wu and Jin, 2011). Financing systems, in particular, have experienced an adaptability evolution process, transforming from government financing system into commercialized investment system based on "loaning to construct roads and collecting fees to pay loans", and finally to a market-oriented financing system based on "the transfer of bridge operating right" (Chen, 2009).

Some studies attempted to discuss the external manifestations and internal causes of the evolution of financing systems. Osei-Kyei and Chan (2015) declared that the

evolution of financing systems has contributed to the diversity of financing methods, such as build–operate–transfer (BOT), public–private partnership (PPP) and asset-backed securitization (ABS). Wu (2010) identified a strong association between infrastructure financing and economic performance, as well as an increasing disparity among cities of different regions in terms of their capability of and performance in financing infrastructure. Wang et al. (2011) argued that the evolution of the infrastructure financing system is closely related to a country's transition to a market-oriented economy. On the basis of these studies, the current work aims to explore the following research questions: 1) What is the form of complexity of financing systems of mega projects? For example, how do the results of the evolution of financing methods reflect complexity from the dimensions of time and regions? 2) Why does complexity occur? How should the essential attributes and causes of complexity be analyzed from the perspective of the clustering of subjects and environmental uncertainty? 3) What is the general path of this complexity evolution? How should the rules of complexity evolution of the financing systems of mega projects be established on the basis of complex adaptive systems (CAS) theory?

2 Literature review

2.1 CAS and mega construction projects

CAS theory is a new theoretical framework based on complexity theory. It emphasizes the association and integration of system components and describes the system evolution process through adaptive learning in a complex and dynamic environment (Schneider and Somers, 2006). CAS theory and its corresponding model focus on the interactions between systems and environments, as well as their co-evolutions (Choi et al., 2001). CAS theory is a subset of nonlinear dynamic systems (Lansing, 2003). The goal of CAS theory in the initial stage is to find the logic and behavioral criteria of complex systems (Kauffman, 1996) and to summarize and analyze the system-level attributes that subjects present (Auyang, 1998). The definition of CAS generally includes a series of rule-based behavior subjects located in a multilevel network interconnection system; these subjects are usually characterized as diverse, dynamic, and capable of high interaction and self-adaptation (Keshavarz et al., 2010).

The impact of mega projects and the extent of such impact on society and the environment make them greatly different from general projects in terms of complexity (Pitsis et al., 2018); hence, these mega projects should be managed as a different project type (Flyvbjerg, 2014). The complexity of mega projects stems from the complexity of environmental factors, such as various financing channels, management processes involving multiple behavior subjects, and administrative regulations regulated to social and organizational norms (Pitsis et al., 2018). Therefore, in addition to complex internal operation mechanisms, mega projects also face the challenges brought by the complex environment that changes continuously. CAS theory is focused on the diversity of systems' internal environments. Over time, we can see how condition changes affect the clustering of subjects in a system and promote the co-evolution of individuals and environments under interactions and feedback from the perspective of adaptability (Keshavarz et al., 2010). Therefore, CAS theory may be used to address the theoretical and practical challenges faced by mega projects. In the study of the complexity of mega projects, scholars have attempted to view the complexity of the evolution mechanism of mega projects in systematic matter and regard it as a regulatory factor for research questions (Berggren et al., 2008; Müller et al., 2012; Teller et al., 2012). The complexity of mega projects can be further decomposed into six elements, namely, the complexity of technology, society, finance, legislation, organization, and time; these elements make up the complex environment faced by mega projects (Sheng and Lin, 2018). With the construction of Terminal 5 in Heathrow Airport and 2012 London Olympic Park as examples, a mega project analysis framework that includes dynamic complexity has been developed (Kujala et al., 2014).

In the complex systems of mega projects, stakeholders adjust their actions according to different emergent situations to adapt to other subjects' behaviors (Morris, 2013). To some extent, the viewpoints of adaptability and evolution can be regarded as another perspective of CAS theory. Relevant scholars believe that the adaptability management of engineering plans can be achieved through strategic balance (Rijke et al., 2014; Li et al., 2018). The complexity may result from the inherent nature of the objective environment or from the subjective ability of subjects. It requires subjects to continue "learning" through wide interactions and then enhance their capabilities of dealing with complexity; such process is called the adaptability of subjects' behaviors (Sheng, 2017). In addition, the concept of deep uncertainty is proposed for the complexity of the subjects and environments of mega projects to provide a clear understanding of the essential attributes and impact mechanism of the complexity of mega projects (Sheng, 2017). In summary, due to the common characteristics between mega projects and CAS, scholars have carried out extensive research in the field of mega projects from the perspective of complexity and adaptability in recent years. However, the detailed mechanism and effective analysis framework of CAS theory in mega projects need to be further improved and expanded, and the financing-related factors require extensive research to some extent. In sum, the complexity of mega project financing necessitates adequate attention.

2.2 CAS in financing systems of mega projects

Compared with those of general projects, the financing systems of mega projects are characterized by a large capital gap, narrow financing channels, and high financing costs. The financing activities related to mega projects directly show complex characteristics. At the level of complex systems, financing systems of mega projects include a group of entities that follow specific decision rules and interact with other individuals and environments (Pathak et al., 2007); the composition of this group is similar to that of CAS (Janssen et al., 1999). Financing systems of mega projects are complex systems comprising financing subjects, financing methods, and financing environments. The main carriers in these systems are materials, capital, energy, and information. These systems are aimed at maximizing the interests of each financing subject. They are in line with the characteristics of CAS, that is, they include various subjects and environments and are aimed at determining the kind of complex dynamics shown by the main system (Railsback, 2001). Therefore, financing systems of mega projects represent the interaction results between financing subjects and environments. They manifest the emergence of a system as a whole, and their essence is a complex adaptability system.

Scholars have applied CAS theory and similar theories to relevant research in the financial field. Relevant research relates to the business ecosystem, which takes financing as a factor as important as CAS; the stock market, taking CAS to explore market efficiency (Mauboussin, 2002); and the application of risk–return analysis (Song et al., 2012). However, the application of CAS theory directly to the financing issues of mega projects has yet to be studied extensively. Therefore, the current study intends to discuss the evolution of the financing systems of mega projects from the perspective of CAS so as to reveal the complex adaptability of these systems effectively.

3 Complexity of financing systems for long-span bridges in China

3.1 Sample collection

In this study, a nationwide sampling investigation of long-span bridges was carried out in the eastern, central, and western regions. The multi-stage stratified sampling and convenience sampling were combined to establish the sampling method. In the first stage, a total samples of 73 typical long-span bridges in 13 provinces in the eastern, central, and western regions of China were selected (see Appendix). Selecting the samples of long-span bridges from different regions allowed a lateral comparison and the verification of the conclusions drawn from the samples of different regions. The 73 long-span bridges were sorted according to geographical dimensions, and the results are shown in Fig. 1. In the second stage, at least four bridges were selected from each province for a detailed study. This selection improved the comparability of the samples as their political and economic environments are similar.

3.2 Complexity of financing systems for long-span bridges

Zeng et al. (2014) analyzed in detail the investment and financing systems for China's renewable energy from five perspectives: Investment situation, investment and financing bodies, investment and financing means, sources of funding, and financing channels. Wang and Yang (2008) proposed that project financing decisions should be in accordance with the size of project financing, sources of funding, financing structures, and financing options. Furthermore, Henisz (2002) demonstrated that financing environment are an important determinant of investment in vital economic infrastructure. On the basis of this research, the present work provided a figure to display the financing systems for long-span bridges, including the financing

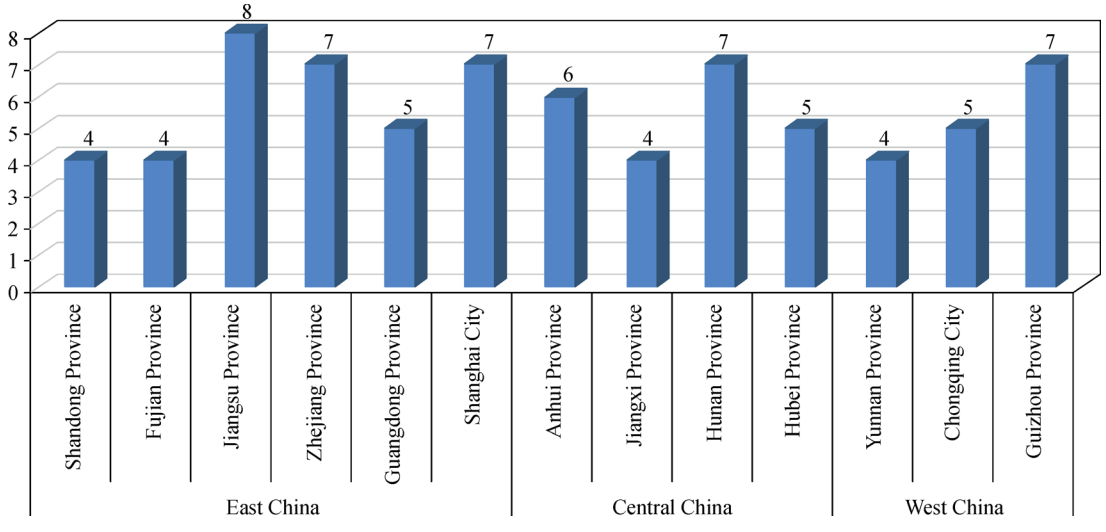

Fig. 1 Samples of long-span bridges and their geographical distributions.

agents, financing environments, and financing methods (Fig. 2).

In China, the agents of financing systems can be roughly classified as project sponsors, lenders, governments, and other third parties, such as suppliers and contractors (Brealey et al., 1996; Sheng, 2017). The financing environment is a system composed of the natural, social, economic, political, and legal environments where the financing activities are located (Henisz, 2002).

In the phase of project feasibility study, various financing methods can be adopted for long-span bridges, and they include government financing and non-cooperative franchise project financing, such as BOT, PPP, and ABS (Zhang et al., 2016; Chan et al., 2018). In this work, the financing methods for long-span bridges were divided into three categories, namely, government financing, government financing + bank loan, and market-oriented financing methods. Financing structure, a combination of debts and equity, describes how a project finances capital. Debt is provided by lending institutions (e.g., banks), and equity is provided by other financing subjects (e.g., governments at all levels) (Dias Jr and Ioannou, 1995).

As shown in Fig. 2, financing methods are important in the financing systems for long-span bridges, which are directly affected by financing environments and financing subjects. The choice of financing method also affects the financing structure of long-span bridges. Therefore, this section takes financing methods as a pointcut to analyze the complexity of financing systems for long-span bridges.

3.2.1 Complexity of time evolution

With the evolution of the financing systems of long-span bridges, new financing methods are emerging and becoming increasingly diversified. At present, financing systems of long-span bridges in China have basically formed a diversified financing pattern, which is characterized by "state investment, local government financing, non-governmental financing, and introduction of foreign investment" and "loaning to construct roads, collecting fees to pay loans, and performing a rolling development pattern". Traditional financing methods, such as governmental financing, debt financing, and internal financing still exist, but their leading roles are gradually weakening. With the introduction of international funds and the growing private capital, project financing channels have broadened continuously. For example, the geographical range of a BOT-based project financing method has further expanded, and its form has become further diversified. The PPP mode of public–private cooperation has also gradually increased. The financing methods for long-span bridges evolve continuously. This evolution has prompted investors to participate in projects, broadened the financing channels of long-span bridges, and enriched the financing methods for long-span bridges. These conditions have prompted various provinces and cities to break through the financial pressure, innovate the financing methods for long-span bridges, and develop the construction of long-span bridges.

3.2.2 Complexity of geographical distributions

The formulation of financing decision-making plans is influenced and restricted by economic development, government financial situations, and the bridging of financial benefits and relevant legal systems in the regions where bridge projects are located. From the perspective of natural, social, political, and economic environments in the eastern, central, and western regions of China, this work explores the complexity of the geographical distributions of the evolution of regional financial systems. As shown in Fig. 3, the financing methods for 73 bridges in the eastern, central, and western regions of China are counted from the angles of government financing, government financing + bank loan, and market-oriented financing.

(1) Eastern regions

As shown in Fig. 3, the application of market-oriented financing methods in the eastern region is more mature

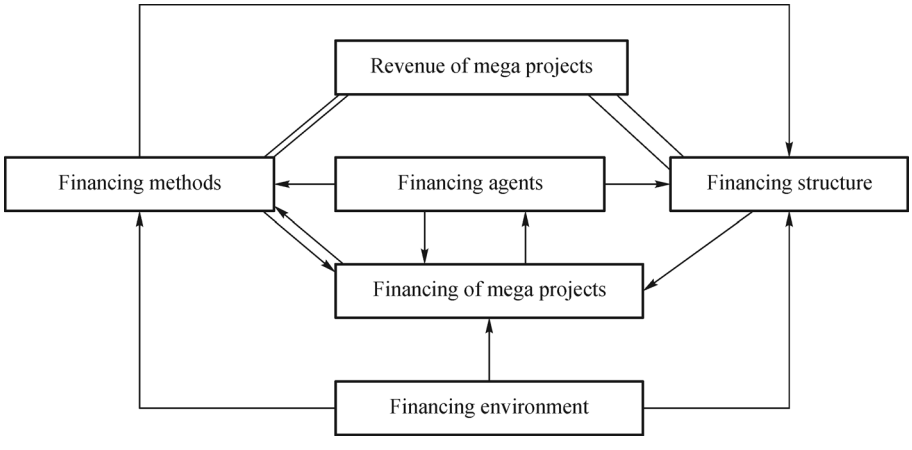

Fig. 2 Complexity of financing systems of mega projects.

than that in the central and western regions. Most of the innovative financing methods for bridge projects, such as bond issuance, financing of the international capital market, and BOT, come from the eastern region. This phenomenon can be explained in three ways. First, the demand for infrastructure, such as highways and bridges, in Eastern China is high because of the developed commodity economy and dense population. Flat terrains and dense rivers provide a good environment for long-span bridge projects. Second, the developed regional economy, abundant social resources, and sufficient fiscal revenue and expenditure in the eastern region promote the development of market-oriented financing methods for bridge projects led by the government. Third, the relatively high economic benefits of toll bridges in Eastern China have attracted large sums of private capital, which is in turn invested in long-span bridge projects. Hence, the eastern region maintains leading advantage in the evolution of financing systems.

(2) Central regions

Figure 3 shows that long-span bridges adopting the modes of government financing and government financing + bank loan are widespread in the central region. Hence, the financing method for long-span bridges in Central China is relatively simple. The economic benefits of long-span bridges in the central region are not significant due to the limitations of traffic flow, which make the construction of long-span bridges unattractive to social capital and restrict the application of innovative financing methods for long-span bridges. Therefore, the pace of the evolution of financing systems of long-span bridges in the central region is slow.

(3) Western regions

Except for Guizhou Province (see Appendix), most of the long-span bridges in the western region result from "state subsidies and government repayment". This mode is mainly due to the important strategic position of the western region in China. The construction of roads and bridges is aimed at maintaining social stability and meeting the strategic needs of western development. Hence, the bridge projects in western provinces focus more on political benefits than on economic benefits. Despite state subsidies, long-span bridge projects in Western China still face issues such as low return on investment and the failure of the government to recover capital and repay bank liabilities.

4 Analysis of adaptability evolution of financing systems of mega projects

4.1 Analysis of financing system subjects and clustering of subjects

As discussed in the previous section, long-span bridges are taken as examples to describe the evolution characteristics of the complexity of financing systems. To further explore the causes of the complexity, this work analyzes the reasons for the complexity of the financing systems of mega projects on the basis of CAS theory. First, subject analysis is the starting point of the theoretical analysis of CAS (Choi et al., 2001). Subjects in CAS have adaptability and initiative, as well as their own goals, attributes, patterns, and internal structures (Pathak et al., 2007). They can also change their own code of conduct through the interactions between themselves and the environment so as to achieve survival and development in a complex environment (Schneider and Somers, 2006). All subjects

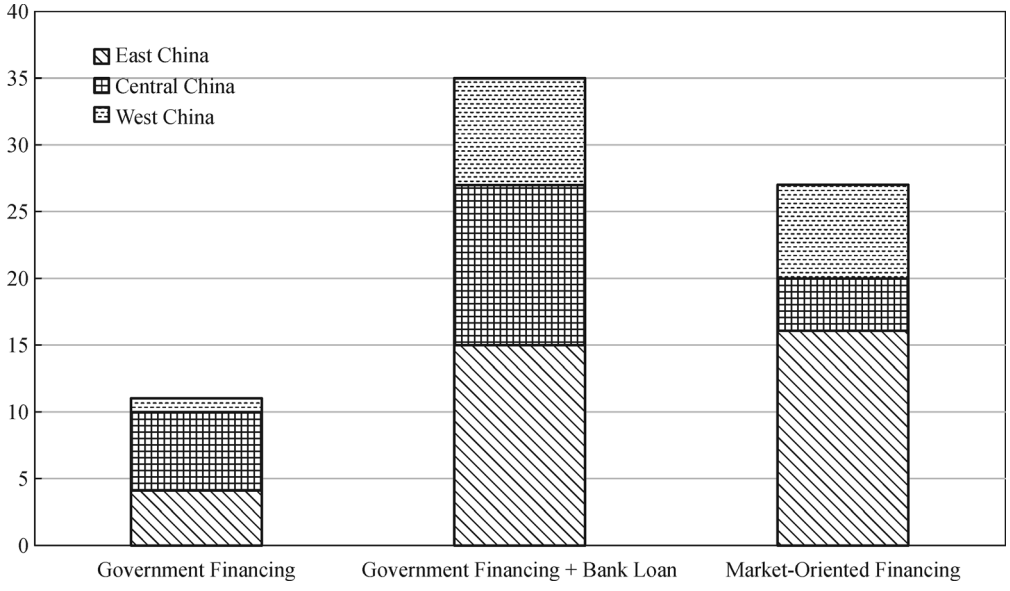

Fig. 3 Geographical distributions of financing methods for sample bridges.

in a financing system have initiatives, financing objectives, and interest considerations (Shen et al., 2002). They take the maximization of their own interests as the fundamental goal. Decision-making behaviors can be adjusted according to other subjects' behaviors in the environment. Therefore, we should attach importance to the interactions among various subjects. Figure 4 shows the participants from all parts and their clustering analyses in financing systems of mega projects.

Unit subject clusters through interactions and then form a large complex system (Holland, 1992). In the financing systems of mega projects, the government mainly brings about policy clustering; promulgates relevant policies to provide subsidies, franchises, and so on for projects; or provides necessary and basic conditions for project development, such as land, infrastructure, and energy supply, so as to reduce the risks of project construction and operation. A project sponsor mainly brings about factor clustering. It refers to the legal entity that directly participates in project investment and project management and takes responsibility for debts and project risks. It can be a company or a union of investors, such as contractors, suppliers, and financial institutions. Product or service users can promote the clustering of public project resources, and their demands and interests need to be considered. The accurate analysis of users can promote the effective supply of services. Third-party professional service organizations, such as financial consultants and legal experts, bring about the clustering of professional services.

4.2 Deep uncertainty analysis of financing environments

In the decision-making process for project financing, the financing environment is generally dynamic and prone to complex self-organizing and self-adaptive phenomena, which are expressions of deep uncertainty in the project financing environment. "Deep uncertainty" is a more serious uncertainty (Sheng, 2017), which originates from the practice of mega project management activities and is no longer applicable to traditional and conventional ideas and methods.

Mega project financing is inevitably related to a series of factors of financing decision-making environments, such as national politics, social stability, economic development, financial security mechanism, and national monetary policies. It is also related to issues such as project construction scheme, total amount of static investment, dynamic investment control of projects, budget adjustment and policy support for immigration and demolition, and reduction and exemption of compensation tax. Similarly, the deep uncertainty of legal, political, natural, economic, and social environments also exerts an impact on the financing decision-making of mega projects. Therefore, the deep uncertainty of the financing environments of mega projects has an important impact on the complexity of financing decision-making for mega projects.

Mega project financing is inevitably related to a series of factors such as national politics, social stability, economic development trend, financial security mechanism, national monetary policy, immigration and demolition policy, and

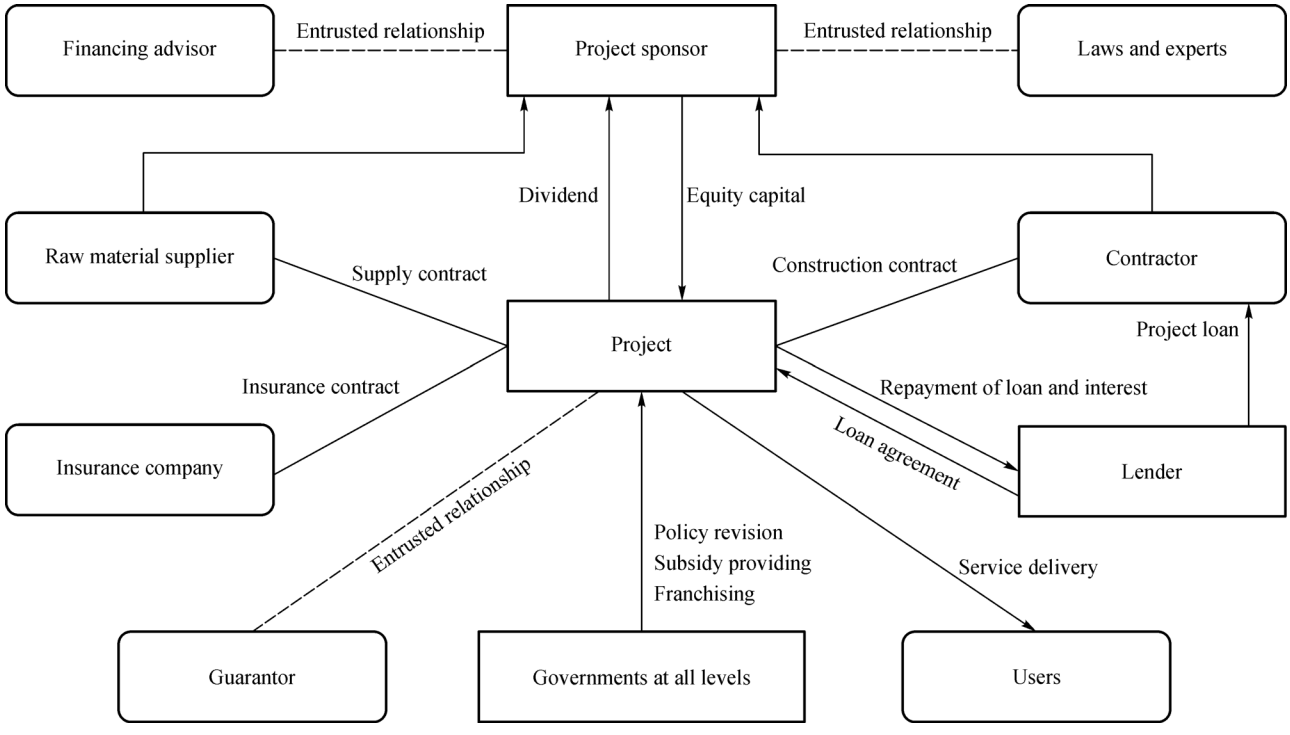

Fig. 4 Analysis of multiple subjects and their clustering in financing systems.

compensation tax reduction and exemption policy. For mega projects, the financing environment system can be defined as a complex self-organizing system consisting of the economic, social, political, and institutional environments where the financing activities exist. Deep uncertainty is generally defined as multiple possible results that cannot describe the future accurately, and it results from the inadequacy of subjective ability and lack of information, the complexity formed by a strong connection structure, and the self-organization and evolution of systems in large scales (Sheng, 2017). According to the definition above, we can conclude that the nature of the financing environment of mega projects is complex and deeply uncertain.

(1) Deep uncertainty formed by the coupling of political and economic environments. Mega projects have dual attributes—social public goods and commodity attributes (Yan et al., 2017). Therefore, market economy factors and rules play increasingly important roles in the financing of mega projects (Geraldi and Adlbrecht, 2007; Bosch, 2011). As China's market economy mechanism is still imperfect, the market information is asymmetric, and excessive interventions to project financing from the government happen frequently. The dual role of the government and the market lead to the deep uncertainty of the financing environment of mega projects.

(2) Deep uncertainty formed by the strong connections between social and institutional environments. In China, mega projects involve the central government and local governments, as well as the subjects with various nature and regions. The corresponding systems and cultures may be inconsistent, which translates to deep uncertainty resulting from cultural and institutional uncertainty at different levels and in different regions.

4.3 Evolution framework of complex adaptability of mega projects' financing systems

According to CAS theory, the interactions of mega projects' financing systems are the basic motivation for the evolution of these systems. Here, interactions refer to those among the subjects within system and those between the financing environments and other stakeholder subjects (Fleming and Sorenson, 2001). Information, material, and financial exchange exist among the subject, method, and environment levels of financing systems. The adaptability of financing systems may improve with the increasing number of factors in various levels, the fluent distribution channels, and the quick turnover. As shown in Fig. 5, the evolution process of financing systems' complexity is reflected in the evolution of financing subjects, financing methods, and institutional environments.

In the evolution of financing subjects, subjects' interactions with financing systems are the basic motivation for evolution (Choi et al., 2001); these interactions occur among the subjects within the systems and between financing environments. The financing subjects that comprise mega projects' financing systems become increasingly complex, as they evolve from the pattern in which the central government guides the local governments during the construction of multi-subject systems. The constant clustering of financing subjects brings about new motivation for evolution.

In the evolution of financing environments, financing policies involve various aspects such as society, economy, politics, and institutions. Hence, the changes of financing policy environments are taken as representative to show the abstract evolution process of financing environments concretely. With the continuous development of China's economy and the increasing demand for mega projects, the planned economy fully funded by the government cannot meet the huge amount of construction funds required, and the amount of investment necessitates further increase (Li et al., 2016). Therefore, policies such as "loaning to construct roads" and "collecting fees to pay loans" have gradually emerged, and capital has been introduced into mega projects' financing systems.

The aforementioned social, economic, political, and institutional financing environment factors affect the financing methods of mega projects through financing policies. The methods evolve from pure financial investments to the combinations of financial investment, enterprise financing, and franchise operation. Then, a complex structure of organic combinations is formed in accordance with specific situations.

As a result of the superposition effects brought by the evolution of different factors and different levels, a longitudinal penetration of information, material, and financial exchange exists among the subjects (Walker, 2004), methods, and environments of financing systems. Such a "flow" includes two aspects. On the one hand, the flow within the level includes deep uncertainty within the level. For example, at the subject level, different subjects take different responsibilities in a multi-subject system that is formed by the clustering of subjects. The government often offers guidance and a certain amount of fund. Project sponsors obtain the capital flow from subjects such as lenders, whereas third parties often obtain funds through material support.

On the other hand, the flow between different levels includes deep uncertainty outside the levels. As shown in Fig. 5, the early planned economic policy provides guiding information unilaterally for mega projects' financing subjects and financing methods (Feltenstein and Farhadian, 1987). However, in the middle and late stages of evolution, institutions such as project capital provide guidance for the combination of various financing methods, and new financing structures provide feedback for the improvement of financing policies under the innovation and practice of multiple subjects. At the same time, the application of financing subjects to financing methods promotes the development of the local economy and society and

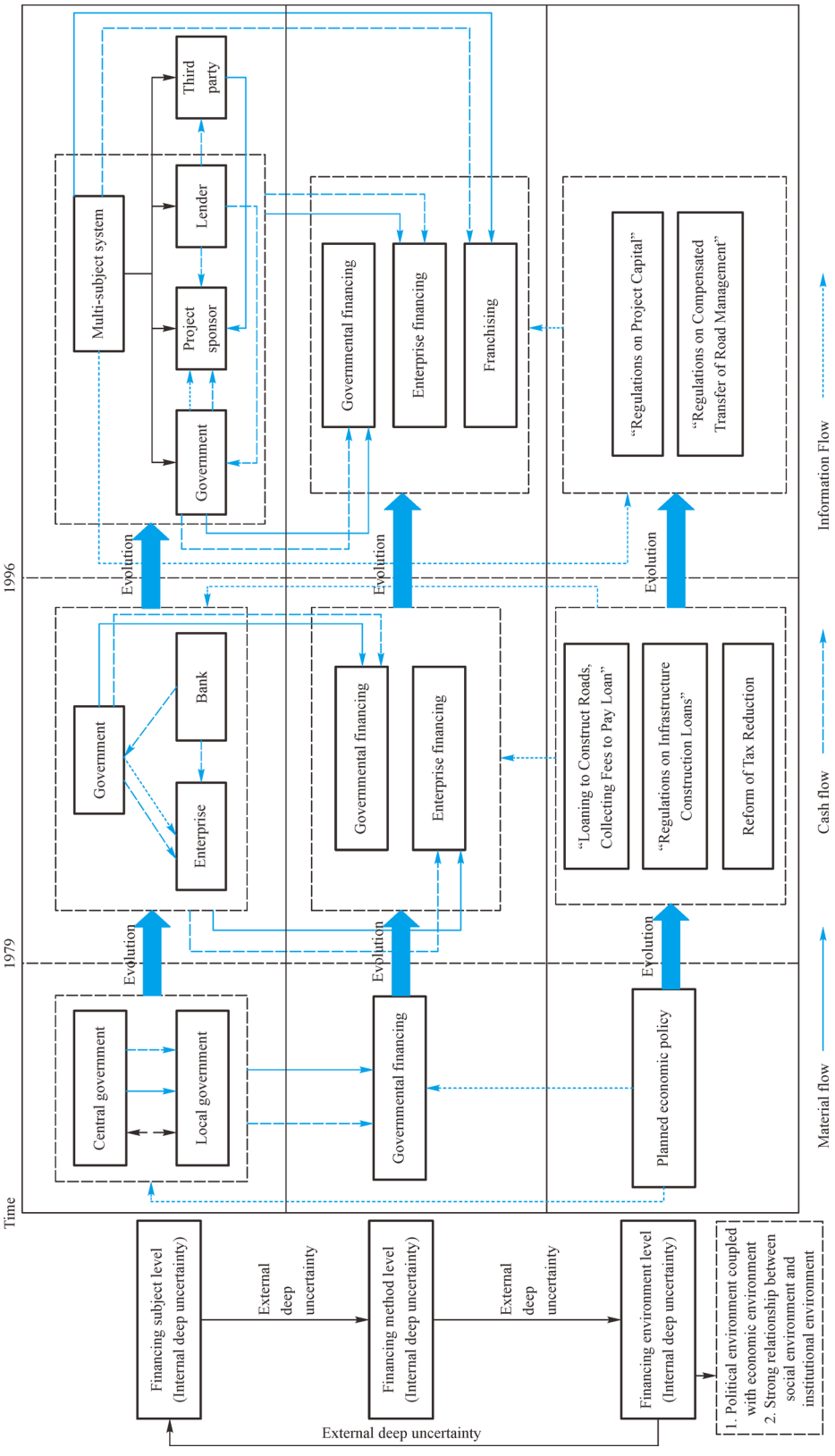

Fig. 5 Evolution framework of complex adaptability of mega projects' financing systems.

changes people's inherent concepts of project financing decision-making. Similarly, among subjects and methods, the initial mode that local governments implement for financial investment has gradually evolved into the mode in which a multi-subject system takes different parts of the financing structure and coordinates and integrates at the system level. For example, project companies composed of governments, lenders, and project sponsors undertake enterprise financing together, and the franchise operation is dominated by a multi-subject system (Combs et al., 2004).

Therefore, we proposed the model of evolution of mega projects' financing systems (Fig. 5) that combines the concept of deep uncertainty and CAS theory. In the evolution of mega projects' financing systems, deep uncertainty becomes obvious if the number of factors at various levels is excessive and the flow between different levels is complex. In the case of fluent distribution channels and rapid turnover, the adaptability of financing systems is expected to improve.

5 Discussion and implications

5.1 Theoretical contributions and implications

This study takes long-span bridges in China as examples to abstract the financing systems of mega projects into CAS, and to thoroughly discuss adaptability evolution. First, CAS theory has been widely used in natural sciences and inter-disciplines (Kauffman, 1996; Janssen et al., 1999), but it is still in the development stage in the field of engineering and finance (Choi et al., 2001; Zhou et al., 2015). From the perspective of time and geographical distributions and on the basis of the complexity analysis of the financing systems of China's long-span bridges, we further analyze the adaptability evolution of mega projects' financing systems and provide a good supplement for the application of CAS theory to mega projects. On the basis of comprehensive analyses, we introduce deep uncertainty into CAS theory (Sheng, 2017), describe in detail the various uncertainties in the complex environment faced by mega projects' financing systems, and finally abstract an evolution optimization framework for complex adaptability that takes deep uncertainty into consideration. Such optimization framework complements and further improves CAS theory.

Secondly, CAS theory is mostly applied at abstract levels and in the conceptual field (Jayanthi and Sinha, 1998; Innes and Booher, 1999). From the perspective of the clustering of subjects and environmental uncertainty, we specifically analyze the causes of the complexity of mega projects' financing systems and then provide new insights into the evolution of mega projects' financing systems for the improvement and usage of the CAS model. First, considering the influence of the clustering of subjects, we analyze the complex clustering effects brought by the specific actions of project sponsors, lenders, governments, and other third parties in the transmission and feedback of systems. Second, we use the definition of deep uncertainty to further expand the dynamics, complexity, and adaptability of the financing environments and operating conditions of mega projects' financing systems. In this process, we consider different scenarios to analyze the effects brought by the subject diversification financing pattern, the complex financing decision-making environment, and the diversification of financing methods included in the mega projects' financing systems. We also discuss the CAS characteristics of deep uncertainty among the financing subject, the financing environment and the financing methods, such as nonlinearity, which is transmitted in the interaction process. On the basis of the progressive analysis, we finally put forward an evolution framework of the complex adaptability of mega projects' financing systems. The goals are to improve CAS theory; conduct an in-depth discussion about the interactions between system subjects, methods, and environments via information, materials, and capital; and provide the analysis methods and framework of CAS in the field of mega projects and project financing.

5.2 Implications for practice

This work provides various viewpoints for owners and stakeholders to understand the attributes of mega projects' financing systems and their evolution processes. First, this study helps project sponsors, lenders, governments, and other third-party stakeholders to understand the complexity of mega projects' financing systems in practice. It also provides two main perspectives.

On the one hand, the influence of the evolution of financing methods and the influence of complexity on the evolution of mega projects' financing systems are considered in the decision-making process. Taking China's long-span bridges for examples, with the continuous evolution of financing methods, bridge types gradually show a diversified trend. The types interact with financing subjects and environments and aggravate the complexity of systems. The causes are closely related to the changes in China's political and economic environments, which act on the administrative system and financing policies and thus change the financing methods indirectly from the time dimension. However, mega projects sometimes take the lead in innovating financing methods and thus guide the changes in financing environments. Therefore, fully understanding the complexity of financing methods and selectively applying them to specific complex environments or timely implementing combinations and innovation can help governments and owners attract financing subjects to participate and make mega projects go smoothly (Klerkx et al., 2010). For stakeholders, fully understanding the complexity of financing methods is conducive to the realization of maximum benefits

(Hämäläinen et al., 2001).

On the other hand, the influence of the formation of regional differences and the influence of complexity on the evolution of mega projects' financing systems are considered in the decision-making process. Fully understanding the complexity of the regional distributions of financing systems' evolution and the different financing environments can help financing subjects understand the regional differences of financing methods and make adaptability choices in accordance with the environmental complexity of different regions. For example, in the case of long-span bridges in China, the evolution of the financing systems in the eastern, central, and western regions is sorted out, and the results show the trend of adaptability selection in different regions. Therefore, owners can adopt different market-oriented financing methods according to the environmental complexity in different regions.

Second, although this work focuses on studying the adaptability evolution of financing systems in the case of long-span bridges, it still offers practical guidance for other mega infrastructure projects, such as highway and hydropower projects. On the one hand, the viewpoints about the clustering of subjects can inspire owners to pay attention to the clustering of policies, factors, resources, and services in the planning and management of mega infrastructure projects, which are brought by the subjects from different levels. On the other hand, this work suggests that owners consider the influence of the deep uncertainty of financing environments on financing decision-making. To ensure the implementation and future operation of projects and to maximize the economic and social benefits as much as possible, the owners who make decisions should implement and continuously adjust the financing issues to understand the multiple characteristics of environmental complexity and the environmental deep uncertainty caused by their interactions.

6 Conclusions

This work makes a thorough analysis of the complexity of mega projects' financing systems, points out the complexity characteristics of time evolution and the regional distribution of project financing systems, explores the causes of the complex adaptability evolution of mega project financing systems from the perspective of the clustering of subjects and the environmental deep uncertainty, and reveals the adaptability evolution rules of mega projects' financing systems from three aspects, namely, financing subjects, financing methods, and financing environments. Although the long-span bridge selected in this work is a typical mega project and can basically represent the common characteristics of mega projects' financing systems, it still has some sampling limitations. The project sample also has typical Chinese characteristics and is thus not universal enough. In the future, we can consider expanding the sample range and further study the relationships between policy evolution and financing method evolution under the drive of system adaptability.

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Appendix

The list of 73 long-span bridges

No.	Project title	Completion time	Location	Financing methods
1	Shengli Yellow River Bridge	1987	Shandong	Market-oriented financing methods
2	Binzhou Yellow River Highway Bridge	1974	Shandong	Government financing + Bank loan
3	Jiyang Yellow River Highway Bridge	2008	Shandong	Market-oriented financing methods
4	Jiaozhou Bay Bridge	2011	Shandong	Market-oriented financing methods
5	Haicang Bridge	1999	Fujian	Government financing
6	Langqi Minjiang Bridge	2014	Fujian	Government financing + Bank loan
7	Xiazhang Bridge	2013	Fujian	Government financing
8	Qingzhou Minjiang Bridge	2002	Fujian	Market-oriented financing methods
9	Jiangyin Yangtze River Bridge	1999	Jiangsu	Government financing + Bank loan
10	The Nanjing Yangtze River Bridge	1968	Jiangsu	Government financing
11	The Second Nanjing Yangtze River Bridge	2001	Jiangsu	Market-oriented financing methods
12	The Third Nanjing Yangtze River Bridge	2005	Jiangsu	Market-oriented financing methods
13	The Fourth Nanjing Yangtze River Bridge	2012	Jiangsu	Government financing + Bank loan
14	Runyang Bridge	2005	Jiangsu	Government financing + Bank loan
15	Sutong Yangtze River Highway Bridge	2008	Jiangsu	Government financing + Bank loan
16	Taizhou Yangtze River Bridge	2012	Jiangsu	Government financing + Bank loan
17	Cengang Bridge	2001	Zhejiang	
18	Xiangjiaomen Bridge	2002	Zhejiang	
19	Taoyaomen Bridge	2003	Zhejiang	Government financing + Bank loan
20	Jintang Bridge	2006	Zhejiang	
21	Xihoumen Bridge	2007	Zhejiang	
22	Hangzhou Bay Bridge	2007	Zhejiang	Market-oriented financing methods
23	Jiashao Bridge	2013	Zhejiang	Market-oriented financing methods
24	Panyu Bridge	1998	Guangdong	Market-oriented financing methods
25	Humen Bridge	1997	Guangdong	Market-oriented financing methods
26	Nansha Bridge	2019	Guangdong	Market-oriented financing methods
27	Huangpu Bridge	2008	Guangdong	Market-oriented financing methods
28	Hong Kong–Zhuhai–Macao Bridge	2018	Guangdong	Government financing + Bank loan
29	Songpu Bridge	1976	Shanghai City	Government financing
30	Nanpu Bridge	1991	Shanghai City	Government financing + Bank loan
31	Yangpu Bridge	1993	Shanghai City	Government financing + Bank loan
32	Fengfu Bridge	1995	Shanghai City	Market-oriented financing methods
33	Lupu Bridge	2003	Shanghai City	Market-oriented financing methods
34	Xupu Bridge	1997	Shanghai City	Market-oriented financing methods
35	Shanghai Yangtze River Tunnel & Bridge	2009	Shanghai City	Market-oriented financing methods
36	Wangdong Yangtze River Bridge	2016	Anhui	Market-oriented financing methods
37	Wuhu Yangtze River No. 2 Bridge	2017	Anhui	Government financing + Bank loan
38	Tongling Yangtze River Bridge	1995	Anhui	Government financing
39	Wuhu Yangtze River Bridge	2000	Anhui	Government financing
40	Anqing Yangtze River Highway Bridge	2004	Anhui	Government financing + Bank loan

(*Continued*)

No.	Project title	Completion time	Location	Financing methods
41	Ma'anshan Yangtze River Highway Bridge	2012	Anhui	Government financing + Bank loan
42	Nanchang Bridge	1995	Jiangxi	Government financing
43	Bayi Bridge	1997	Jiangxi	Government financing
44	Yingxiong Bridge	2009	Jiangxi	Government financing
45	The Second Jiujiang Bridge	2013	Jiangxi	Government financing
46	Aizhai Bridge	2012	Hunan	Government financing + Bank loan
47	Chishi Bridge	2014	Hunan	Government financing + Bank loan
48	Dongting Lake Bridge	2000	Hunan	Government financing + Bank loan
49	Wenming Bridge	2012	Hunan	Government financing + Bank loan
50	Hanshou–Yuanshui Bridge	2008	Hunan	Government financing + Bank loan
51	Liancheng Bridge	2007	Hunan	Market-oriented financing methods
52	Changling Bridge	2019	Hunan	Government financing + Bank loan
53	Huangshi Bridge	1995	Hubei	Government financing + Bank loan
54	Yangluo Bridge	2007	Hubei	Government financing + Bank loan
55	Tianxingzhou Bridge	2009	Hubei	Market-oriented financing methods
56	Edong Bridge	2010	Hubei	Market-oriented financing methods
57	Jingyue Bridge	2010	Hubei	Government financing + Bank loan
58	Longjiang Bridge	2016	Yunnan	Government financing + Bank loan
59	Puli Bridge	2015	Yunnan	Government financing + Bank loan
60	Niulan River Bridge	2015	Yunnan	Government financing + Bank loan
61	The First Beipan River Bridge	2016	Yunnan	Government financing + Bank loan
62	Wanzhou Bridge	1997	Chongqing City	Government financing
63	Chaotianmen Bridge	2009	Chongqing City	Market-oriented financing methods
64	Zhongxian Bridge	2001	Chongqing City	Government financing + Bank loan
65	Yunyang Yangtze River Bridge	2005	Chongqing City	Government financing + Bank loan
66	New Baishatuo Yangtze River Bridge	2018	Chongqing City	Government financing + Bank loan
67	Beipan River Bridge (Zhensheng)	2016	Guizhou	Market-oriented financing methods
68	Balinghe Bridge	2009	Guizhou	Government financing + Bank loan
69	Liuchong Bridge	2013	Guizhou	Market-oriented financing methods
70	Qingshuihe Bridge	2015	Guizhou	Market-oriented financing methods
71	Yachihe Bridge	2016	Guizhou	Market-oriented financing methods
72	Beipan River Bridge (Shuipan)	2013	Guizhou	Market-oriented financing methods
73	Sanchahe Bridge (Xiarong)	2015	Guizhou	Market-oriented financing methods